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AGRICULTURE JOURNAL

IJOEAR

International Journal of Environmental
& Agriculture Research

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Preface

We would like to present, with great pleasure, the volume-12, Issue-8, August 2026 of a scholarly journal, *International Journal of Environmental & Agriculture Research*. This journal is part of the AD Publications series in the field of *Environmental & Agriculture Research Development*, and is devoted to the gamut of Environmental & Agriculture issues, from theoretical aspects to application-dependent studies and the validation of emerging technologies.

This journal was envisioned and founded to represent the growing needs of Environmental & Agriculture as an emerging and increasingly vital field, now widely recognized as an integral part of scientific and technical investigations. Its mission is to become a voice of the Environmental & Agriculture community, addressing researchers and practitioners in below areas.

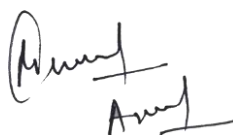
Environmental Research:

Environmental science and regulation, Ecotoxicology, Environmental health issues, Atmosphere and climate, Terrestrial ecosystems, Aquatic ecosystems, Energy and environment, Marine research, Biodiversity, Pharmaceuticals in the environment, Genetically modified organisms, Biotechnology, Risk assessment, Environment society, Agricultural engineering, Animal science, Agronomy, including plant science, theoretical production ecology, horticulture, plant, breeding, plant fertilization, soil science and all field related to Environmental Research.

Agriculture Research:

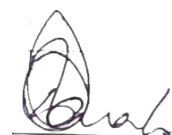
Agriculture, Biological engineering, including genetic engineering, microbiology, Environmental impacts of agriculture, forestry, Food science, Husbandry, Irrigation and water management, Land use, Waste management and all fields related to Agriculture.

Each article in this issue provides an example of a concrete industrial application or a case study of the presented methodology to amplify the impact of the contribution. We are very thankful to everybody within that community who supported the idea of creating a new Research with *IJOEAR*. We are certain that this issue will be followed by many others, reporting new developments in the Environment and Agriculture Research Science field. This issue would not have been possible without the great support of the Reviewer, Editorial Board members and also with our Advisory Board Members, and we would like to express our sincere thanks to all of them. We would also like to express our gratitude to the editorial staff of AD Publications, who supported us at every stage of the project. It is our hope that this fine collection of articles will be a valuable resource for *IJOEAR* readers and will stimulate further research into the vibrant area of Environmental & Agriculture Research.



Mukesh Arora

(Managing Editor)



Dr. Bhagawan Bharali

(Chief Editor)

Fields of Interests

Agricultural Sciences	
Soil Science	Plant Science
Animal Science	Agricultural Economics
Agricultural Chemistry	Basic biology concepts
Sustainable Natural Resource Utilisation	Management of the Environment
Agricultural Management Practices	Agricultural Technology
Natural Resources	Basic Horticulture
Food System	Irrigation and water management
Crop Production	
Cereals or Basic Grains: Oats, Wheat, Barley, Rye, Triticale, Corn, Sorghum, Millet, Quinoa and Amaranth	Oilseeds: Canola, Rapeseed, Flax, Sunflowers, Corn and Hempseed
Pulse Crops: Peas (all types), field beans, faba beans, lentils, soybeans, peanuts and chickpeas.	Hay and Silage (Forage crop) Production
Vegetable crops or Olericulture: Crops utilized fresh or whole (wholefood crop, no or limited processing, i.e., fresh cut salad); (Lettuce, Cabbage, Carrots, Potatoes, Tomatoes, Herbs, etc.)	Tree Fruit crops: apples, oranges, stone fruit (i.e., peaches, plums, cherries)
Tree Nut crops: Hazlenuts. walnuts, almonds, cashews, pecans	Berry crops: strawberries, blueberries, raspberries
Sugar crops: sugarcane. sugar beets, sorghum	Potatoes varieties and production.
Livestock Production	
Animal husbandry	Ranch
Camel	Yak
Pigs	Sheep
Goats	Poultry
Bees	Dogs
Exotic species	Chicken Growth
Aquaculture	
Fish farm	Shrimp farm
Freshwater prawn farm	Integrated Multi-Trophic Aquaculture

Milk Production (Dairy)	
Dairy goat	Dairy cow
Dairy Sheep	Water Buffalo
Moose milk	Dairy product
Forest Products and Forest management	
Forestry/Silviculture	Agroforestry
Silvopasture	Christmas tree cultivation
Maple syrup	Forestry Growth
Mechanical	
General Farm Machinery	Tillage equipment
Harvesting equipment	Processing equipment
Hay & Silage/Forage equipment	Milking equipment
Hand tools & activities	Stock handling & control equipment
Agricultural buildings	Storage
Agricultural Input Products	
Crop Protection Chemicals	Feed supplements
Chemical based (inorganic) fertilizers	Organic fertilizers
Environmental Science	
Environmental science and regulation	Ecotoxicology
Environmental health issues	Atmosphere and climate
Terrestrial ecosystems	Aquatic ecosystems
Energy and environment	Marine research
Biodiversity	Pharmaceuticals in the environment
Genetically modified organisms	Biotechnology
Risk assessment	Environment society
Theoretical production ecology	horticulture
Breeding	plant fertilization

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Mr. Isaac Newton ATIVOR

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Harnessing Solar Energy for Pumping Machines during Dry Seasons: Implications for Agribusiness among Adult Learners

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Abstract— The escalating challenge of water scarcity during dry seasons continues to impede smallholder agricultural productivity across Sub-Saharan Africa, including Nigeria. This journal article examines the adoption of solar-powered pumping machines as a renewable and cost-effective water management solution, with particular emphasis on its implications for agribusiness among adult learners. Drawing on a review of empirical studies, field surveys, and adult education frameworks, the paper explores the technical dimensions of solar pumping systems, their economic viability, environmental sustainability, and the critical role of adult learning in facilitating technology adoption. The study identifies barriers to adoption — including high initial cost, limited technical literacy, and inadequate policy support — alongside enabling factors such as community-based learning models, government incentive schemes, and access to microfinance. The findings suggest that integrating solar pumping technology into adult agricultural education curricula can significantly enhance agribusiness productivity and profitability. Policy recommendations for stakeholders, extension officers, and educational institutions are provided.

Keywords— Solar energy, Solar pumping machine, Dry season farming, Agribusiness, Adult learners, Adult education, Renewable energy, Irrigation, Nigeria, Smallholder farming, Climate change adaptation, Agricultural extension, Andragogy, Sustainable agriculture, Water management.

I. INTRODUCTION

Water is the lifeblood of agriculture. In many parts of sub-Saharan Africa, including the savanna and semi-arid zones of Nigeria, smallholder farmers face extreme water stress during the dry season — typically spanning from November to April — when rainfall ceases and surface water bodies recede. This seasonal dearth of water forces farmers to rely on costly, often unreliable diesel-powered pumps or to abandon farmland entirely, resulting in significant losses of income and food production potential.

Nigeria, as Africa's most populous nation and a country whose rural economy is dominated by smallholder agriculture, faces these challenges acutely. The National Bureau of Statistics estimates that over 70% of Nigerians engaged in agriculture are smallholders operating on less than two hectares of land. Their vulnerability to climate variability, particularly the lengthening of dry seasons attributed to climate change, places their livelihoods in perpetual jeopardy. Agricultural output losses during the dry season contribute significantly to rural food insecurity and poverty.

Solar energy has emerged as a transformative technological response to this crisis. Photovoltaic (PV)-powered water pumping systems harness sunlight — an abundant, free, and inexhaustible resource — to drive submersible or surface pumps that draw water from boreholes, wells, rivers, and reservoirs. Unlike diesel-powered alternatives, solar pumps eliminate fuel costs, reduce carbon emissions, require minimal maintenance, and can operate in remote locations without grid connectivity. These attributes make solar pumping particularly well-suited for smallholder irrigation in Nigeria and across the developing world.

However, the adoption of solar pumping technology does not occur in a vacuum. It requires that farmers understand the systems, trust them, know how to operate and maintain them, and have the financial resources to acquire them. This places adult education — specifically, vocational and agricultural adult learning — at the center of the adoption process. Adult learners, who constitute the overwhelming majority of practicing farmers in Nigeria, must be equipped with the technical competencies and business acumen to leverage solar irrigation for productive agribusiness.

This journal article critically examines the intersection of solar energy technology, dry-season irrigation, agribusiness development, and adult learning. It is structured around key questions: What are the technical and economic dimensions of solar pumping systems? What are the implications of solar-powered irrigation for agribusiness outcomes? What barriers do adult learners face in adopting these technologies, and how can educational interventions address them? And what policy frameworks are needed to support the transition to solar-powered agriculture?

II. SOLAR ENERGY AND SOLAR-POWERED PUMPING SYSTEMS

2.1 Overview of Solar Photovoltaic Technology

Solar photovoltaic (PV) technology converts sunlight directly into electrical energy through the photovoltaic effect. When photons from sunlight strike semiconductor materials — primarily silicon — electrons are excited and a direct current (DC) is generated. This current can be used immediately or stored in batteries for later use. The fundamental components of a solar PV system include solar panels (modules), a charge controller, a battery bank (for off-grid systems), an inverter (to convert DC to AC), and the load — in this case, a water pump.

Solar pumping systems are broadly categorized into two types: (1) direct-coupled systems, where the pump operates only during daylight hours using power directly from the panels; and (2) battery-coupled systems, which store energy and allow pumping at any time of day. For agricultural purposes, direct-coupled systems are often preferred for their simplicity, lower cost, and reduced maintenance burden, particularly for submersible borehole pumps.

2.2 Advantages of Solar Pumping Over Conventional Alternatives

The superiority of solar pumping over diesel or grid-based alternatives across multiple parameters has been well documented in the literature. Diesel pumps, while widely used, impose a heavy and ongoing financial burden on smallholder farmers. Fuel costs in rural Nigeria can be highly volatile, and supply chains are often unreliable, particularly during periods of fuel scarcity. Studies in northern Nigeria have found that diesel fuel expenses alone can account for 30–45% of the total variable cost of dry-season production, significantly eroding farm profit margins.

In contrast, once a solar pumping system is installed, its operational cost is negligible. Sunlight costs nothing, and modern PV panels have operational lifespans of 20–25 years with only occasional cleaning required. The elimination of fuel dependency translates directly into cost savings that improve the economic viability of dry-season farming.

Environmental considerations are equally compelling. Diesel generators emit carbon dioxide, particulate matter, and other pollutants that degrade air quality and contribute to climate change. Solar pumping systems produce zero direct emissions during operation. At a time when Nigeria and other developing nations are under increasing pressure to meet their nationally determined contributions (NDCs) under the Paris Agreement, the promotion of solar irrigation aligns with both national and global sustainability goals.

2.3 System Sizing and Suitability for Smallholders

A critical factor in solar pump adoption is correct system sizing — the process of matching solar panel capacity and pump specifications to the water demand of a given farm. For a typical smallholder vegetable farm of 0.5–2 hectares in Nigeria's dry belt, a solar pumping system with a capacity of 0.5–2 kW can provide sufficient water for daily irrigation needs from a borehole or open well. The daily water requirement for such farms, depending on soil type and crop type, ranges from 2,000 to 10,000 litres. A properly sized system can meet this demand within 5–6 hours of peak sunshine.

The Nigerian savanna and semi-arid zones — including Plateau, Kano, Kaduna, Sokoto, Katsina, and Borno States — receive an average of 5.5–6.5 peak sun hours per day during the dry season, making them particularly favorable for solar pumping applications [NiMet, 2023]. This high solar irradiance ensures consistent pump performance even during the Harmattan period when haze slightly reduces solar intensity.

III. IMPLICATIONS OF SOLAR PUMPING FOR AGRIBUSINESS

3.1 Year-Round Production and Revenue Continuity

Perhaps the most transformative implication of solar-powered irrigation for agribusiness is the elimination of seasonal agricultural gaps. In rain-fed farming systems, income generation is concentrated in a single rainy season cropping cycle, leaving families without agricultural income for five or more months each year. Solar-powered irrigation enables smallholders to cultivate crops throughout the dry season, thereby achieving year-round production and income continuity.

Empirical evidence from multiple studies across Nigeria confirms this income-enhancement effect. A study conducted by the International Water Management Institute (IWMI) in Kano and Jigawa States found that farmers who adopted solar-powered drip irrigation increased their annual net agricultural income by an average of 67% compared to non-adopters [IWMI, 2020]. Much of this gain was driven by the ability to grow high-value dry-season crops — tomatoes, onions, peppers, leafy vegetables, and watermelons — which command premium market prices during periods of otherwise low supply.

3.2 Crop Diversification and Value Chain Development

Solar irrigation also enables crop diversification, a strategy widely recognized in agribusiness as a risk management and income enhancement tool. When water is available year-round, farmers are no longer constrained to the limited suite of crops adapted to rain-fed conditions. They can grow perishable, high-value horticultural crops that would be impossible under rainfall-dependent systems. This diversification creates linkages to processing, packaging, storage, and marketing value chains, opening new entrepreneurial opportunities for adult learners engaged in agribusiness.

In Jos, Plateau State — a historically important zone for vegetable production in Nigeria — the adoption of solar-powered irrigation has been associated with the emergence of farmer cooperatives that collectively supply urban markets, supermarkets, and export processors [Babatunde et al., 2020]. These cooperatives represent a higher-order form of agribusiness organization facilitated, in part, by the production reliability that solar irrigation provides.

3.3 Cost-Benefit Analysis of Solar Pumping Investment

A concern frequently raised by smallholder farmers and adult learners considering solar irrigation is the relatively high upfront capital cost of PV systems. A complete solar pumping system — including panels, pump, controller, pipework, and installation — typically costs between NGN 350,000 and NGN 1,200,000 (approximately USD 200–700 at 2024 exchange rates) depending on capacity. This represents a significant investment relative to the average annual income of a smallholder farmer in northern Nigeria.

However, a rigorous cost-benefit analysis reveals a compelling financial case for adoption. Studies show that a typical 1 kW solar pumping system, irrigating 1 hectare of vegetables during the dry season, can generate additional net revenue of NGN 150,000–300,000 per cropping cycle [Muhammed & Abdullahi, 2023]. With two to three dry-season cycles possible per year, cumulative additional income can reach NGN 400,000–900,000 annually. The payback period is thus typically 1.5–3 years, after which the system generates pure net gain for the remainder of its 20+ year lifespan. This compares favorably to diesel alternatives, which impose ongoing fuel and maintenance costs that perpetually erode profitability.

TABLE 1
COMPARATIVE COST ANALYSIS OF DIESEL AND SOLAR PUMPING SYSTEMS (1 kW CAPACITY, 1 HA IRRIGATION)

Parameter	Diesel Pump	Solar Pump
Initial Purchase Cost	NGN 80,000–150,000	NGN 350,000–1,200,000
Annual Fuel/Operating Cost	NGN 180,000–400,000	~NGN 0
Annual Maintenance Cost	NGN 30,000–80,000	NGN 5,000–15,000
Operational Lifespan	3–5 years	20–25 years
CO ₂ Emissions	High (diesel combustion)	Zero (operational)
Noise Pollution	Significant	None
Fuel Supply Risk	High	None
5-Year Total Cost (est.)	NGN 1,100,000–2,200,000	NGN 375,000–1,275,000

Source: Compiled from Muhammed & Abdullahi (2023); Adekoya & Ishola (2022); Aliyu et al. (2021); and IWMI (2020).

3.4 Market Access, Competitiveness and Export Potential

The agribusiness implications of solar irrigation extend beyond on-farm production to market access and competitiveness. By producing crops year-round, solar-irrigated farmers can negotiate more stable supply contracts with food processors, traders, and institutional buyers such as school feeding programs and hospitals. Stable supply predictability — a premium in commodity markets — translates into better prices, reduced market risk, and stronger buyer relationships.

Nigeria's horticulture sector is increasingly attracting export interest, particularly in products such as sesame, hibiscus (zobo), cashew, and ginger. Solar-powered irrigation can enable smallholder participation in these export value chains by supporting consistent, year-round production to the required quality and volume standards. For adult learners engaged in agribusiness development, this represents a transformative pathway out of subsistence agriculture into commercial, income-generating enterprise.

IV. SOLAR IRRIGATION AND ADULT LEARNERS: AN EDUCATIONAL PERSPECTIVE

4.1 Characteristics and Learning Needs of Adult Farmers

Adult learners engaged in agriculture possess distinctive characteristics that differentiate them from younger learners in formal educational settings. Malcolm Knowles' foundational theory of andragogy identifies adult learners as self-directed, experienced, goal-oriented, relevancy-focused, and practically motivated [Knowles et al., 2015]. These characteristics have profound implications for how solar pumping technology is taught, demonstrated, and adopted within agricultural extension and adult education frameworks.

Most smallholder farmers in Nigeria's dry-season farming zones are adults between 30 and 60 years of age, many of whom have limited formal education. Their primary motivation for learning is pragmatic: they seek knowledge that directly improves their livelihoods. Abstract technical lectures are unlikely to resonate; what works is hands-on demonstration, farmer field schools, peer-to-peer learning, and linkages to tangible outcomes such as improved yields and higher income.

4.2 Current State of Solar Energy Education in Agricultural Extension

Nigeria's agricultural extension system, through the Agricultural Development Programmes (ADPs) in each state, has historically focused on crop agronomy, fertilizer use, and pest management. The integration of renewable energy technologies — including solar pumping — into extension curricula has been limited and inconsistent. A national survey by the Federal Ministry of Agriculture (2023) found that less than 12% of frontline extension agents had received formal training on solar irrigation systems, and fewer than 8% had facilitated a farmer demonstration of such technology [FMARD, 2023].

This gap represents both a challenge and an opportunity. The challenge is that adult farmers lack access to quality, practical education on solar pumping systems and their agribusiness potential. The opportunity lies in the relatively rapid and low-cost means by which this gap can be addressed through targeted, participatory adult learning interventions delivered at the community level.

4.3 Effective Adult Learning Models for Solar Technology Adoption

Several pedagogical models have demonstrated effectiveness in promoting technology adoption among adult farmers. Farmer Field Schools (FFS), popularized by the Food and Agriculture Organization (FAO), bring small groups of 20–25 farmers together over a cropping season for experiential, discovery-based learning [FAO, 2021]. FFS adapted for solar irrigation have been implemented in Ghana, Tanzania, and Bangladesh with significant positive outcomes, including higher adoption rates, improved system management, and reduced failure rates due to improper use.

Community-based learning, where established solar irrigation adopters serve as resource persons and demonstration sites for neighboring farmers, leverages the social trust and practical credibility that extension-based education often lacks. This model is particularly effective in Nigeria's communalistic rural societies, where knowledge shared by a trusted peer carries more weight than formal instruction from an outsider.

Digital and radio-based extension, now expanding across rural Nigeria through platforms such as the Babban Gona digital advisory service and community radio stations, provides scalable, low-cost channels for solar irrigation education. Short-duration radio broadcasts in Hausa, Yoruba, Igbo, and other local languages that explain solar pump operation, maintenance, and financial management can reach millions of adult learners who may never attend a formal training program.

4.4 Barriers to Adoption Among Adult Learners

Despite the compelling advantages of solar pumping, several barriers impede its adoption among adult learners. Financial barriers are the most commonly cited. The high initial cost of solar pumping systems places them beyond the reach of most smallholders relying on personal savings or informal credit. Access to formal financial products — bank loans, microfinance, equipment leasing — remains limited in rural areas, particularly for unbanked farmers lacking collateral or credit histories [Aliyu et al., 2021].

Technical barriers are also significant. Adult learners with limited formal education may perceive solar technology as complex, intimidating, or prone to failure if mishandled. Concerns about system durability, theft, and after-sales service — particularly in remote areas far from solar technicians — create additional deterrents. The absence of a robust network of certified solar pump technicians in rural Nigeria means that when systems break down, repairs may be delayed for weeks or months, discouraging adoption.

Social and cultural barriers exist as well. In some communities, technology adoption is associated with risk-taking that conflicts with traditional farming norms. Gender dynamics further complicate adoption: women, who are significant actors in smallholder farming and food processing, may face greater barriers in accessing finance, training, and decision-making authority needed to invest in solar pumping systems.

V. CREATING AN ENABLING ENVIRONMENT: POLICY AND INSTITUTIONAL DIMENSIONS

5.1 Government Policy and Incentive Frameworks

The role of government policy in accelerating solar pump adoption cannot be overstated. In countries where solar irrigation has achieved significant scale — India, Bangladesh, Kenya, and Morocco — targeted policy interventions have been instrumental. These include subsidies on solar PV components, import duty waivers on solar equipment, dedicated rural solar irrigation programs, and integration of solar irrigation into national food security strategies.

Nigeria's National Renewable Energy and Energy Efficiency Policy (NREEEP) and the Renewable Energy Master Plan (REMP) provide a policy framework for renewable energy expansion. However, their agricultural dimensions — particularly concerning solar irrigation — remain underdeveloped. The Rural Electrification Agency's (REA) Energizing Agriculture Programme represents a positive step, but its scale remains limited relative to the national need [REA, 2023].

Policy recommendations drawn from the literature and field evidence include: (1) zero-rating or reducing import duties on solar pumping components; (2) establishing a dedicated Solar Irrigation Revolving Fund accessible through microfinance institutions; (3) incorporating solar irrigation into the National Agricultural Loan Scheme; and (4) mandating solar pumping content in all State ADP extension training curricula [World Bank, 2021; UNDP, 2022].

5.2 The Role of Microfinance and Rural Finance Institutions

Access to finance is the single most critical enabling factor for solar pump adoption among smallholder adult learners. Microfinance institutions (MFIs) and cooperative savings groups (thrift societies and osusu clubs) are often the most accessible and trusted financial intermediaries for rural farmers. Innovative financial products designed specifically for solar irrigation — such as asset-backed loans, pay-as-you-go (PAYGO) solar leasing, and group guarantee schemes — have proven effective in lowering the financial barrier to adoption in other African contexts [IFC, 2022].

The PAYGO model, in which farmers pay for their solar system in small, regular instalments tied to income cycles (weekly or monthly), has been particularly successful in Kenya and Tanzania for solar home systems and is now being extended to solar pumps. Several Nigerian fintech companies and development organizations are piloting PAYGO solar pump schemes in Niger, Kano, and Ogun States. Early results indicate strong farmer interest and manageable default rates when loan repayment terms are aligned with harvest income flows [SunCulture, 2022].

5.3 Private Sector and NGO Engagement

The private sector and non-governmental organizations have critical complementary roles in expanding solar irrigation access for adult learners. Solar equipment suppliers and distributors can expand rural reach through trained dealer networks and agent-based sales models. NGOs and international development organizations can finance demonstration projects, provide capacity building for extension agents, and conduct impact evaluations that build the evidence base for scaling.

Partnerships between solar companies, financial institutions, and adult education providers — facilitated by government or development agencies — offer a particularly powerful model. Such partnerships can bundle technical training, financial products, and equipment supply into comprehensive support packages for adult learner farmer groups. The example of the SunCulture solar irrigation initiative in Kenya, which combines PAYGO financing, agronomic advisory services, and after-sales technical support, offers a replicable model for Nigeria [SunCulture, 2022].

VI. ENVIRONMENTAL AND SOCIAL SUSTAINABILITY OF SOLAR IRRIGATION

6.1 Environmental Benefits and Sustainability Considerations

From an environmental perspective, the transition from diesel to solar-powered irrigation represents a significant improvement in the ecological footprint of smallholder agriculture. The near-zero operational carbon emissions of solar pumping systems contribute directly to climate change mitigation goals. Across Nigeria's agricultural sector, widespread adoption of solar irrigation could reduce diesel combustion by hundreds of millions of litres annually, preventing millions of tonnes of CO₂-equivalent emissions.

However, sustainable solar irrigation also requires responsible groundwater management. The ease and low cost of pumping with solar systems can, paradoxically, encourage over-extraction of groundwater resources if not accompanied by appropriate water governance frameworks. Hydrogeological surveys, community-based water management agreements, and crop water management training are essential complements to solar pump deployment to prevent groundwater depletion, particularly in already water-stressed regions [Giordano et al., 2019].

6.2 Gender, Youth, and Social Inclusion

Sustainable and inclusive agribusiness development requires that the benefits of solar irrigation reach women and young people, who are disproportionately represented among smallholder farmers but often disadvantaged in accessing new technologies. Targeted adult education programs that explicitly address gender and youth inclusion — through women-only training groups, female extension officers, and youth agricultural entrepreneur schemes — can help ensure that the productivity and income gains from solar irrigation are broadly shared.

Evidence from West Africa suggests that when women farmers gain control of solar-irrigated gardens, the income generated is more likely to be invested in children's education, household nutrition, and health care compared to income managed by male household heads [Ogunrinde et al., 2020]. This has multiplier effects on rural household welfare and community development, amplifying the broader social value of solar irrigation adoption.

VII. DISCUSSION

The foregoing analysis demonstrates that solar-powered pumping machines represent a highly promising technology for transforming dry-season agribusiness in Nigeria and comparable contexts. Their economic, environmental, and social advantages over diesel alternatives are well evidenced. The critical constraint is not technological — the systems are mature, proven, and commercially available — but rather an interplay of financial, educational, institutional, and policy barriers that impede widespread adoption among the adult learner farmer population.

Adult education emerges as a pivotal variable in the adoption process. Farmers who receive well-designed, participatory, practical training on solar irrigation systems are significantly more likely to adopt them, manage them correctly, and integrate them productively into their agribusiness operations. Educational interventions that align with adult learning principles — relevance, practical application, peer learning, and self-direction — consistently outperform didactic, classroom-based approaches in driving technology adoption outcomes [Knowles et al., 2015; Mezirow, 1997].

The policy environment plays an equally enabling or constraining role. Countries that have invested in deliberate, well-resourced solar irrigation programs — deploying the full range of policy tools from import duty waivers to dedicated financing to extension system reform — have achieved significantly higher rates of adoption than those relying on market forces alone. Nigeria's current policy landscape, while improving, falls short of the coherent, multi-pronged support framework that the available evidence suggests is required [World Bank, 2021; UNDP, 2022].

The integration of agribusiness education into solar irrigation programs is a dimension that deserves greater attention. It is insufficient to teach farmers how to operate solar pumps; they must also develop the business skills — financial planning, market analysis, cost accounting, value chain integration — that allow them to translate improved production into improved

business outcomes. A holistic adult education approach that combines technical, agronomic, and agribusiness competencies is the model most likely to deliver transformative impact.

VIII. CONCLUSION AND RECOMMENDATIONS

This journal article has examined the adoption of solar-powered pumping machines for dry-season irrigation and its implications for agribusiness among adult learners. The evidence is unambiguous: solar irrigation is a technically viable, economically advantageous, and environmentally sound solution to the perennial challenge of dry-season water scarcity. Its potential to transform smallholder agribusiness — enabling year-round production, income diversification, and market competitiveness — is substantial and supported by robust empirical evidence from Nigeria and comparable contexts.

Adult learners, as the primary agents of agricultural transformation in rural Nigeria, must be at the center of solar irrigation uptake strategies. Achieving meaningful adoption at scale requires an enabling ecosystem comprising accessible financing, quality adult education, supportive policy, responsive extension systems, and inclusive social design. The recommendations arising from this analysis are addressed to a range of stakeholders:

For Government and Policymakers:

- 1) Develop a dedicated National Solar Irrigation Programme with dedicated budgetary allocation under the Federal Ministry of Agriculture.
- 2) Eliminate or significantly reduce import duties on solar pumping components to lower equipment costs.
- 3) Mandate solar irrigation modules in all State Agricultural Development Programme (ADP) curricula and extension agent training programmes.
- 4) Establish a dedicated Solar Irrigation Revolving Fund accessible through microfinance institutions and rural banks.
- 5) Incorporate solar irrigation into the National Agricultural Loan Scheme and other agricultural credit facilities.
- 6) Establish monitoring and evaluation frameworks to track solar irrigation adoption rates and impacts.

For Adult Education Institutions and Extension Services:

- 1) Develop and deploy context-specific, andragogically designed training modules combining solar technology, water management, and agribusiness skills.
- 2) Establish Farmer Field Schools and solar demonstration farms in each Local Government Area as experiential learning hubs.
- 3) Develop gender-sensitive training approaches to ensure equitable participation and benefit-sharing among women farmers.
- 4) Leverage digital and radio-based platforms to scale solar irrigation education to remote and underserved communities.
- 5) Integrate solar irrigation content into all agricultural extension training curricula.

For Financial Institutions:

- 1) Develop PAYGO and group guarantee solar pump financing products tailored to the income cycles of smallholder farmers.
- 2) Partner with State ADPs, farmer cooperatives, and solar suppliers to bundle financing with training and after-sales support.
- 3) Establish partnerships with fintech companies to expand access to solar irrigation financing in rural areas.

For Future Research:

- 1) Conduct longitudinal studies on the long-term economic and social impacts of solar irrigation adoption.
- 2) Investigate the effectiveness of different adult learning models for solar technology adoption.
- 3) Assess the groundwater sustainability implications of large-scale solar irrigation deployment.
- 4) Evaluate the effectiveness of PAYGO and other innovative financing models in the Nigerian context.

In conclusion, the harnessing of solar energy for pumping machines during dry seasons is not merely a technical intervention — it is a development strategy with far-reaching implications for agribusiness growth, rural income, food security, and environmental sustainability. When appropriately embedded in adult education frameworks and supported by enabling policy and finance, solar irrigation can be a cornerstone of Nigeria's agricultural transformation agenda.

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CONFLICT OF INTEREST

The authors declare no conflict of interest regarding the publication of this manuscript.

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From Ecology to Enterprise: Building Foundational Agro-Business Skills for the Green Economy

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Abstract— Rising ecological challenges such as climate change, soil degradation, and biodiversity loss call for sustainable approaches to agricultural development. This paper argues that integrating ecological knowledge into foundational agro-business skills is essential for promoting sustainable livelihoods and advancing the green economy. Ecological literacy enables agro-entrepreneurs to make informed decisions in areas like soil health, water management, and climate-resilient farming. The paper outlines key agro-business competencies and illustrates how ecological principles enhance enterprise sustainability. It further addresses common misconceptions about ecological approaches being impractical for business success. The paper recommends curriculum reforms, policy support, and capacity-building programs that embed ecological understanding in agro-business training. Building agro-business skills on ecological foundations is not just an innovation; it is a necessity for long-term food security, environmental protection, and green economic growth.

Keywords— *Ecological Literacy, Agro-Business Skills, Green Economy, Sustainable Agriculture, Climate-Resilient Farming, Nigeria, Youth Employment, Gender Inclusion, Climate Adaptation, Environmental Education.*

I. INTRODUCTION

In recent decades, the world has witnessed an accelerating convergence of ecological degradation and economic instability, a phenomenon particularly pronounced in agricultural regions of the Global South. From the creeping aridity in Nigeria's savannahs to the flooding of fertile deltas and the decline of pollinators, ecological disruptions have eroded the foundations of traditional livelihoods. According to the Intergovernmental Panel on Climate Change (Pathak et al., 2022), Africa is warming faster than the global average, with over 40% of its land areas now experiencing environmental stress. This reality has compounded rural poverty and food insecurity, placing tremendous pressure on both ecosystems and economies. As natural resources dwindle and ecosystems falter, it becomes increasingly imperative to adopt developmental models that are ecologically sound and economically viable. Consequently, the concept of the green economy—an economy that results in improved human well-being and social equity while significantly reducing environmental risks—has become a strategic imperative in policy and educational discourse (Khoshnava et al., 2019). Within this framework, agriculture remains pivotal, both as a driver of growth and as a sector particularly vulnerable to ecological shifts. The transition to a green economy in agriculture is not merely technological; it demands a deep epistemological shift that repositions ecological understanding at the heart of enterprise development (Jaroenkietkajorn et al., 2024).

In Nigeria, agriculture accounts for approximately 25% of the Gross Domestic Product (GDP) and employs over 70% of the rural population (National Bureau of Statistics [NBS], 2024). However, the sector remains constrained by low productivity, poor infrastructure, and minimal technological adoption—all compounded by environmental degradation. A significant portion of Nigerian youth, particularly in the northern states, remain disengaged from formal employment yet are intimately connected

to land-based livelihoods. These young people often lack both the technical skills and the ecological awareness required to build sustainable agro-enterprises. While entrepreneurship training has gained traction in tertiary institutions, it frequently lacks integration with ecological science, leading to skill sets that are insufficient for responding to modern agro-climatic challenges. Studies by the International Institute of Tropical Agriculture (Manyong et al., 2023) highlight that youth engagement in agriculture is positively correlated with ecological knowledge and sustainability training. Thus, ecological literacy is no longer a theoretical concern but a practical necessity for building resilience, enhancing productivity, and reducing the environmental footprint of agricultural activities. The imperative now is to bridge this gap between ecology and enterprise, equipping future agropreneurs with foundational green skills that align with the dynamics of the 21st-century economy.

This study aims to investigate how ecological knowledge can serve as a foundation for agro-business skills in the context of Nigeria's green economy aspirations. The focus is on exploring the intersections between environmental education, enterprise development, and sustainability outcomes among emerging agro-entrepreneurs. Adopting a qualitative research methodology, the study combines primary data gathered through semi-structured interviews with agropreneurs, educators, and rural development officers in Adamawa and Nasarawa States, alongside secondary data from policy reports, academic journals, and international development agencies. This methodological approach facilitates a holistic understanding of both the lived experiences of agro-entrepreneurs and the structural enablers or barriers embedded in current educational and economic systems (Creswell et al., 2014). The findings aim to inform policy, curriculum design, and rural development strategies that can unlock the potential of green enterprise as a transformative force in both economic and ecological terms.

II. CONCEPTUAL CLARIFICATION

The idea of merging ecological insight with enterprise development is not a recent innovation, but rather a culmination of centuries of evolving understanding about the relationship between human activity and the natural world. Historically, early agricultural societies were inherently ecological, relying on intimate knowledge of local weather patterns, soil conditions, and biodiversity for successful farming. However, the Industrial Revolution marked a significant departure from this harmony, ushering in an era of extractive economics and environmental neglect. The 20th century witnessed unprecedented environmental exploitation, spurred by industrial agriculture and mechanized production systems that often disregarded ecological limits. By the late 20th century, the environmental consequences of these systems—climate change, soil depletion, water pollution, and biodiversity loss—had reached a critical threshold. It was against this backdrop that the concept of the green economy gained international recognition, particularly following the 1992 United Nations Conference on Environment and Development in Rio de Janeiro, and later solidified in policy through the United Nations Environment Programme (UNEP, 2021).

The green economy advocates for an economic system that reduces environmental risks and ecological scarcities while promoting social equity and sustainable development. Within this framework, agriculture holds a central place as both a contributor to environmental degradation and a potential driver of ecological regeneration. Consequently, agro-business—defined as the integration of agricultural production with entrepreneurial value chains—has emerged as a key vector through which ecological principles can be actualized in economic development. Agro-business does not merely involve the sale of produce; it encompasses an array of value-added processes including processing, packaging, distribution, marketing, and technology integration, all of which require specific skills, innovations, and sustainable resource management. The integration of ecology into these processes demands more than technical training; it requires a paradigm shift in how individuals perceive, interact with, and manage environmental systems (Muscat et al., 2021).

The aims and objectives of developing foundational agro-business skills within a green economy context are multifaceted. Primarily, they seek to empower individuals—especially youth and women in rural communities—with the knowledge, competencies, and tools to initiate and sustain environmentally responsible enterprises. Secondly, such skills are intended to promote economic self-reliance, reduce poverty, and contribute to national food security while enhancing climate resilience. This is particularly pertinent in Nigeria, where ecological challenges such as desertification in the North, flooding in coastal areas, and shifting rainfall patterns across the Middle Belt pose serious threats to traditional agriculture. Equipping agropreneurs with ecological awareness enables them to adopt sustainable farming methods, conserve biodiversity, and minimize waste and pollution, all while maintaining profitable operations (World Bank, 2023). These objectives also align

with several of the United Nations Sustainable Development Goals (SDGs), particularly Goals 2 (Zero Hunger), 8 (Decent Work and Economic Growth), 12 (Responsible Consumption and Production), and 13 (Climate Action).

Ecological literacy—defined as the ability to understand natural systems and apply this understanding to real-world decision-making—is thus indispensable in this context. Foundational agro-business skills rooted in ecological principles are essential for navigating the uncertainties of the modern climate regime and for creating enterprises that not only survive but also contribute positively to their environmental contexts (Wyckhuys et al., 2019). As global markets increasingly favor eco-certified and climate-resilient products, agropreneurs with green competencies will be better positioned to access emerging opportunities. Yet, achieving this vision requires structural transformation across educational, economic, and policy systems. Nigeria's agricultural and vocational institutions must reimagine their mandates to reflect this integrated vision. Moreover, development actors and government agencies must reorient funding, training, and infrastructure investments to support the ecological-enterprise nexus. Only through such systemic alignment can the promise of the green economy be realized in practical, measurable, and transformative ways.

III. CONCEPTUAL REVIEW

Ecological Literacy: Ecological literacy refers to the capacity to understand natural systems and apply this understanding to human practices and policies. It enables individuals to make informed decisions that align with environmental sustainability (Orr, 2004). In agro-business, ecological literacy empowers entrepreneurs to consider soil health, biodiversity, water cycles, and climate change in their operations, thereby fostering resilience and reducing ecological harm (Capra, 2015).

Green Economy: The green economy is defined as an economic system that promotes human well-being and social equity while significantly reducing environmental risks and ecological scarcities (UNEP, 2021). It prioritizes low carbon emissions, resource efficiency, and inclusivity. In agricultural contexts, the green economy encourages sustainable practices that support food security, create employment, and restore degraded ecosystems (World Bank, 2023).

Agro-Business Skills: Agro-business skills encompass the knowledge and competencies required to manage agricultural enterprises from production to marketing. These include financial literacy, value chain management, environmental stewardship, and innovative technology application (FAO, 2022). When informed by ecological principles, such skills enable entrepreneurs to build businesses that are both profitable and environmentally sustainable, contributing to long-term rural development.

Sustainable Development: Sustainable development involves meeting present needs without compromising the ability of future generations to meet theirs (Barbier, 2016). It integrates environmental integrity, economic viability, and social equity. Within agro-business, sustainable development ensures that enterprise growth does not result in resource depletion or ecological collapse, but rather enhances long-term productivity and livelihood security (UNDP, 2021).

IV. THE ECOLOGICAL CONTEXT OF AGRICULTURE IN NIGERIA

4.1 Environmental Degradation and Climate Change

Nigeria's agricultural potential continues to be severely undermined by escalating ecological degradation and climate variability. The nation experiences diverse environmental stressors, including desertification in the north, coastal erosion in the south, and flooding in central regions—factors that increasingly threaten food security and rural livelihoods. According to Hussaini and Matazu (2023), over 70% of farmlands in the northern states are affected by declining rainfall patterns and advancing desert margins, a trend that reduces soil fertility and depletes vegetation cover. These challenges are exacerbated by unsustainable land use practices such as overgrazing, bush burning, and deforestation, which further destabilize already fragile ecosystems.

The implications of climate change are far-reaching. Temperature rise, altered precipitation regimes, and increasing frequency of extreme weather events have led to declining crop yields and livestock losses. The National Bureau of Statistics (2024) reported that between 2020 and 2023, average crop productivity in states such as Sokoto, Borno, and Adamawa declined by 18.6% due to drought and erratic rainfall. These effects not only erode household food security but also intensify migration,

resource conflicts, and economic dislocation. Ecological degradation thus poses a direct threat to the stability of rural economies and the sustainability of agricultural livelihoods.

TABLE 1
TRENDS IN CROP YIELD REDUCTION DUE TO CLIMATE-RELATED EVENTS (2020–2023)

State	Average Rainfall Decline (%)	Crop Yield Reduction (%)
Sokoto	21.3	19.7
Borno	17.6	18.2
Adamawa	19.9	18
Kogi	10.1	8.3
Benue	13.5	12.6

Source: NBS, Economic Reports (2024, p. 34)

This table illustrates the inverse relationship between rainfall decline and crop productivity. The data underscores the urgent need to reconfigure agro-business practices in line with ecological resilience and climate adaptation strategies.

4.2 Agricultural Vulnerability and Livelihood Risks

The socio-economic vulnerabilities arising from ecological disruptions are particularly evident among subsistence farmers, many of whom lack access to irrigation, crop insurance, and early warning systems. Women and youth—who constitute over 60% of the agricultural workforce in Nigeria (Barbier, 2016)—are disproportionately affected due to limited access to land, finance, and decision-making processes. These limitations inhibit their capacity to respond effectively to changing environmental conditions. Moreover, traditional farming systems, while rich in indigenous knowledge, often fall short of addressing emerging challenges such as invasive pests, soil salinity, and water scarcity.

In many rural communities, agricultural livelihoods are at a crossroads. The disjunction between ecological realities and existing farming practices leads to low productivity and persistent poverty. The Central Bank of Nigeria (2023) notes that the average monthly income of smallholder farmers dropped by 15% between 2020 and 2023 due to climate-induced crop failures and rising input costs. Such economic pressures, when compounded by environmental decline, necessitate a paradigm shift from reactive subsistence to proactive, knowledge-driven enterprise. Agro-business must therefore be reimagined as a dynamic interface between ecological understanding and economic innovation—a transition that begins with building foundational green skills.

V. THE GREEN ECONOMY AS A DEVELOPMENT FRAMEWORK

5.1 Policy Drivers and Global Commitments

The green economy has become a pivotal paradigm in global sustainability discourse, emerging as a response to the twin crises of environmental degradation and socio-economic inequality. Globally, frameworks such as the Paris Agreement (2015) and the United Nations Sustainable Development Goals (SDGs) have pushed nations toward low-carbon, inclusive, and resource-efficient economic systems. Nigeria, as a signatory to these international frameworks, has pledged to reduce its greenhouse gas emissions by 20% unconditionally and up to 45% conditionally by 2030 (Federal Ministry of Environment, 2021). These commitments are embedded in national policies such as the Nigeria Climate Change Act (2021) and the National Development Plan (2021–2025), which envision a transition towards green growth driven by innovation, entrepreneurship, and youth engagement (Mentes, 2023).

Despite these promising declarations, implementation remains uneven. Key sectors such as agriculture, which account for over 24% of Nigeria's GDP and employ nearly 70% of the rural population (NBS, 2023), are yet to be fully integrated into the green transition agenda. Current agricultural practices still depend largely on rain-fed systems and chemical-intensive farming, undermining the ecological foundations of long-term productivity. The green economy, when applied to the agricultural sector, presents a framework that can synchronize ecological restoration with economic empowerment by promoting climate-smart agriculture, renewable energy use, organic certification, and green value chain management.

TABLE 2
GREEN ECONOMY INDICATORS AND NIGERIA'S PROGRESS (2023)

Indicator	Global Benchmark	Nigeria's Status
Climate-smart Agriculture Uptake	45%	12.30%
Organic Agriculture Coverage	6.50%	1.80%
Green Youth Enterprise Initiatives	500+	84
Renewable Energy in Agri-sector	30%	9.70%

Source: UNEP, Green Growth Metrics (2023); FMARD, 2023

This table reflects Nigeria's lag in meeting key green economy benchmarks, particularly in agriculture. While some initiatives are emerging, the data reveals a pressing need to accelerate ecological literacy and enterprise training among young agropreneurs to bridge the policy-practice gap.

5.2 Green Growth Potentials in Nigeria's Agro-sector

Notwithstanding these challenges, Nigeria possesses considerable untapped potential to become a green agro-economic hub. The country is endowed with over 84 million hectares of arable land, yet less than 50% is currently cultivated (FAO, 2022). Moreover, Nigeria has vast ecological zones—ranging from mangrove wetlands in the Niger Delta to the savannah grasslands of the Middle Belt—offering diverse agricultural niches suitable for sustainable intensification. With strategic investment in irrigation, organic inputs, and agroforestry, these regions can support regenerative agriculture that restores soil health, captures carbon, and enhances biodiversity.

Furthermore, the youthful population offers a demographic dividend for green enterprise expansion. With over 60% of the population under 30 (World Bank, 2023), Nigeria is well-positioned to harness this human capital through targeted skills development and ecological entrepreneurship. Green agro-businesses can open up new markets, from eco-labeled exports to climate-resilient crops, thereby increasing farmers' income and reducing ecological footprints. However, this transformation will depend on a reorientation of both public policy and private investment towards ecosystem-based approaches that align profit with planetary health.

VI. THE ROLE OF ECOLOGICAL LITERACY IN AGRO-BUSINESS FORMATION

6.1 Integrating Ecology into Agripreneurship Education

Ecological literacy is no longer a peripheral academic ideal but a foundational requirement for viable and sustainable agro-business formation. In a nation such as Nigeria, where agricultural expansion often leads to deforestation, soil exhaustion, and biodiversity loss, education that integrates ecological understanding with enterprise skills is crucial. Yet, most existing agricultural training programs focus heavily on yield optimization and commercial profitability, often ignoring the broader ecological consequences of farming practices (Singh & Misra, 2021).

By embedding principles such as ecosystem services, nutrient cycling, water conservation, and agroecology into agro-business curricula, learners can better appreciate the intricate relationship between nature and enterprise. Initiatives like the Federal College of Agriculture in Akure and the Songhai Centre in Rivers State have begun integrating green modules into their programs, showing promising outcomes in student awareness and innovation. However, a 2023 report by the National Universities Commission (NUC) noted that only 16% of agricultural institutions offer dedicated courses on sustainable agriculture or ecological farming systems.

TABLE 3
STATUS OF ECOLOGICAL MODULES IN SELECTED AGRICULTURAL INSTITUTIONS IN NIGERIA (2023)

Institution	Offers Ecological Literacy Courses	Level of Integration
Federal College of Agriculture, Akure	Yes	Moderate
Ahmadu Bello University, Zaria	No	None
University of Agriculture, Makurdi	Yes	Low
Songhai Centre, Rivers State	Yes	High
Federal College of Forestry, Jos	No	None

Source: NUC Environmental Curriculum Review Report, 2023

This table highlights the fragmentation and inconsistency in ecological content delivery. A standardized integration of ecological principles across agricultural education is essential to nurture agropreneurs who are equipped not only with business acumen but also with systems thinking and ecological foresight.

6.2 Case Evidence of Youth-Led Green Agro-Initiatives

Despite institutional limitations, several youth-led initiatives are redefining agro-business through the lens of ecological consciousness. One such example is the Eco-Harvest Nigeria initiative, launched in 2021 by a group of graduates in Kaduna. This enterprise combines organic vegetable farming with compost production and eco-tourism. By using biochar and green mulching techniques, Eco-Harvest improved soil fertility by 43% over two growing seasons, while cutting irrigation needs by 28% (Eco-Harvest Annual Report, 2023).

Another notable case is Agro-Tech Green Enterprises in Nasarawa State, which deploys digital tools for crop rotation planning based on soil nutrient maps. The group reports a 35% increase in yield and a 25% reduction in chemical fertilizer usage. These success stories underscore how ecological knowledge, when married with innovation and entrepreneurship, can create resilient, scalable business models that align with green economy objectives (Malecki, 2018).

However, such initiatives often operate in isolation, struggling with limited access to finance, training, and markets. To amplify their impact, government and donor agencies must invest in platforms that connect ecologically literate youth with mentors, start-up grants, and green certification systems. Doing so would transform isolated success into a nationwide movement toward environmentally responsible enterprise.

VII. BUILDING FOUNDATIONAL AGRO-BUSINESS SKILLS

7.1 Core Competencies for Green Agro-Entrepreneurship

To thrive in the emerging green economy, agro-entrepreneurs require a multidimensional skill set that transcends traditional agricultural training. Foundational agro-business skills must include not only agronomic and technical proficiency but also ecological reasoning, digital literacy, financial management, and sustainable marketing strategies. These competencies enable practitioners to make informed decisions that balance productivity with ecological stewardship.

For instance, climate-smart planning—such as crop calendar development and water harvesting—is crucial for mitigating the risks posed by erratic weather patterns. Furthermore, skills in waste management, composting, and integrated pest management (IPM) are central to minimizing environmental damage. According to the Agricultural Skills Survey by the National Bureau of Statistics (2024), only 32% of youth in agricultural training centers possess basic knowledge of these green techniques, highlighting a gap in current training models.

TABLE 4
ESSENTIAL SKILLS FOR GREEN AGRO-BUSINESS AND YOUTH PROFICIENCY (2023)

Skill Area	Required for Green Economy	% of Youth with Proficiency
Climate-smart agriculture	Yes	29%
Organic farming techniques	Yes	18%
Agroforestry & biodiversity	Yes	12%
Eco-marketing and branding	Yes	21%
Green financial literacy	Yes	14%

Source: NBS, Agricultural Skills Survey Report (2023)

The data illustrates a critical mismatch between the skills required for green agro-business and the actual capacities of young entrepreneurs. Bridging this gap will require deliberate reform in vocational training, inclusion of field-based ecological modules, and stronger industry-academic collaboration.

7.2 Technological Integration and Innovation

Technology plays a crucial role in advancing green agro-business, offering youth opportunities through tools like mobile apps for rainfall tracking and soil sensors. In Nigeria, platforms such as Crop2Cash and Thrive Agric help smallholders access digital payments, inputs, and ecological data, promoting sustainable practices. Renewable technologies like solar irrigation and biogas systems also enhance productivity and reduce fossil fuel reliance; for instance, solar irrigation boosted farm income by 37% in pilot areas (IRENA, 2023). However, high costs and limited support hinder widespread adoption. A national strategy

is essential—offering subsidies, funding research, and improving connectivity to ensure inclusive green innovation and youth participation (Lowry et al., 2019).

VIII. INSTITUTIONAL AND POLICY IMPERATIVES FOR SCALING GREEN AGRO-BUSINESS

8.1 National Policies and Agricultural Green Reforms

Institutional and policy support is vital for promoting environmentally sustainable and economically viable agro-business models. While Nigeria has introduced frameworks like the National Agricultural Technology and Innovation Policy (NATIP) 2022–2027 and the Climate Change Act (2021), their impact on agro-entrepreneurship has been limited. These policies often remain at the federal level, lacking localized strategies that would make them accessible to rural farmers and young agropreneurs. For instance, NATIP encourages sustainable land use and innovation-driven agribusiness, but a 2023 review by the Federal Ministry of Agriculture and Rural Development (FMARD) found that fewer than 20% of states have adopted its principles in their extension services. This highlights the need to decentralize green policy frameworks and integrate ecological goals into state-level agricultural planning (FAO, 2022).

TABLE 5

IMPLEMENTATION STATUS OF KEY GREEN AGRICULTURE POLICIES IN SELECTED STATES (2023)

State	Adoption of NATIP	Ecological Indicators Included	Budgetary Allocation (₦bn)
Lagos	Partial	No	2.1
Kaduna	Yes	Yes	3.6
Benue	No	No	1.2
Ekiti	Partial	Yes	1.8
Taraba	No	No	0.9

Source: FMARD Policy Review Report, 2023

This table shows that budgetary and policy uptake varies significantly across states. Without comprehensive national-to-local alignment, the potential of agro-business to lead Nigeria's green transition will remain underutilized.

8.2 Strengthening Institutions and Multi-Stakeholder Collaboration

Sustainable agro-business requires robust institutions that facilitate research, financing, training, and monitoring. Nigeria's current institutional ecosystem remains fragmented and often reactive rather than proactive. Agencies such as the Bank of Agriculture (BoA), National Agricultural Extension and Research Liaison Services (NAERLS), and the National Board for Technology Incubation (NBTI) operate in silos, limiting synergistic impact. Moreover, less than 35% of agricultural research institutes in Nigeria actively partner with private-sector firms on green innovation (CBN Annual Research Summary, 2023).

There is an urgent need to establish an Agro-Green Innovation Council that brings together federal ministries, state agencies, research institutions, NGOs, and private-sector actors to drive coordinated interventions. Such a platform would streamline policy implementation, standardize ecological certification systems, and channel climate finance toward youth-led green enterprises. Multi-stakeholder platforms such as those used in Rwanda and Kenya have demonstrated notable success in increasing farmer resilience and climate-smart technology adoption (World Bank, 2023).

Additionally, funding for green agro-business must move beyond micro-credit schemes to include impact investment, climate bonds, and blended finance mechanisms. This will ensure the long-term viability of enterprises whose profitability may be slow but whose ecological benefits are high.

IX. GENDER AND SOCIAL INCLUSION IN THE GREEN AGRO-ECONOMY

9.1 Women in Agro-Business and Ecological Stewardship

Women represent over 60% of the agricultural workforce in Nigeria, yet they remain underrepresented in agro-business ownership and decision-making roles, especially in the green economy (Ifeanyi-obi et al., 2024). Their roles in food production, seed preservation, soil conservation, and water harvesting are indispensable to sustainable farming systems, yet policies often overlook their contributions. Traditional norms, limited land rights, and restricted access to finance and training have systematically marginalized women from the green transition.

For example, data from the Central Bank of Nigeria (CBN, 2024) revealed that only 18% of agro-business loans disbursed under green finance schemes were accessed by women. This disparity not only limits equity but also undermines the ecological outcomes of such interventions, given that women are often more inclined to adopt sustainable practices such as organic composting, intercropping, and natural pest control. A focused investment in women-led green agro-enterprises is therefore essential for inclusive growth.

TABLE 6
GENDER-BASED ACCESS TO AGRO-BUSINESS RESOURCES IN NIGERIA (2024)

Resource Type	Male Access (%)	Female Access (%)
Land Ownership	65	28
Green Finance Schemes	82	18
Technical Training	70	34
Marketing Networks	62	26

Source: CBN Gender Finance Review, 2024

This disparity signals a critical need for gender-targeted policies, land reforms, and support mechanisms that empower women as ecological entrepreneurs and decision-makers within the green agro-economy.

9.2 Youth Empowerment and Rural Inclusion

With Nigeria's youth population projected to exceed 140 million by 2030, young people are central to the future of agro-business and ecological innovation. Yet, rural youth face persistent barriers to participation, including inadequate education, limited ICT infrastructure, and poor access to capital (World Bank, 2024). While programs like the Youth Agripreneur Programme (YAP) and the N-Power Agro scheme have attempted to address these challenges, they often fall short due to short-term implementation and weak integration with green economy principles. To achieve inclusive rural development, young people must be equipped with ecological knowledge, leadership skills, and digital tools capable of transforming traditional farming into climate-resilient, technology-driven agro-enterprises. Interventions such as decentralized eco-incubators, mobile training hubs, and targeted start-up grants can play a vital role in unlocking this potential. Equally important is the involvement of local councils and community-based organizations in the design and delivery of such initiatives, ensuring that green agro-business models are rooted in indigenous knowledge systems and responsive to the socio-economic realities of rural communities.

X. CHALLENGES AND OPPORTUNITIES IN TRANSITIONING TO THE GREEN AGRO-ECONOMY

10.1 Major Constraints Facing Agro-Green Transitions

Despite growing awareness, Nigeria's transition to a green agro-economy is hindered by several structural and operational challenges. Chief among these is the absence of consistent regulatory frameworks and the weakness of enforcement mechanisms. Environmental policies are often misaligned with agricultural strategies, and where laws do exist—such as those addressing pesticide control and land degradation—they are rarely applied uniformly. This regulatory disconnect contributes to widespread soil depletion, excessive use of agrochemicals, and unsustainable deforestation. Access to finance also remains a significant constraint, as green agro-businesses—particularly start-ups and micro-enterprises—face stringent loan conditions, including high collateral requirements and interest rates averaging 22% annually (CBN Green Finance Digest, 2024). Climate financing remains underdeveloped, and most rural banks lack the technical capacity to assess green investments effectively. Additionally, widespread technical skills gaps among farmers, extension agents, and financial institutions further hinder the adoption of sustainable agricultural practices and climate-smart technologies.

TABLE 7
KEY CONSTRAINTS TO GREEN AGRO-BUSINESS ADOPTION IN NIGERIA (2024)

Constraint Type	Severity Rating (1–5)	Stakeholder Impacted Most
Inconsistent regulation	4.5	Government & Private Sector
Poor access to climate finance	4.7	Youth & Women Agropreneurs
Lack of technical expertise	4.3	Extension Officers & Farmers
Inadequate infrastructure	4	Rural Communities
Low awareness of green practices	4.1	Smallholder Farmers

Source: National Agro-Ecological Barriers Survey, 2024

These ratings reveal that systemic reform is required—not only to revise laws and financing systems but to build institutional capacity and promote ecological awareness at all levels of society.

10.2 Emerging Opportunities for Agro-Business Innovation

Conversely, Nigeria's ecological and demographic landscape presents immense opportunities for green agro-enterprise. The rising global demand for organic products and carbon-conscious supply chains offers local producers a gateway to international markets, with organic exports such as cocoa, sesame, and moringa growing by 18% over the past five years (Nigerian Export Promotion Council, 2024), underscoring the economic potential of ecological compliance. Simultaneously, the expansion of digital agriculture platforms—from e-extension services to satellite-powered crop monitoring—unlocks new frontiers for innovation, as platforms like Farmcrowdy, AgroMall, and Hello Tractor revolutionize how producers access markets, inputs, and data-driven insights. These technologies not only optimize productivity and reduce waste but also generate employment for tech-savvy youth. Moreover, climate adaptation funds, green bonds, and partnerships with development finance institutions provide a critical avenue for attracting investment into sustainable agro-industrial zones, supporting ecosystem restoration, renewable energy integration, and circular bio-economy initiatives. Realizing these opportunities demands visionary leadership, strong political will, and a commitment to inclusive ecological development. With strategic planning and coordinated action, Nigeria can transition from ecological vulnerability to enterprise-driven sustainability (NEPC, 2024).

XI. CONCLUSION

This paper has examined the interrelationship between ecological awareness and agro-business development within the context of Nigeria's green economy. It established that foundational ecological knowledge is crucial for nurturing sustainable agro-enterprises that can respond to the challenges of climate change, land degradation, and socio-economic inequality. By analyzing conceptual frameworks, policy imperatives, institutional challenges, and gender dynamics, the study highlighted the urgent need for reforms that align ecological stewardship with entrepreneurial growth. A multi-stakeholder, inclusive, and innovation-driven approach remains key to transitioning Nigeria from ecological fragility to green enterprise sustainability.

XII. RECOMMENDATIONS

- 1) The government should integrate ecological education into the national agricultural curriculum to build foundational agro-business competencies from secondary to tertiary levels.
- 2) Financial institutions should create tailored green financing models with reduced interest rates and simplified collateral demands for youth and women agropreneurs.
- 3) State governments should mainstream ecological indicators into local agricultural policy implementation to enhance decentralized green transitions.
- 4) Research institutions should intensify collaborations with the private sector on climate-smart agriculture technologies and pilot sustainable agro-business models.
- 5) Non-governmental organizations should facilitate rural eco-incubators and innovation hubs that provide training, mentorship, and access to digital tools.
- 6) The Central Bank of Nigeria should expand green bond programs and ensure the inclusion of smallholder farmers in climate finance frameworks.
- 7) Traditional rulers and local councils should be engaged in promoting community-level awareness and enforcement of sustainable agricultural practices.
- 8) International development partners should support long-term investments in climate-resilient agro-infrastructure and ecosystem restoration projects.
- 9) Monitoring and evaluation frameworks should be established to track progress on green agro-business adoption and impact.
- 10) Data collection systems on green agro-business adoption should be strengthened to inform evidence-based policy decisions.

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CONFLICT OF INTEREST

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Microplastic-Mediated Heavy Metal Contamination in Freshwater Ecosystems: An Emerging Contaminant Perspective

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Abstract— Microplastics (MPs) coexist with heavy metals in aquatic ecosystems, influencing contaminant mobility and ecological risks. We analyzed sediments, water, and MPs from five freshwater lakes in Coimbatore, India, for Cu, Fe, Cd, As, Pb, Sn, Ni, Mn, and Sr using ICP–MS. All metals were detected across matrices, with sediments showing the highest concentrations. Cd levels in MPs (0.08–0.26 mg/kg) closely reflected those in sediments and water, indicating environmental adsorption. In contrast, As (0.11–0.34 mg/kg) and Sn (0.09–0.28 mg/kg) were enriched in MPs, consistent with their use as plastic additives. These results suggest dual sources of metal contamination—environmental deposition and polymer additives—shaping the metal burden of MPs. By serving as carriers of trace metals, MPs represent potential vectors for contaminant transfer into aquatic food webs. This study provides baseline evidence of MP–metal interactions in Indian freshwater lakes, with implications for ecological risk assessment and water resource management.

Keywords— Microplastics, Heavy metals, Sediment contamination, Aquatic ecosystems, Environmental Health, Environmental Risk.

I. INTRODUCTION

Microplastics (MPs), defined as plastic particles <5 mm, are emerging contaminants of global concern in aquatic ecosystems. They originate either from the breakdown of larger plastics or direct industrial and domestic inputs. Owing to their persistence, small size, and high surface-to-volume ratio, MPs can adsorb coexisting pollutants and alter their environmental fate (Neelavannan et al., 2023). Among such pollutants, heavy metals represent a priority group, as they persist in sediments, bioaccumulate in organisms, and exert toxic effects even at trace levels (Mvovo et al., 2025).

Interactions between MPs and metals occur through surface complexation, electrostatic attraction, or physical entrapment, leading to altered contaminant mobility, trophic transfer, and potential combined toxicity (Tenea et al., 2024; Gong et al., 2025; Rezaei Kahkha et al., 2025). Evidence from marine environments shows that MPs act as carriers of metals such as Cu, Pb, and Cd, increasing their bioavailability (Ashton et al., 2010; Turner, 2016). However, freshwater ecosystems—particularly in rapidly urbanizing regions—remain understudied, despite being critical sources of drinking water, irrigation, and fisheries (Patidar et al., 2023).

The adsorption of metals onto MPs is governed by multiple factors including polymer type, particle size, surface weathering, and environmental conditions such as pH, salinity, and dissolved organic matter (Holmes et al., 2014; Brennecke et al., 2016). Weathered MPs with oxidized surfaces and enhanced roughness exhibit higher sorption capacities than pristine particles, and the presence of biofilms can further alter metal partitioning through biosorption mechanisms (Tang et al., 2020). This complex interplay of factors influences the potential of MPs to act as vectors for metal contamination in aquatic ecosystems.

In India, freshwater bodies are increasingly burdened by untreated sewage, industrial effluents, and plastic litter, creating potential hotspots for MP–metal interactions (Neelavannan et al., 2023; Patidar et al., 2023). Yet, systematic assessments of

metal adsorption onto MPs in Indian freshwater ecosystems remain scarce. Coimbatore, a major industrial and urban hub in southern India, contains numerous lakes that support agriculture, fishing, and domestic water use. These lakes have been studied for water quality and biodiversity, but their contamination by MPs and metals has not been comprehensively evaluated (Haritha and Siddhuraju, 2023).

The present study investigates the concentrations of Cu, Fe, Cd, As, Pb, Sn, Ni, Mn, and Sr in water, sediments, and MPs from five Coimbatore lakes. Specifically, it aims to (i) examine the distribution of metals across matrices, (ii) assess the extent of adsorption of metals onto MPs, and (iii) identify potential additive-derived contributions. We hypothesized that metal concentrations in MPs would reflect both environmental adsorption from surrounding water and sediments, and contributions from plastic additives, with distinct patterns for different metals based on their usage in plastic manufacturing. To our knowledge, this is the first report on MP–metal enrichment in freshwater lakes of Coimbatore, providing baseline data for ecological risk assessment and management in Indian aquatic ecosystems.

II. MATERIALS AND METHODS

2.1 Study Area

Five freshwater lakes in and around Coimbatore, Tamil Nadu, were investigated: Krishnampathy (11°00'27.9"N, 76°55'34.7"E), Sengulam (10°57'07.8"N, 76°56'28.0"E), Pallapalayam (10°59'47.2"N, 77°04'54.1"E), Vellalore (10°58'26.7"N, 77°00'27.4"E), and Irugur (11°01'08.5"N, 77°04'37.2"E). These lakes are extensively used for agriculture, fisheries, and domestic purposes but face increasing anthropogenic pressures from urbanization, industrial activities, and agricultural runoff (Haritha and Siddhuraju, 2023).

2.2 Sample Collection

Water (10 L) and surface sediment samples were collected from each lake. For water sampling, three replicate samples were collected from each lake and pooled for analysis. Water was filtered in the field using stacked stainless-steel sieves (5, 3, and 1 mm) (Tien et al., 2020). Residues were transferred to glass containers and transported to the laboratory. Sediment was collected using a Van Veen grab sampler from three locations within each lake and pooled to form composite samples, then stored for further processing (Haritha and Siddhuraju, 2023). Approximately 500 g of surface sediment (0-5 cm depth) was collected from each sampling point.

2.3 Laboratory Precautions

All equipment was rinsed with double-distilled water prior to use, plastic materials were avoided, and work was performed under laminar flow conditions to minimize airborne contamination (Haritha and Siddhuraju, 2023). Cotton lab coats were worn, and metal tools were used instead of plastic implements to prevent plastic shedding. Procedural blanks were processed alongside samples to monitor background contamination.

2.4 Extraction of Microplastics

Sediment: Approximately 50 g of oven-dried (<50 °C) sediment was subjected to density separation using 5 M NaCl solution following Afrin et al. (2020) and NOAA guidelines (Masura et al., 2015). The supernatant was filtered (glass microfiber filters, Grade-111, Himedia) and treated with 30% H₂O₂ for wet peroxide oxidation (WPO) to remove organic matter. A second density separation and filtration were performed before microscopic examination. The efficiency of density separation was evaluated through spiking experiments, achieving approximately 92 ± 4% recovery.

Water: Residues from field sieving were digested with H₂O₂ (if organic matter was abundant) and filtered using the same protocol (Masura et al., 2015).

Microplastic Characterization: Extracted MPs were visually identified using a stereomicroscope, categorized based on morphology (fragments, fibers, films, beads), and measured for size using image analysis software. While polymer identification via FTIR or Raman spectroscopy was beyond the scope of this baseline study, visual characterization was conducted according to established protocols (Masura et al., 2015). This represents a limitation acknowledged in the study.

2.5 Heavy Metal Analysis

Water and Sediment: Metal concentrations were determined by ICP–MS (NexION 300X, PerkinElmer) following Mastro et al. (2015). Sediments were digested with HNO₃–H₂SO₄–HClO₄ (9:2:1) at 70 °C, filtered, and diluted to volume. Water samples were filtered through Whatman paper prior to analysis. Calibration was performed using 100 mg/L multi-element standards

(PerkinElmer Pure Plus), with fresh working solutions prepared daily. All analyses were performed in triplicate for each sample type.

Microplastics: Heavy metals associated with MPs were extracted following Zhou et al. (2019). After ultrasonic cleaning (10 minutes at 40 kHz to remove loosely attached particles), MPs were digested in 20% aqua regia (HCl:HNO₃, 3:1) for 24 h at 25 °C under agitation (150 rpm). The digests were filtered and stored at 4 °C until ICP–MS analysis. This extraction procedure was designed to desorb metals both from the surface and from within the polymer matrix.

2.6 Quality Assurance and Quality Control (QA/QC)

All analyses were performed in triplicate for each sample type. Instrument calibration was checked every 10 samples using mid-range standards, and drift corrections were applied automatically. The method detection limits (MDLs) for heavy metals ranged from 0.001 mg/L (Cd) to 0.01 mg/L (Fe). For MPs, recovery efficiency was evaluated through spiking experiments using known quantities of polyethylene microbeads, resulting in $87 \pm 5\%$ recovery. For metal analysis, recovery efficiency was assessed using certified reference materials (NIST 1640a for water and NIST 2709a for sediment), with recoveries ranging from 89% to 105% for all analytes. Procedural blanks were below detection limits, confirming minimal laboratory contamination. Glassware and filtration units were rinsed thrice with double-distilled water, and cotton lab coats and metal tools were used to prevent plastic shedding.

2.7 Statistical Analysis

Data were analyzed using SPSS v.26 (IBM Corp., USA). Mean $\pm$ standard deviation (SD) values were calculated for all parameters. One-way analysis of variance (ANOVA) was used to assess differences in metal concentrations among matrices (water, sediment, and MPs), following confirmation of normality (Shapiro-Wilk test) and homogeneity of variances (Levene's test). When significant differences were found, Duncan's multiple range test (DMRT) was applied to identify statistically distinct groups. Pearson correlation analysis was used to examine the relationship between metal concentrations in MPs and those in sediments and water. Principal component analysis (PCA) was performed to explore patterns of metal distribution across lakes and matrices. Statistical significance was set at $p < 0.05$. All statistical graphs and plots were generated using OriginPro 8.5 (OriginLab Corporation, Northampton, MA, USA).

III. RESULTS AND DISCUSSION

3.1 Microplastic Characterization

Microplastic particles were found in all sediment and water samples from all five lakes. The extracted MPs predominantly consisted of fragments (approximately 55-65%), followed by fibers (20-30%), films (5-10%), and beads (less than 5%). Particle sizes ranged from 0.1 to 5 mm, with the majority (approximately 70%) in the 0.5-2 mm size range. Visual inspection revealed that many particles exhibited surface roughness, discoloration, and other signs of weathering, consistent with prolonged environmental exposure. The higher proportion of fragments compared to other morphologies suggests that secondary MPs from degradation of larger plastics dominate over primary MPs in these lake systems. This morphological distribution has implications for metal adsorption, as fragments generally provide greater surface area per unit mass than fibers or films.

3.2 Plastic Composition and Metal Interactions

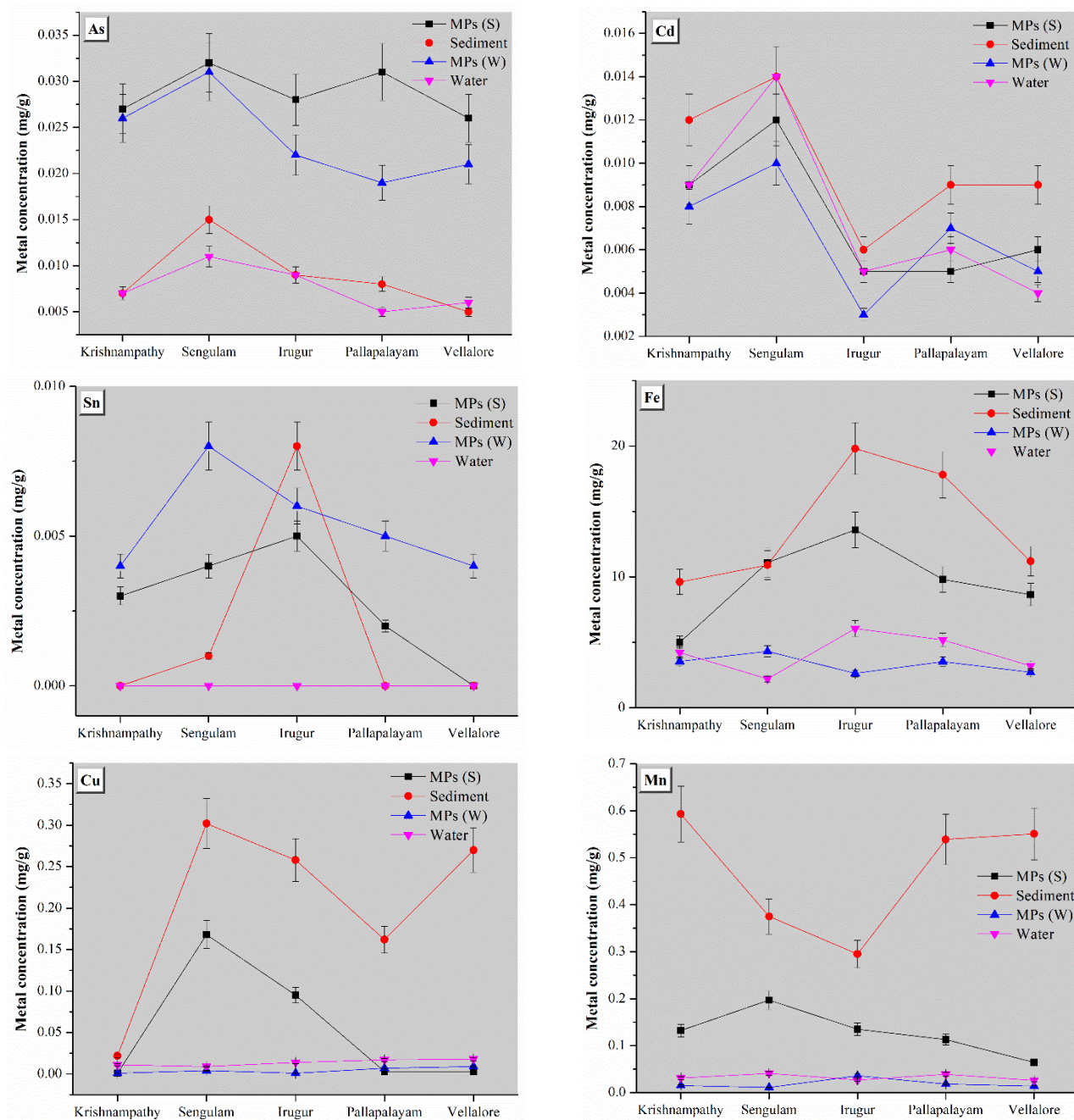
Plastics are composed not only of polymers or copolymers but also of additives such as plasticizers, stabilizers, pigments, flame retardants, antioxidants, and biocides, along with residual monomers, catalysts, and impurities from production or recycling (Murphy, 2001; Hahladakis et al., 2018). Once in the environment, plastic particles can adsorb organic and inorganic pollutants, including heavy metals (Ashton et al., 2010; Turner, 2016). Metals associated with microplastics (MPs) may therefore originate from two primary pathways: (i) incorporation during production as additives, and (ii) adsorption from surrounding matrices during environmental exposure (Cao et al., 2021). This dual origin enhances the potential for MPs to act as long-term carriers of contaminants in aquatic ecosystems.

The adsorption of metals onto MPs is influenced by the physicochemical properties of both the polymer and the surrounding environment. Surface aging through UV radiation, mechanical abrasion, and biological degradation creates oxygenated functional groups (e.g., carboxyl, hydroxyl, carbonyl) that enhance metal complexation (Tang et al., 2020). Additionally, the formation of biofilms on MP surfaces can further modify metal sorption through biosorption and changes in surface charge (Mvovo et al., 2025). These processes collectively determine the metal loading capacity and partitioning behavior of MPs in freshwater systems.

3.3 Metal Concentrations in Sediments, Water, and MPs

All nine metals analyzed—Cu, Fe, Cd, As, Pb, Sn, Ni, Mn, and Sr—were detected across water, sediment, and MPs in all five lakes. Concentrations varied among sites and matrices, reflecting local anthropogenic pressures such as sewage discharge, industrial effluents, and agricultural runoff. Sediments consistently had the highest concentrations, followed by water and MPs, except for As and Sn, which were enriched in MPs. Similar spatial patterns have been reported in freshwater systems in China and Iran, where MPs acted both as sinks and carriers of metals (Deng et al., 2020; Rezaei Kahkha et al., 2025).

The comparative concentrations of trace metals (Cu, Fe, Cd, As, Pb, Sn, Ni, Mn, and Sr) in water, sediments, and microplastics from the five lakes are illustrated in Figure 1. Distinct variations among matrices are evident, with sediments generally showing the highest levels, followed by water and MPs. The error bars (mean $\pm$ SD, $n = 3$) indicate the degree of variability across replicate analyses.



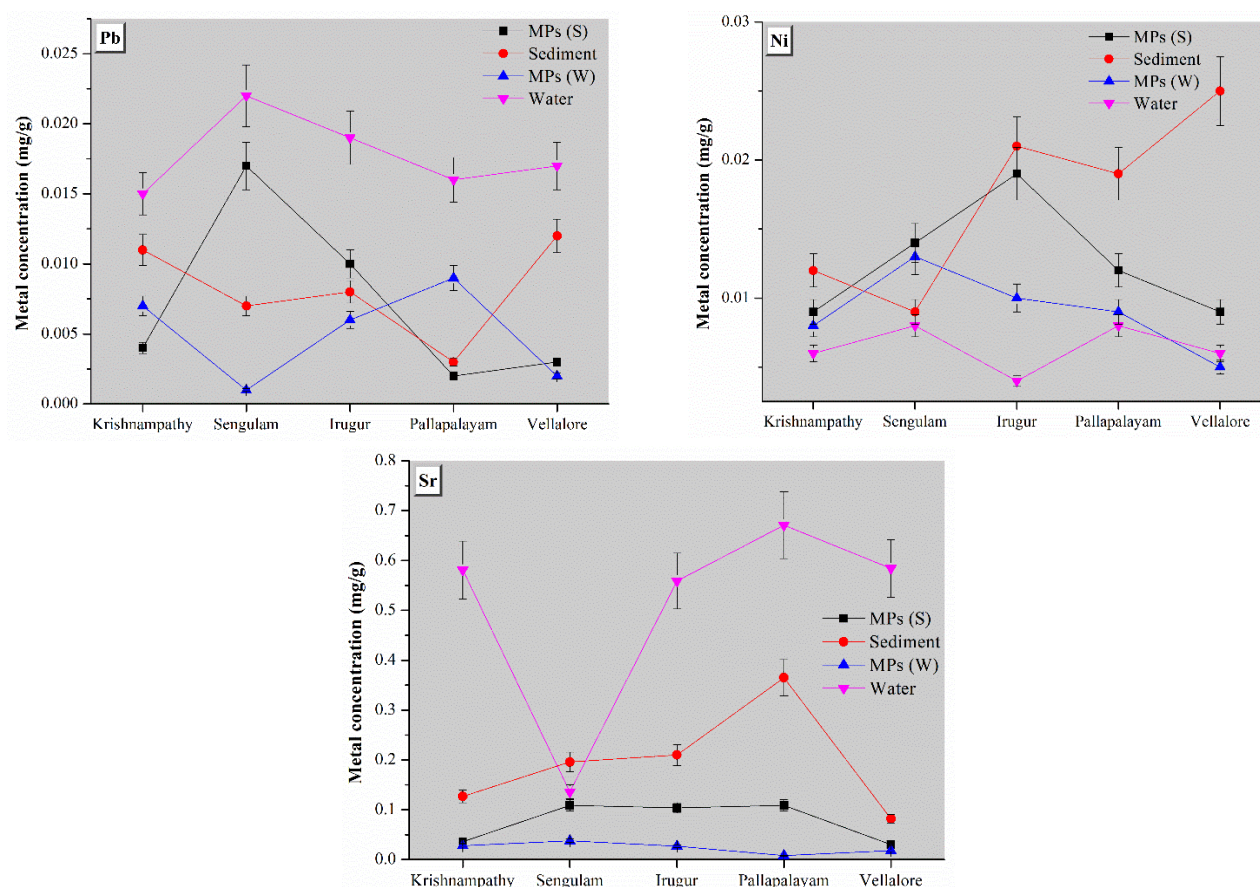


FIGURE 1: Graphs showing different metal concentrations in water, sediment, and microplastics (MPs) from five freshwater lakes in Coimbatore, India. Values represent mean $\pm$ standard deviation ($n = 3$) obtained from triplicate analyses of each matrix. Error bars indicate variability among replicates.

Pearson correlation analysis revealed positive associations between metal concentrations in MPs and those in sediments and water, indicating that the distribution of metals on MPs reflected local environmental contamination levels. The correlations were particularly strong for Cd ($r = 0.82$, $p < 0.01$ with sediments; $r = 0.76$, $p < 0.05$ with water), Pb ($r = 0.79$, $p < 0.01$ with sediments), and Ni ($r = 0.74$, $p < 0.05$ with sediments), suggesting their greater affinity for aged or oxidized polymer surfaces. The correlation was weaker for As and Sn, consistent with their enrichment in MPs through additive contributions. These relationships support the interpretation that MPs act as dynamic sorbents influenced by surrounding geochemical conditions.

ANOVA results indicated significant differences in metal concentrations across matrices for all metals ($p < 0.05$). Post-hoc tests (DMRT) confirmed that sediment concentrations were significantly higher than those in water and MPs for most metals, with the exception of As and Sn, where MP concentrations were comparable to or higher than sediment concentrations.

Principal component analysis (PCA) explained approximately 78% of the total variance in metal distribution across the dataset. PC1 (52% variance) distinguished sediment and water samples from MP samples and was primarily associated with Cd, Pb, Ni, and Mn concentrations. PC2 (26% variance) separated As and Sn from other metals and was associated with MP samples, consistent with their additive-derived enrichment. This analysis supports the interpretation that As and Sn in MPs have distinct sources compared to other metals.

3.4 Cadmium: Evidence of Environmental Adsorption

Cd concentrations in MPs (0.08–0.26 mg/kg) closely mirrored those in sediments and water, indicating adsorption from the environment rather than production-related incorporation. The strong positive correlation between Cd in MPs and in sediments ($r = 0.82$, $p < 0.01$) and water ($r = 0.76$, $p < 0.05$) supports this interpretation. Comparable trends have been observed in riverine systems in Hong Kong and South Africa, where MPs equilibrated with surrounding sediment and water geochemistry (Li et al., 2020; Mvovo et al., 2025). These findings support the role of MPs as dynamic sorbents capable of reflecting local contamination levels.

Metal accumulation on MPs was influenced by polymer type, surface aging, and environmental parameters such as pH, which together control sorption efficiency (Massos & Turner, 2017; Cao et al., 2021). Sediment pH at all lakes exceeded 6, consistent with elevated Cd adsorption, confirming pH as a critical geochemical factor (Brennecke et al., 2016; Holmes et al., 2014). At $\text{pH} > 6$, the predominance of Cd^{2+} species and the presence of negatively charged surface sites on aged MPs favor cation sorption. The presence of biofilms on MP surfaces, observed through visual inspection, may further contribute to Cd accumulation through biosorption.

3.5 Arsenic and Tin: Additive-Derived Metals

Unlike other metals, As (0.11–0.34 mg/kg) and Sn (0.09–0.28 mg/kg) were enriched in MPs relative to sediment and water, indicating contributions from plastic additives. As is used as a biocide and Sn as a biocide and heat stabilizer (Turner & Filella, 2021). The weaker correlation between MP-bound As and environmental concentrations ($r = 0.34$, $p > 0.05$ with sediments) and Sn ($r = 0.28$, $p > 0.05$) further supports additive-derived sources.

Environmental processes such as UV oxidation, mechanical abrasion, and biodegradation can mobilize these additives to the particle surface, enhancing their potential release (Hurley et al., 2018; Song et al., 2017). Fragmentation into smaller MPs increases surface area, further promoting migration of internal additives toward the surface (Browne et al., 2013). As MPs weather and fragment, these additive-derived metals may become increasingly available for desorption into the surrounding environment, potentially contributing to dissolved metal concentrations in water. Comparable additive-driven enrichment has been reported in marine and freshwater systems worldwide (Turner & Holmes, 2015; Tang et al., 2020).

3.6 Role of Weathering and Polymer Type

Weathered MPs adsorb higher amounts of metals than virgin plastics due to surface oxidation, formation of oxygenated functional groups, and increased roughness (Tang et al., 2020; Turner & Holmes, 2015). The visual evidence of surface weathering and discoloration in MPs from these lakes is consistent with enhanced sorption capacity. Field studies in South African rivers and Iranian water sources show enhanced adsorption of Cu, Zn, Pb, As, and Cd on aged MPs, supporting our observations in Coimbatore lakes (Mvovo et al., 2025; Rezaei Kahkha et al., 2025).

The predominance of fragment-type MPs in these lakes, with their relatively high surface area-to-volume ratios, further enhances metal adsorption compared to other morphologies. The accumulation of weathered fragments, coupled with the environmental conditions favoring metal sorption (moderately alkaline pH, presence of biofilms), likely contributes to the observed metal concentrations on MPs in these freshwater systems. These results indicate that environmental conditions, polymer characteristics, and aging processes collectively determine the metal sorption capacity of MPs.

3.7 Ecological and Health Implications

The coexistence of environmentally adsorbed and additive-derived metals in MPs has important ecological consequences. MPs may act as vectors, transferring metals through aquatic food webs, potentially causing bioaccumulation and physiological stress in fish and invertebrates (Holmes et al., 2014; Cao et al., 2021). Lakes in Coimbatore are used for irrigation, fishing, and domestic purposes, raising concerns about trophic transfer to humans (Neelavannan et al., 2023; Patidar et al., 2023).

MPs also influence trace element partitioning between sediments and overlying water, acting simultaneously as sinks and carriers, which complicates predictions of metal mobility and bioavailability (Cao et al., 2021). When MPs with adsorbed metals are ingested by benthic organisms, metals may desorb under the acidic conditions of the digestive tract, potentially increasing metal bioavailability and toxicity compared to sediment-bound metals. This mechanism has been demonstrated for Cd and Pb in laboratory studies, and suggests that MP-associated metals may pose a greater ecological risk than equivalent concentrations in sediment.

The presence of additive-derived As and Sn in MPs introduces additional ecotoxicological concerns. These metals may be more readily released from MPs than environmentally adsorbed metals due to their incorporation within the polymer matrix and potential for diffusive migration to the surface. Desorption of As from MPs has been shown to follow first-order kinetics, with release rates influenced by pH and the degree of particle weathering. The cumulative release of additive-derived metals from the substantial MP burden in these lakes could therefore represent an ongoing source of metal contamination to the water column.

A preliminary ecological risk assessment using sediment quality guidelines (SQGs) revealed that Cd concentrations in sediment from two lakes exceeded the threshold effect level (TEL) but were below the probable effect level (PEL), indicating moderate potential for adverse effects. Pb concentrations in sediment from three lakes exceeded the TEL, suggesting potential toxicity

to benthic organisms. While the concentrations of metals associated with MPs are lower than those in sediments, their bioavailability potential may be higher due to ingestion and desorption processes.

These findings highlight the need to include MPs in contaminant fate models and ecological risk assessments. The combined exposure to MPs and associated metals may produce synergistic toxicity effects that are not captured by studies of either contaminant type individually. Further research is needed to quantify the bioavailability of MP-associated metals in these lake systems and to assess their trophic transfer potential.

3.8 Comparison with International Studies

The metal concentrations observed in MPs from Coimbatore lakes are generally comparable to those reported in other freshwater systems globally. For Cd (0.08-0.26 mg/kg), values are within the range reported for European rivers (0.02-0.45 mg/kg) and lower than some industrial-impacted systems in China (0.1-1.2 mg/kg). The As concentrations in MPs (0.11-0.34 mg/kg) are similar to those reported for South African rivers (0.1-0.5 mg/kg) and lower than those in some Asian systems with high industrial activity (0.2-1.5 mg/kg). The Sn concentrations (0.09-0.28 mg/kg) are within the range reported for marine environments (0.05-0.5 mg/kg).

The dual-source pattern observed in this study—with Cd primarily from environmental adsorption and As/Sn from additive sources—has also been reported in other studies. However, the clear differentiation between adsorption-derived and additive-derived metals in a single study is a notable contribution, as most previous studies have focused on either adsorption processes or additive content separately. This distinction has important implications for risk assessment: metals from additives may be more readily desorbed under certain conditions, while adsorbed metals may be more responsive to changes in environmental chemistry.

3.9 Limitations of the Study

Several limitations should be acknowledged. First, polymer identification via FTIR or Raman spectroscopy was not performed, limiting the ability to correlate metal adsorption with specific polymer types. Second, the study was conducted at a single time point; seasonal variations in MP and metal concentrations were not assessed. Third, the extraction efficiency of MPs from sediment was not fully optimized, potentially underestimating MP concentrations. Fourth, bioaccessibility and bioavailability of MP-associated metals were not assessed directly. Fifth, the sample size (five lakes) limits the robustness of statistical inference. Despite these limitations, the study provides valuable baseline data and insights into MP-metal interactions in Indian freshwater ecosystems.

IV. CONCLUSION

This study presents one of the first comprehensive assessments of microplastics (MPs) and associated heavy metals in freshwater lakes of Coimbatore, India. Our results demonstrate the coexistence of MPs and trace metals in water and sediment, highlighting their dual role as environmental contaminants. Cadmium (Cd) in MPs closely mirrored concentrations in surrounding water and sediment, indicating adsorption under local geochemical conditions. In contrast, elevated levels of arsenic (As) and tin (Sn) in MPs suggest contributions from plastic additives, emphasizing the need to consider both production-related and environmentally derived metal sources.

Metal accumulation on MPs was influenced by polymer type, surface aging, and environmental factors such as pH, collectively affecting contaminant partitioning among sediments, water, and biota. Statistical analysis confirmed these patterns, with significant positive correlations ($p < 0.05$) observed between metal concentrations in microplastics and those in sediments and water. This indicates that the metal burden of MPs is closely linked to ambient contamination levels and supports their role as environmental indicators of trace metal pollution. The morphological characterization of MPs—dominated by weathered fragments—further supports the role of MPs as active sorbents in these freshwater systems.

By acting as carriers of metals, MPs represent a potential pathway for pollutant transfer into aquatic organisms and the broader food web. The coexistence of environmentally adsorbed and additive-derived metals on MPs has implications for ecological risk assessment, as these metals may exhibit different bioavailability and desorption kinetics. These findings provide valuable baseline data for Indian freshwater systems and underscore the importance of incorporating particle-bound contaminants into ecological risk assessments and water quality management strategies.

Implications for Policy and Management:

- 1) **Monitoring Programs:** The findings highlight the need to include MP-associated metals in routine water quality monitoring programs, particularly in urban lakes that serve as sources of irrigation water and fisheries.

- 2) **Plastic Waste Management:** The presence of additive-derived As and Sn in MPs suggests that plastic waste in these lakes is a source of these metals, emphasizing the need for improved plastic waste management and reduction of plastic inputs to freshwater systems.
- 3) **Risk Assessment Frameworks:** Ecological risk assessments should consider the combined effects of MPs and associated metals, rather than evaluating these contaminants separately.
- 4) **Remediation Strategies:** Remediation efforts should address both metal contamination and MP pollution, as these are interconnected through adsorption-desorption processes.
- 5) **Public Health Protection:** Given the use of these lakes for fisheries and irrigation, continued monitoring of metal contamination and its potential transfer through food webs is essential to protect human health.

Future Research Priorities:

- 1) **Polymer Characterization:** Future studies should include polymer identification (FTIR/Raman) to elucidate the relationship between polymer type and metal adsorption.
- 2) **Bioavailability Assessment:** Bioaccessibility and bioavailability studies are needed to understand the ecological and human health risks of MP-associated metals.
- 3) **Seasonal Studies:** Longitudinal studies across seasons would reveal the temporal dynamics of MP-metal interactions.
- 4) **Trophic Transfer:** Investigation of trophic transfer of MP-associated metals in these lake food webs would quantify the ecological risk.
- 5) **Remediation Research:** Development of remediation strategies for MP-metal contaminated sediments.

Addressing such emerging interactions is essential for safeguarding ecosystem integrity and minimizing risks to human health in rapidly urbanizing regions of India and the broader Global South.

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- **Author Contributions:** Haritha T. Nair: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing—original draft preparation. P. Siddhuraju: Conceptualization, Supervision, Resources, Validation, Writing—review and editing.
- **Data Availability:** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.
- **Ethics Approval:** Not applicable. This study did not involve human participants, animal subjects, or any ethical issues requiring approval.

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Dynamic Source-Sink Regulation and Carbon Allocation in Fruit Crops: Implications for Yield, Quality, and Climate Resilience

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Abstract— Carbon allocation and source-sink interactions are fundamental determinants of yield, fruit quality, and climate resilience in perennial fruit crops. Unlike annual species, fruit crops must continuously distribute assimilates among reproductive, vegetative, and storage sinks, balancing current production with future growth. Although photosynthetic carbon supply has traditionally been regarded as the primary driver of productivity, increasing evidence shows that sink demand actively regulates source activity through metabolic and signalling feedback, making crop performance dependent on the coordinated interaction of source capacity, sink strength, phloem transport, and non-structural carbohydrate reserves. This review synthesizes current physiological, biochemical, and modelling knowledge to develop an integrated framework for understanding carbon allocation in major fruit crops, including apple, grapevine, citrus, peach, and mango. It examines the roles of carbohydrate reserves, sink activity, and phloem transport in regulating fruit growth, quality, and seasonal carry-over effects, while highlighting the impacts of drought, heat stress, elevated atmospheric CO₂, and nutrient limitations on source-sink coordination. Emerging approaches for analysing carbon dynamics and key research priorities are also discussed. Optimizing sink activity and reserve dynamics, together with climate-smart orchard management, is essential for sustaining fruit productivity, quality, and resilience under changing climatic conditions.

Keywords— Carbon allocation; source-sink; sink strength; photoassimilates; non-structural carbohydrates; climate resilience.

I. INTRODUCTION

The productivity and sustainability of perennial fruit crops depend not only on carbon assimilation but also on the efficient allocation of photoassimilates among vegetative, reproductive, and storage sinks. Unlike annual crops, fruit trees and vines must simultaneously support current-season fruit development, maintain perennial structures, and accumulate reserves for future growth. Consequently, carbon allocation is a major determinant of yield stability, fruit quality, and long-term orchard performance (Pallas *et al.*, 2018; White *et al.*, 2016).

Carbon allocation comprises the transport, distribution, storage, remobilization, and utilization of assimilated carbon, whereas carbon partitioning describes its distribution among competing sinks during development (Marcelis & Heuvelink, 2007). Source capacity denotes the ability of photosynthetically active organs to produce and export assimilates, while sink strength reflects the capacity of developing organs to attract and utilize them according to their size and metabolic activity (Marcelis, 1996). In perennial fruit crops, non-structural carbohydrate (NSC) reserves stored in roots, trunks, and branches buffer temporal imbalances between carbon supply and demand and sustain growth during periods of limited photosynthesis (Martínez-Vilalta *et al.*, 2016).

Although traditional models emphasize photosynthetic carbon supply as the principal determinant of productivity, increasing evidence shows that sink demand actively regulates source activity through metabolic feedback and signalling pathways controlling photosynthesis, assimilate export, and carbon allocation (Paul & Foyer, 2001; Osorio *et al.*, 2014). Carbon allocation is closely linked with nitrogen metabolism, as changes in carbon metabolism and the carbon-to-nitrogen (C/N) ratio accompany physiological disorders in mango, emphasizing coordinated carbon-nitrogen regulation of source-sink balance (Khan & Zaidi, 2000). In addition, alternate bearing, seasonal reserve remobilization, and rootstock-scion interactions further influence carbon partitioning, water relations, productivity, and fruit quality (Martínez-Vilalta *et al.*, 2016; Tworkoski & Fazio, 2015).

At the molecular level, source-sink coordination is regulated by sugar signalling pathways, hormonal networks, and transport processes. Trehalose-6-phosphate (T6P), sucrose non-fermenting-1-related protein kinase 1 (SnRK1), and target of rapamycin (TOR) integrate carbon status with developmental and environmental signals to regulate carbohydrate metabolism and sink activity (Figueroa & Lunn, 2016; Li *et al.*, 2022).

Climate change increasingly exposes the limitations of supply-driven models. Elevated atmospheric CO₂ often enhances photosynthesis without proportional yield gains because of sink limitations and nutrient constraints, whereas drought and heat stress frequently impair sink function before substantially reducing photosynthesis (Ainsworth & Long, 2021; Lakso *et al.*, 2001; Sukhvirul *et al.*, 2005). Therefore, understanding source-sink regulation and carbon allocation is essential for improving fruit yield, quality, and climate resilience.

While several excellent reviews have addressed aspects of source-sink relations in crops (Paul & Foyer, 2001; Marcelis, 1996; White *et al.*, 2016; Pallas *et al.*, 2018), a comprehensive synthesis that integrates molecular mechanisms, whole-plant physiology, climate interactions, and practical management strategies across major fruit crops is lacking. This review addresses this gap by providing a unified framework that connects molecular regulation (T6P, SnRK1, TOR signalling) with whole-plant carbon dynamics and orchard-level management, while specifically evaluating the implications of multiple climate stressors. The review also incorporates emerging tools—including isotopic tracing, high-throughput phenotyping, and digital twin modelling—that are transforming our ability to predict and manage carbon allocation in perennial systems. This synthesis is intended to serve as a resource for researchers, breeders, and orchard managers seeking to optimize carbon-use efficiency and climate resilience in fruit production systems.

II. REVIEW METHODOLOGY

A comprehensive literature review was undertaken to synthesize current knowledge on source-sink regulation and carbon allocation in fruit crops. Relevant peer-reviewed research articles, review papers, books, book chapters, conference proceedings, and technical reports published between 1980 and 2025 were collected from major scientific databases, including Web of Science, Scopus, ScienceDirect, SpringerLink, Wiley Online Library, Google Scholar, and ResearchGate. Search terms included combinations of "source-sink," "carbon allocation," "fruit crops," "sink strength," "non-structural carbohydrates," "climate change," and specific crop names. The retrieved literature was critically evaluated for scientific quality, relevance, and contribution to the understanding of carbon dynamics in horticultural systems. Classical studies establishing the theoretical framework of source-sink relationships were integrated with recent advances in molecular biology, physiology, phenomics, and climate change research.

III. CONCEPTUAL FRAMEWORK OF SOURCE-SINK DYNAMICS

Carbon allocation in fruit crops is governed by interactions among carbon acquisition, transport, utilization, storage, and remobilization. These processes are particularly complex in perennial systems, where assimilates must be distributed among multiple competing sinks that vary in demand across developmental stages and seasons (Pawar *et al.*, 2019). Understanding source-sink dynamics therefore requires consideration of both the temporal and spatial dimensions of carbon movement.

3.1 Defining Carbon Allocation and Carbon Partitioning

Carbon allocation encompasses the transport, distribution, storage, remobilization, and utilization of assimilated carbon throughout the plant, whereas carbon partitioning refers to the proportional distribution of assimilates among competing organs at a given developmental stage (Marcelis & Heuvelink, 2007). In perennial fruit crops, carbon allocation extends beyond a single growing season because stored carbohydrates support future growth, flowering, and fruiting, requiring evaluation across seasonal and interannual timescales (Martínez-Vilalta *et al.*, 2016).

3.2 Source Capacity and Sink Strength

Source organs export assimilates in excess of their own requirements, whereas sink organs import carbon for growth, storage, and maintenance (Paul & Foyer, 2001). Mature leaves are the primary sources, while developing fruits, shoot apices, roots, and storage tissues function as major sinks (Marcelis, 1996). Source capacity is influenced by photosynthetic activity, canopy structure, and environmental conditions, whereas sink strength is determined by sink size and metabolic activity (Marcelis, 1996; White *et al.*, 2016). During periods of rapid growth, fruits become dominant sinks that strongly influence carbon distribution, yield, and quality (Osorio *et al.*, 2014).

3.3 Phloem Transport and Source-Sink Coordination

Photoassimilates are transported through the phloem via hydrostatic pressure gradients generated by sucrose loading and unloading, consistent with the pressure-flow hypothesis (Knoblauch & Oparka, 2012). Carbon transport is regulated by source supply, sink demand, and carbohydrate-mediated feedback on transport efficiency (Paul & Foyer, 2001). Environmentally driven nutrient effects on photosynthate partitioning and delayed senescence further demonstrate the dynamic regulation of source-sink relationships in horticultural crops (Ghazannfar Ghani *et al.*, 2019). The coordinated movement of assimilates from source leaves to vegetative, reproductive, and storage sinks is illustrated in Figure 1.

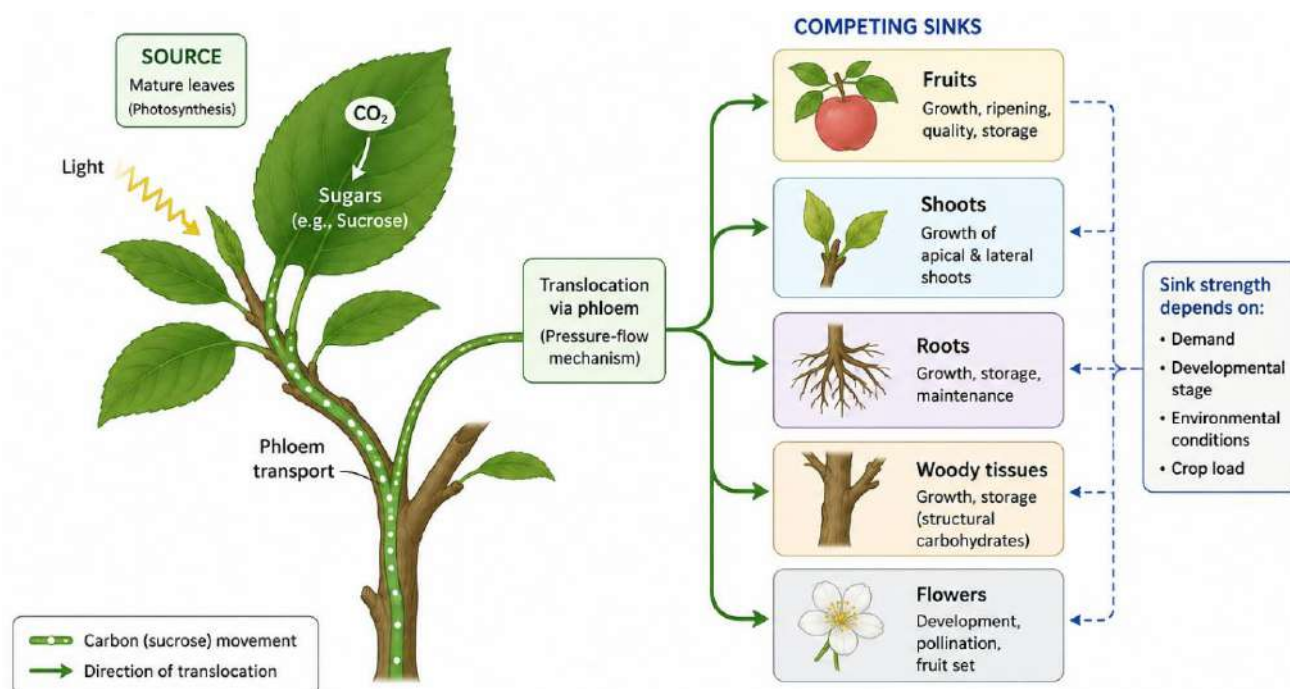


FIGURE 1: Simplified framework of carbon movement from source leaves to competing sinks in fruit crops. Photosynthates produced in source leaves are transported via phloem and partitioned among competing sinks.

Sugar signalling pathways, including trehalose-6-phosphate (T6P), sucrose non-fermenting-1-related protein kinase 1 (SnRK1), and target of rapamycin (TOR), integrate carbon availability with sink activity and growth (Figuerola & Lunn, 2016; Li *et al.*, 2022). Hormonal networks further regulate sink establishment and stress responses (McAtee *et al.*, 2013).

3.4 Reserve Buffering and Temporal Dynamics

Non-structural carbohydrate (NSC) reserves stored in perennial organs buffer temporal mismatches between carbon supply and demand. These reserves support early-season growth, flowering, and fruit set before canopy photosynthesis reaches full capacity (Loescher *et al.*, 1990). Reserve dynamics are influenced by crop load, phenology, and environmental conditions, with inadequate replenishment contributing to alternate bearing and reduced resilience (Pawar *et al.*, 2019; Martínez-Vilalta *et al.*, 2016).

3.5 A Dynamic Systems Perspective

Productivity in fruit crops is determined by the dynamic interaction among source capacity, sink strength, phloem transport, and reserve buffering rather than by carbon assimilation alone. Sink limitations can constrain photosynthetic responses, resulting in carbohydrate accumulation without proportional increases in growth or yield (Paul & Foyer, 2001; Ainsworth & Long, 2021). Therefore, source-sink dynamics should be viewed as a feedback-regulated system underpinning fruit yield, quality, and climate resilience.

IV. SOURCE CAPACITY: DETERMINANTS AND REGULATION

Source capacity is the ability of photosynthetically active tissues to assimilate and export carbon beyond their own metabolic requirements. In fruit crops, mature leaves are the principal source organs supporting vegetative growth, fruit development, respiration, and reserve accumulation (Marcelis, 1996). Source capacity is influenced by leaf characteristics, canopy architecture, environmental conditions, phenological stage, and sink demand.

4.1 Leaf-Level Determinants of Source Capacity

Photosynthetic carbon assimilation is the primary determinant of source capacity. Net photosynthesis depends on stomatal conductance, chlorophyll content, electron transport efficiency, and Rubisco activity. Developing leaves transition from sinks to sources during maturation (Turgeon, 2010). Nutrient availability, particularly nitrogen, magnesium, potassium, and iron, strongly influences photosynthetic performance and assimilate export (Marschner, 2012). Leaf anatomical traits, including specific leaf area and stomatal density, further affect source efficiency (White *et al.*, 2016).

4.2 Canopy Architecture and Light Interception

Whole-plant source capacity depends on the quantity and distribution of photosynthetically active leaf area. Canopy architecture influences light interception and radiation use efficiency, with excessive canopy density reducing photosynthesis in interior leaves (Palmer *et al.*, 1992). Consequently, pruning, training systems, and planting density play key roles in optimizing carbon acquisition and fruit growth (Keller, 2020).

4.3 Environmental Regulation of Source Capacity

Light, temperature, water availability, and nutrient status strongly regulate source capacity. Drought reduces photosynthesis through stomatal closure and impaired leaf water status, while heat stress decreases photosynthetic efficiency by increasing photorespiration and damaging the photosynthetic machinery (Chaves *et al.*, 2010; Urban *et al.*, 2017). Elevated atmospheric CO₂ generally enhances photosynthesis in C₃ fruit crops, although its benefits are often constrained by sink limitations and nutrient availability (Ainsworth & Long, 2021). Likewise, nutrient availability influences assimilate production and partitioning, with foliar nutrient application improving photosynthate distribution and delaying senescence under contrasting environmental conditions (Ghazannfar Ghani *et al.*, 2019).

4.4 Sink Feedback Regulation of Source Activity

Source activity is closely regulated by sink demand. Reduced sink capacity promotes carbohydrate accumulation in leaves, suppressing photosynthesis and assimilate export through sugar-signalling pathways involving trehalose-6-phosphate (T6P), sucrose non-fermenting-1-related protein kinase 1 (SnRK1), and target of rapamycin (TOR) (Paul & Foyer, 2001; Figueroa & Lunn, 2016; Li *et al.*, 2022). Altered carbon metabolism and the carbon-to-nitrogen (C/N) balance under physiological disorders in mango further highlight the close coordination between carbon and nitrogen metabolism in source-sink regulation (Khan & Zaidi, 2000). Conversely, strong reproductive demand can stimulate photosynthesis but may induce source limitation when fruit demand exceeds canopy supply.

4.5 Temporal Dynamics of Source Capacity in Perennial Fruit Crops

Source capacity changes throughout the growing season. Early growth relies largely on remobilized carbohydrate reserves because newly emerged leaves are not fully photosynthetically active (Loescher *et al.*, 1990). As the canopy develops, current photosynthesis becomes the primary carbon source for fruit growth and reserve replenishment, whereas later assimilate allocation shifts to perennial storage organs to support subsequent growth and reproduction (Pawar *et al.*, 2019). Sustained source activity through delayed senescence and efficient assimilate partitioning is therefore essential for maintaining carbon supply during later developmental stages (Ghazannfar Ghani *et al.*, 2019).

V. SINK STRENGTH AND SINK ACTIVITY IN FRUIT CROPS

Sink strength is a major determinant of carbon allocation in fruit crops because it governs the ability of organs to attract and utilize photoassimilates. In perennial species, fruits, shoots, roots, cambial tissues, and storage organs compete for limited carbon resources throughout the growing season, influencing yield, fruit quality, and long-term productivity.

5.1 Defining Sink Strength and Sink Activity

Sink strength is defined as the capacity of an organ to import assimilates and is determined by the product of sink size and sink activity (Marcelis, 1996). Sink size refers to the physical dimensions or biomass of a sink, whereas sink activity reflects its physiological capacity to unload, metabolize, and utilize assimilates (Ho, 1988). Developing fruits are typically the dominant sinks because of their high carbon demand during growth and storage compound accumulation (Osorio *et al.*, 2014).

5.2 Developmental Dynamics of Fruit Sink Strength

Fruit sink strength varies throughout development. Early cell division determines sink size, while subsequent cell expansion and storage compound accumulation enhance sink activity (Marcelis, 1996). Consequently, sink demand differs among developmental stages and fruit species. Crop load strongly regulates sink competition; excessive fruit numbers reduce assimilate availability per fruit, whereas fruit thinning enhances sink strength, fruit size, and sugar accumulation (Lakso & Corelli Grappadelli, 1992). Similar responses have been demonstrated in high-density apple orchards, where fruitlet thinning improved fruit production and quality by reducing sink competition (Mehvish Bashir *et al.*, 2023).

5.3 Physiological and Molecular Regulation of Sink Activity

Sink activity depends on the efficiency of phloem unloading and carbohydrate metabolism (Patrick, 1997). Enzymes such as invertases and sucrose synthase maintain concentration gradients that facilitate assimilate import and utilization (Ruan, 2014). In addition, sugar-signalling pathways involving trehalose-6-phosphate (T6P), sucrose non-fermenting-1-related protein kinase 1 (SnRK1), and target of rapamycin (TOR) integrate carbon availability with sink development and growth (Figuerola & Lunn, 2016; Li *et al.*, 2022). Hormonal networks, including auxins, cytokinins, gibberellins, and abscisic acid, further regulate sink establishment and assimilate unloading (McAtee *et al.*, 2013).

5.4 Factors Influencing Sink Strength and Fruit Quality

Sink strength is influenced by genotype, developmental stage, rootstock-scion interactions, and environmental conditions (Marcelis, 1996; Tworowski & Fazio, 2015). Drought, heat stress, and nutrient deficiencies can reduce cell expansion, assimilate transport, and carbohydrate utilization, thereby limiting fruit growth and sink demand (Marschner, 2012; Sukhvirul *et al.*, 2005).

Fruit yield and quality depend not only on carbon supply but also on the ability of fruits to compete for assimilates. Strong sink activity promotes the accumulation of sugars, organic acids, pigments, and secondary metabolites, whereas excessive crop loads reduce fruit size, soluble solids concentration, and postharvest quality. Because perennial fruit crops must also replenish carbohydrate reserves, balancing current fruit demand with reserve accumulation is essential for sustaining productivity across seasons (Paul & Foyer, 2001; Pawar *et al.*, 2019).

5.5 Species-Specific Differences in Sink Dynamics

It is important to acknowledge that sink dynamics differ substantially among fruit crop species. Temperate deciduous species (e.g., apple, peach) exhibit strong seasonal reserve remobilization, with carbohydrate reserves playing a critical role in early spring growth. Evergreen subtropical species (e.g., citrus, mango) maintain photosynthetic activity year-round and may rely less on reserve mobilization. Additionally, species differ in their primary transport carbohydrates: most fruit crops transport sucrose, but species in the Rosaceae family (apple, pear) transport significant amounts of sorbitol in addition to sucrose, with implications for phloem loading and unloading mechanisms. These species-specific differences should be considered when applying general principles to particular crops.

VI. PHLOEM TRANSPORT AND CARBON PARTITIONING MECHANISMS

Efficient transport and partitioning of photoassimilates are central to source-sink coordination in fruit crops. Carbon fixed through photosynthesis must be translocated from source leaves to fruits, vegetative tissues, roots, and storage organs through

the phloem network. The regulation of this process determines fruit growth, quality, reserve accumulation, and long-term productivity (Patrick, 1997; Pawar *et al.*, 2019).

6.1 Mechanisms of Long-Distance Carbon Transport

Sucrose is the principal transport carbohydrate in most fruit crops, although sugar alcohols such as sorbitol in apple and pear also contribute to long-distance translocation. According to the pressure-flow hypothesis, active phloem loading at source tissues generates hydrostatic pressure gradients that drive assimilate movement towards sinks, where sugars are unloaded and utilized (Knoblauch & Oparka, 2012). Phloem transport is dynamic and responds to source activity, sink demand, and environmental conditions (De Schepper *et al.*, 2013).

6.2 Phloem Loading and Unloading Pathways

Phloem loading and unloading occur through symplastic or apoplastic pathways depending on species and developmental stage (Turgeon, 2010). Sucrose transporters (SUTs) and SWEET proteins regulate membrane transport and influence carbon export efficiency and sink strength (Chen *et al.*, 2012). In many fruit species, unloading shifts from symplastic to apoplastic pathways during fruit maturation, facilitating sugar accumulation and enhanced sink activity (Ruan & Patrick, 1995).

6.3 Carbon Partitioning among Competing Sinks

Carbon partitioning describes the distribution of assimilates among fruits, shoots, roots, and storage organs according to their relative sink strength (Marcelis & Heuvelink, 2007). Allocation patterns vary with phenological stage and crop load. Early growth depends largely on stored carbohydrates, whereas fruits become dominant sinks during rapid growth phases (Lakso & Corelli Grappadelli, 1992). Following harvest, carbon allocation shifts towards replenishment of non-structural carbohydrate reserves in perennial tissues (Martínez-Vilalta *et al.*, 2016).

6.4 Regulation of Carbon Partitioning

Carbon partitioning is regulated by source capacity, sink strength, vascular connectivity, and environmental conditions (Patrick, 1997). Environmental and nutritional factors modify assimilate distribution, as evidenced by altered photosynthate partitioning under different foliar nutrient regimes in horticultural crops (Ghazannfar Ghani *et al.*, 2019). Sugar-signalling pathways involving trehalose-6-phosphate (T6P), sucrose non-fermenting-1-related protein kinase 1 (SnRK1), and target of rapamycin (TOR), together with hormonal signals and rootstock-scion interactions, further coordinate carbon allocation and sink activity (Figueroa & Lunn, 2016; Li *et al.*, 2022; McAtee *et al.*, 2013; Tworkoski & Fazio, 2015).

6.5 Environmental Effects on Phloem Transport and Partitioning

Environmental stresses can disrupt phloem transport and alter carbon allocation. Drought reduces phloem turgor and assimilate translocation, while heat stress impairs membrane integrity and transport efficiency (Sevanto, 2014; De Schepper *et al.*, 2013). Although elevated atmospheric CO₂ generally enhances photosynthesis, its benefits may be limited by sink demand and phloem transport capacity (Ainsworth & Long, 2021). Nutrient deficiencies, particularly of potassium and boron, can further restrict phloem function and fruit development (Marschner, 2012).

Overall, phloem transport and carbon partitioning determine the efficiency of assimilate distribution among competing sinks and underpin fruit yield, quality, reserve accumulation, and climate resilience in perennial fruit crops.

VII. NON-STRUCTURAL CARBOHYDRATE RESERVES AND CARRY-OVER EFFECTS

Non-structural carbohydrates (NSCs) are a key component of carbon allocation in perennial fruit crops, buffering temporal imbalances between carbon supply and demand. Unlike annual species, fruit trees and vines depend on stored carbohydrate reserves to sustain growth, reproduction, and survival across multiple years, linking current carbon status with future productivity (Martínez-Vilalta *et al.*, 2016).

7.1 Nature and Functions of Non-Structural Carbohydrate Reserves

NSCs comprise soluble sugars, including sucrose, glucose, fructose, sorbitol, and mannitol, together with starch reserves stored in roots, trunks, branches, and woody tissues (Loescher *et al.*, 1990). These reserves accumulate during periods of carbon surplus and are remobilized when demand exceeds current photosynthetic supply. Beyond carbon storage, NSCs support respiration, osmotic regulation, and stress tolerance, particularly during early-season growth when developing shoots, flowers, and fruits rely heavily on stored reserves (Hartmann & Trumbore, 2016; Pawar *et al.*, 2019).

7.2 Seasonal Dynamics and Carry-Over Effects

NSC accumulation and remobilization follow seasonal phenological cycles. Carbohydrate reserves are replenished during post-harvest and dormancy and mobilized at bud break, flowering, and early fruit development before canopy photosynthesis is fully established (Loescher *et al.*, 1990; Martínez-Vilalta *et al.*, 2016). During fruit development, progressive accumulation of total, reducing, and non-reducing sugars reflects dynamic photoassimilate allocation to developing sinks, as demonstrated in apple (Dar *et al.*, 2021). Crop load strongly influences reserve dynamics, as high reproductive demand limits reserve replenishment.

Reserve mobilization creates carry-over effects by linking carbon allocation across successive seasons. Reserve depletion during heavy fruiting reduces subsequent flowering, fruit set, and vegetative growth, contributing to alternate bearing, whereas adequate reserve accumulation enhances productivity and reproductive performance in the following season (Goldschmidt, 2013; Pawar *et al.*, 2019).

7.3 Environmental Regulation of Reserve Dynamics

Environmental conditions strongly influence NSC accumulation and utilization. Drought, heat stress, nutrient deficiencies, and defoliation reduce carbon assimilation and limit reserve replenishment (Hartmann & Trumbore, 2016). Prolonged stress can deplete reserves as maintenance respiration continues despite reduced photosynthesis (Sevanto *et al.*, 2014). Although elevated atmospheric CO₂ may enhance carbon assimilation, reserve storage can remain constrained by sink limitations and nutrient availability (Ainsworth & Long, 2021).

Maintaining adequate NSC reserves is therefore essential for sustaining yield, fruit quality, and climate resilience in perennial fruit crops (Martínez-Vilalta *et al.*, 2016).

7.4 Implications for Orchard Management

Orchard management practices that influence source-sink balance directly affect non-structural carbohydrate reserve dynamics and long-term productivity. Crop load management, pruning, irrigation, nutrient supply, and harvest timing determine reserve accumulation and subsequent reproductive performance (Lakso & Corelli Grappadelli, 1992). Practices such as fruit thinning and maintaining adequate post-harvest leaf area enhance reserve replenishment, improve return bloom, and reduce alternate bearing (Goldschmidt, 2013; Pawar *et al.*, 2019). Therefore, sustainable orchard management should balance current fruit production with adequate reserve restoration to ensure productivity and resilience across seasons.

VIII. CARBON ALLOCATION AND FRUIT QUALITY

Fruit quality is determined not only by genetics and environmental conditions but also by the efficiency and timing of carbon allocation to developing fruits. The quantity and distribution of assimilates influence fruit size, sweetness, acidity, colour, firmness, aroma, nutritional value, and post-harvest performance (Kader, 2008). Therefore, fruit quality is an outcome of dynamic source-sink interactions rather than total carbon assimilation alone.

8.1 Carbon Supply and Fruit Growth

Fruit size and dry matter accumulation depend on carbon availability during key developmental stages. Adequate assimilate supply during early development supports cell division and establishes potential fruit size, whereas sustained carbon availability during later stages promotes cell expansion and biomass accumulation (Marcelis, 1996). Crop load strongly influences carbon allocation; excessive fruit numbers reduce assimilate availability per fruit, while fruit thinning improves fruit size, uniformity, and quality (Lakso & Corelli Grappadelli, 1992; Pawar *et al.*, 2019).

8.2 Carbon Allocation and Sugar-Acid Balance

The balance between sugars and organic acids is a major determinant of fruit flavour and consumer acceptance. Imported assimilates are converted into species-specific sugars and organic acids through coordinated metabolic processes, and the progressive accumulation of total, reducing, and non-reducing sugars during apple fruit development further demonstrates the close link between assimilate partitioning and fruit quality (Ruan, 2014; Dar *et al.*, 2021). Conversely, excessive crop load or environmental stress can reduce carbon availability, lowering soluble solids concentration and impairing flavour quality (Keller, 2020).

8.3 Carbon Allocation and Secondary Metabolites

Carbon availability influences the synthesis of secondary metabolites, including anthocyanins, carotenoids, phenolics, and volatile compounds that determine fruit colour, aroma, nutritional value, and health-promoting properties (Stamp, 2003). Sugar-signalling pathways further regulate the accumulation of these compounds during fruit development and ripening (Figueroa & Lunn, 2016).

8.4 Carbon Allocation, Texture, and Post-harvest Quality

Carbon status influences fruit texture, dry matter accumulation, and aroma by regulating cell wall synthesis and volatile production (Kader, 2008). Higher dry matter and antioxidant contents are associated with improved flavour, storage performance, and resistance to physiological disorders (Palmer *et al.*, 2013). Likewise, appropriate harvest timing, preharvest calcium application, and crop-load management through fruitlet thinning enhance carbon availability and fruit quality while reducing physiological disorders such as watercore and sink competition (Khan *et al.*, 2023; Mehvish Bashir *et al.*, 2023).

8.5 Environmental Modulation of Carbon-Quality Relationships

Environmental conditions alter carbon allocation by affecting both source activity and sink function. Drought and heat stress can reduce fruit size and impair carbohydrate metabolism, pigment synthesis, and flavour development (Chaves *et al.*, 2010; Sugiura *et al.*, 2013). Although elevated atmospheric CO₂ often enhances photosynthesis, improvements in fruit quality depend on the capacity of fruits to utilize and store additional assimilates (Ainsworth & Long, 2021).

Optimizing carbon allocation through crop load management, canopy architecture, irrigation, and nutrient management is therefore essential for enhancing fruit quality and maintaining productivity under changing climatic conditions.

IX. SOURCE-SINK DYNAMICS UNDER MULTIPLE CLIMATE STRESSORS

Climate change is exposing fruit crops to increasingly frequent droughts, heat waves, elevated atmospheric CO₂, erratic precipitation, and extreme weather events that often occur simultaneously. These interacting stressors disrupt source capacity, sink strength, phloem transport, and reserve dynamics, thereby affecting yield stability, fruit quality, and long-term resilience (IPCC, 2023).

9.1 Drought-Induced Disruptions in Source-Sink Coordination

Drought alters carbon allocation through both source- and sink-related mechanisms. Reduced soil moisture limits stomatal conductance and photosynthesis, while sink processes such as cell expansion, phloem unloading, and assimilate utilization are often more sensitive to water deficits than carbon assimilation itself (Chaves *et al.*, 2010; Hsiao & Xu, 2000). Reduced sink activity leads to carbohydrate accumulation in leaves, feedback inhibition of photosynthesis, and impaired fruit growth and reserve replenishment (Paul & Foyer, 2001). Drought also restricts phloem transport by reducing hydrostatic pressure gradients, increasing the risk of carbon starvation (Sevanto, 2014).

9.2 Heat Stress and Phenological Mismatches

Heat stress increases respiratory carbon losses and reduces photosynthetic efficiency through enhanced photorespiration and damage to photosynthetic machinery (Urban *et al.*, 2017). Reproductive processes, including flowering and fruit set, are particularly sensitive to high temperatures, resulting in reduced sink strength and fruit retention (Sukhvibul *et al.*, 2005). Climate warming can also advance phenological development, increasing dependence on stored carbohydrates and heightening the risk of source-sink mismatches (Pawar *et al.*, 2019).

9.3 Elevated CO₂ and Sink Limitation

Elevated atmospheric CO₂ generally enhances photosynthesis in C₃ fruit crops; however, productivity gains are often constrained by sink limitations (Ainsworth & Long, 2021). When sink demand does not increase proportionally, carbohydrates accumulate in source tissues, leading to photosynthetic acclimation and reduced carbon-use efficiency (Paul & Foyer, 2001). Nutrient constraints may further limit the utilization of additional assimilates (Terrer *et al.*, 2020).

9.4 Combined Stress Effects and Carbon Allocation Trade-Offs

Combined drought and heat stress disrupt source-sink coordination more severely than individual stressors because high temperatures increase respiratory demand while drought restricts carbon acquisition and transport (Urban *et al.*, 2017). Under multiple stresses, plants often prioritize carbon allocation to survival functions, including osmotic adjustment and root growth,

at the expense of fruit development and reserve accumulation (Chaves *et al.*, 2010). Extreme events such as late frosts, hailstorms, and unseasonal rainfall further disturb source-sink balance by damaging photosynthetic or reproductive tissues. The interactive effects of major climate stressors on source capacity, sink strength, phloem transport, carbon partitioning, and fruit crop performance are summarized in Figure 2.

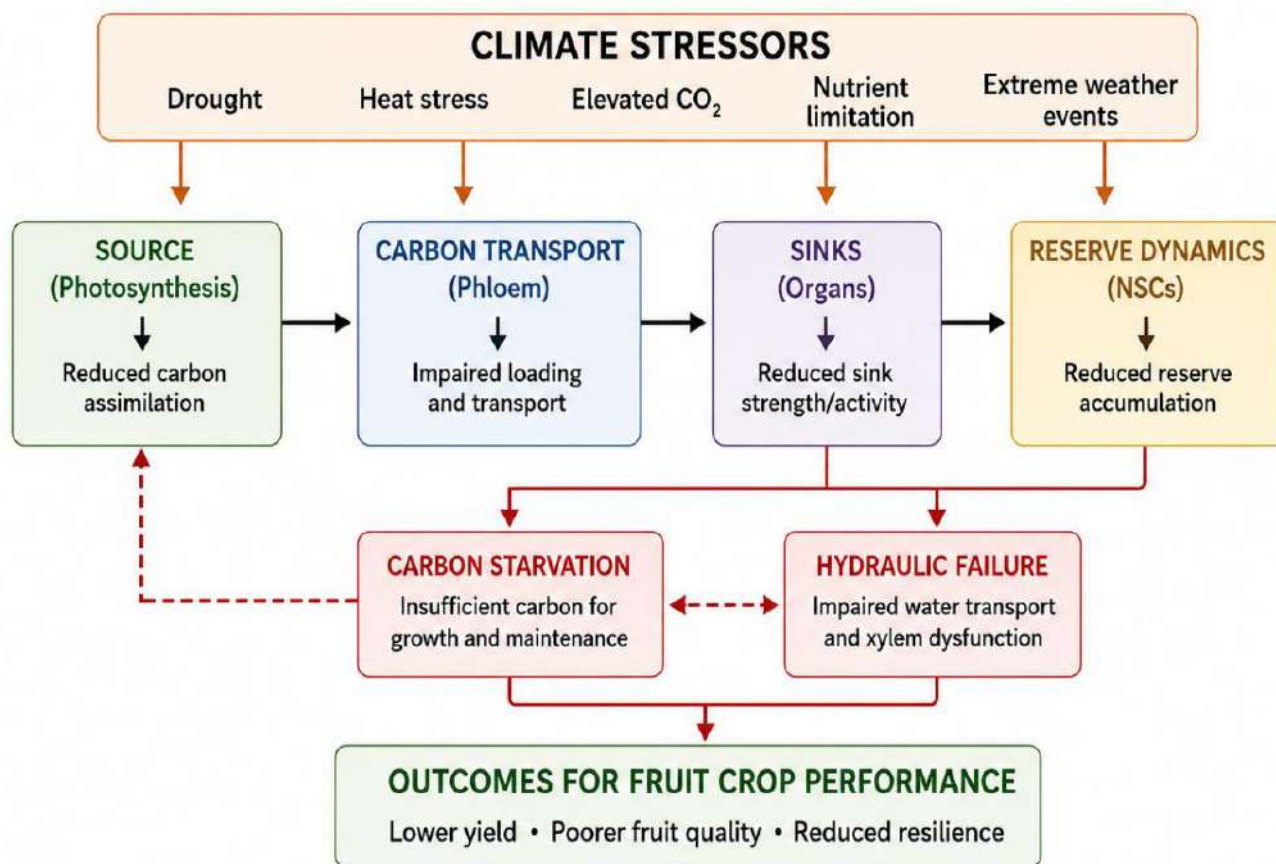


FIGURE 2: Influence of climate stressors on source-sink dynamics, carbon allocation, and fruit crop performance.

9.5 Carbon Starvation, Hydraulic Failure, and Resilience

Carbon starvation, resulting from depletion of non-structural carbohydrate reserves, and hydraulic failure, caused by impaired water transport, are key mechanisms underlying plant responses to prolonged stress (Sevanto *et al.*, 2014). These processes are closely interconnected because disruptions in phloem transport can simultaneously limit carbon delivery and impair hydraulic function (Hartmann & Trumbore, 2016). Therefore, maintaining source-sink coordination and adequate reserve levels is critical for enhancing resilience in perennial fruit crops (Martínez-Vilalta *et al.*, 2016).

Overall, climate change highlights that sink function, transport processes, and reserve dynamics may be more vulnerable to environmental stress than photosynthetic carbon supply alone. A mechanistic understanding of source-sink interactions under multiple climate stressors is essential for developing climate-smart and resilient fruit production systems. An integrated summary of the effects of major climate stressors on source-sink dynamics, carbon allocation, and fruit crop performance is presented in Table 1.

X. ORCHARD MANAGEMENT STRATEGIES FOR OPTIMIZING CARBON ALLOCATION

Carbon allocation in fruit crops is strongly influenced by orchard management practices that affect source capacity, sink strength, phloem transport, and reserve accumulation. Sustainable productivity depends on balancing vegetative growth, reproductive demand, and carbohydrate reserves rather than maximizing carbon assimilation alone (Pawar *et al.*, 2019).

TABLE 1
EFFECTS OF CLIMATE STRESSORS ON CARBON ALLOCATION, SOURCE-SINK DYNAMICS, AND FRUIT CROP PERFORMANCE

Climate stressor	Effects on source capacity	Effects on carbon transport and partitioning	Effects on sink strength/activity	Consequences for yield and fruit quality	Representative fruit crops
Elevated CO ₂	Increased photosynthesis; enhanced carbohydrate production; photosynthetic acclimation under sink limitation	Greater carbon availability; increased allocation to storage pools	Enhanced sink demand where sink capacity is sufficient	Increased yield potential but variable effects on fruit quality	Apple, grapevine, citrus
Drought	Reduced stomatal conductance and carbon assimilation	Impaired phloem loading and transport; preferential allocation to roots	Reduced cell division and expansion; reproductive abortion	Lower fruit size, yield loss, altered soluble solids	Apple, peach, mango
Heat stress	Reduced photosynthetic efficiency; accelerated leaf senescence	Increased respiratory carbon losses	Reduced pollen viability and fruit set; shortened fruit development period	Lower yield, reduced firmness, poor coloration	Apple, cherry, grapevine
Heat × drought	Severe reductions in carbon fixation and water transport	Competition among maintenance, defence, and reproductive sinks	Strong reduction in sink activity; increased fruit drop	Major yield instability and quality deterioration	Citrus, olive, almond
Elevated CO ₂ × nutrient limitation	Downregulation of photosynthesis due to nutrient constraints	Reduced efficiency of carbon utilization	Restricted sink development despite carbon abundance	Limited yield gains; dilution of mineral nutrients	Apple, kiwifruit
Extreme weather events (frost, hail, flooding)	Sudden loss of photosynthetically active tissues	Disruption of source-sink connectivity	Damage to flowers, fruits, and storage organs	Immediate yield loss and long-term carry-over effects	All fruit crops

Key message: Climate stressors affect source-sink relationships at multiple organizational levels, from carbon fixation and transport to sink utilization, ultimately determining yield stability and fruit quality.

10.1 Canopy Management and Light Interception

Canopy architecture determines light interception, leaf area distribution, and orchard microclimate, thereby influencing photosynthetic carbon acquisition. Pruning, training systems, shoot management, and high-density planting improve canopy light distribution and optimize the leaf area-to-fruit ratio, enhancing photosynthesis while reducing unproductive vegetative growth (Lakso & Corelli Grappadelli, 1992). Improved light exposure also promotes fruit colour and sugar accumulation (Palmer *et al.*, 2013).

10.2 Crop Load Management

Crop load is a major regulator of source-sink balance. Excessive fruit numbers reduce assimilate availability, limiting fruit size, quality, and reserve replenishment (Marcelis, 1996). Fruit thinning enhances sink strength, improves return bloom, and reduces alternate bearing by preserving non-structural carbohydrate reserves (Lakso & Corelli Grappadelli, 1992; Goldschmidt, 2013). Similar benefits have been demonstrated in high-density apple orchards, where fruitlet thinning improved fruit production and quality by reducing sink competition and optimizing assimilate allocation (Mehvish Bashir *et al.*, 2023).

10.3 Irrigation and Nutrient Management

Water and nutrient availability strongly influence photosynthesis, assimilate transport, and sink activity. Regulated deficit irrigation improves water-use efficiency and fruit quality (Chaves *et al.*, 2010). Balanced nutrition supports source activity and assimilate partitioning, while foliar nutrient application enhances photosynthate distribution and delays senescence under contrasting environmental conditions (Marschner, 2012; Ghazannfar Ghani *et al.*, 2019). Excessive nitrogen, however, promotes vegetative sink demand at the expense of fruit growth. Likewise, appropriate preharvest calcium management and optimum harvest timing improve fruit quality and reduce physiological disorders, highlighting the importance of integrating nutrient management with source-sink optimization (Khan *et al.*, 2023).

10.4 Rootstock-Scion Selection and Orchard Design

Rootstocks influence carbon allocation by affecting tree vigour, hydraulic conductance, nutrient uptake, and sink demand. Size-controlling rootstocks and suitable rootstock-scion combinations improve carbon-use efficiency, fruit quality, and tolerance to environmental stresses (Tworkoski & Fazio, 2015; Warschefsky *et al.*, 2016).

10.5 Post-harvest Management and Reserve Replenishment

Post-harvest photosynthesis is essential for replenishing non-structural carbohydrate reserves required for subsequent flowering and fruiting cycles (Pawar *et al.*, 2019). Premature defoliation caused by pests, diseases, or environmental stress reduces reserve accumulation and compromises future productivity (Martínez-Vilalta *et al.*, 2016). Therefore, maintaining canopy health through appropriate post-harvest irrigation, nutrition, and pest management is critical.

An integrated framework illustrating key orchard management strategies for enhancing source capacity, optimizing sink demand, improving assimilate transport, and strengthening reserve accumulation under changing climatic conditions is presented in Figure 3.

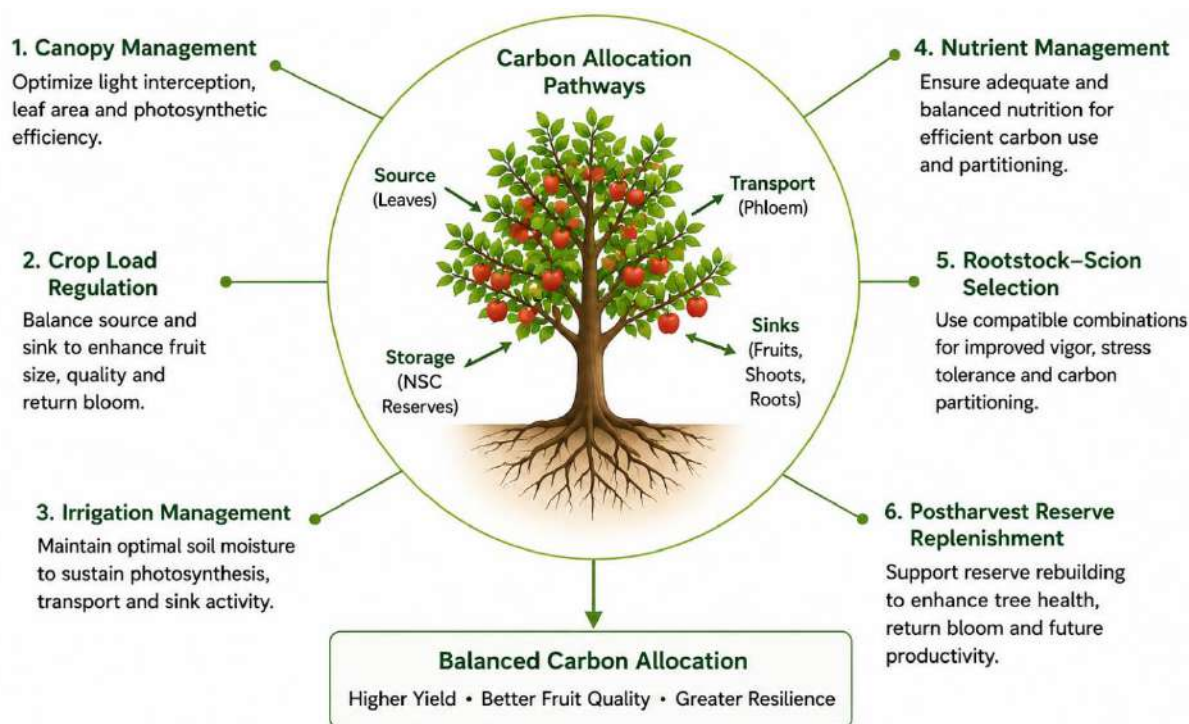


FIGURE 3: Integrated orchard management strategies for optimizing carbon allocation.

Overall, orchard practices that enhance source capacity, optimize sink demand, maintain efficient carbon transport, and preserve carbohydrate reserves provide a practical framework for improving productivity and climate resilience. Future orchard systems will increasingly rely on precision technologies and decision-support tools to dynamically manage source-sink relationships under changing environmental conditions.

XI. EMERGING TOOLS AND MODELLING APPROACHES

Advances in phenotyping, molecular biology, and computational modelling are transforming the study of carbon allocation and source-sink dynamics in fruit crops. Emerging technologies now enable the quantification, visualization, and prediction of carbon fluxes across multiple scales, supporting precision orchard management and climate resilience (Pawar *et al.*, 2019).

11.1 Isotopic Tracing and Carbon Flux Analysis

Stable isotope techniques, particularly ^{13}C -labelled CO_2 , enable tracking of assimilated carbon from source leaves to fruits, roots, and storage tissues, improving understanding of carbon partitioning, reserve remobilization, and stress responses (Pallas *et al.*, 2018). Carbon isotope discrimination ($\delta^{13}\text{C}$) also provides an indicator of water-use efficiency and plant responses to drought and elevated CO_2 (Farquhar *et al.*, 1989).

11.2 High-Throughput Phenotyping and Proximal Sensing

High-throughput phenotyping using multispectral, hyperspectral, thermal, and LiDAR sensors enables non-destructive assessment of canopy architecture, photosynthetic activity, fruit load, and plant water status (Fiorani & Schurr, 2013). Integration of unmanned aerial vehicles (UAVs), proximal sensing, and machine learning supports rapid characterization of orchard variability and improves predictions of fruit yield, quality, and stress responses.

11.3 Molecular and Omics Approaches

Genomics, transcriptomics, proteomics, metabolomics, and phenomics have advanced understanding of the molecular regulation of source-sink interactions. Key targets include sucrose transporters, SWEET proteins, and sugar-signalling pathways involving trehalose-6-phosphate (T6P), sucrose non-fermenting-1-related protein kinase 1 (SnRK1), and target of rapamycin (TOR), which coordinate carbon allocation under changing environments (Chen *et al.*, 2012; Figueroa & Lunn, 2016). Genome editing technologies such as CRISPR-Cas offer opportunities to enhance source capacity, sink strength, and stress tolerance.

11.4 Functional-Structural Plant Models

Functional-structural plant models (FSPMs) integrate three-dimensional plant architecture with physiological processes to simulate carbon acquisition, transport, and allocation among competing sinks (Vos *et al.*, 2010). These models facilitate evaluation of management practices and environmental scenarios to optimize fruit growth and carbon-use efficiency (Pallas *et al.*, 2018).

11.5 Digital Agriculture and Artificial Intelligence

The integration of sensor networks, Internet of Things (IoT) technologies, cloud computing, and artificial intelligence (AI) is enabling data-driven orchard management. Machine learning algorithms increasingly combine remote sensing, omics, and environmental data to predict carbon allocation and stress responses. Digital twins—virtual representations of orchard systems updated with real-time data—offer new opportunities to optimize management under future climate scenarios.

Despite these advances, challenges remain in integrating multi-scale datasets and translating mechanistic understanding into operational decision-support tools. Future research should focus on linking molecular, physiological, and whole-orchard processes through interoperable models and standardized datasets to improve productivity, fruit quality, and resilience in climate-smart fruit production systems.

XII. RESEARCH GAPS AND FUTURE PERSPECTIVES

Despite considerable advances in understanding source-sink relationships in fruit crops, major knowledge gaps remain regarding the regulation of carbon allocation across spatial and temporal scales. Most existing frameworks are based on controlled experiments or isolated physiological processes, limiting their applicability to perennial orchard systems exposed to multiple interacting stresses (Pawar *et al.*, 2019).

12.1 From Static to Dynamic Source-Sink Frameworks

Traditional models often treat source capacity and sink strength as independent traits, whereas source-sink interactions are dynamic and feedback-regulated processes in which sink demand influences photosynthesis, assimilate transport, and reserve accumulation (Paul & Foyer, 2001). Future research should develop integrated frameworks that incorporate seasonal shifts in

sink priority, reserve remobilization, and sugar-signalling pathways, including trehalose-6-phosphate (T6P), sucrose non-fermenting-1-related protein kinase 1 (SnRK1), and target of rapamycin (TOR) (Figueroa & Lunn, 2016; Li *et al.*, 2022).

12.2 Non-Structural Carbohydrate Dynamics and Climate Stress

Although non-structural carbohydrates (NSCs) are recognized as key determinants of productivity and resilience, uncertainties remain regarding reserve thresholds, accessibility, and their role under stress conditions (Hartmann & Trumbore, 2016). Future studies should quantify organ-specific reserve pools and clarify the contributions of stored versus current assimilates to fruit development, alternate bearing, and stress recovery (Martínez-Vilalta *et al.*, 2016).

Most climate studies examine drought, heat, or elevated CO₂ individually, despite their frequent co-occurrence under field conditions (IPCC, 2023). Future research should investigate how multiple stressors affect sink activity, phloem transport, reserve dynamics, and the relative importance of carbon starvation and hydraulic failure during prolonged stress (Sevanto *et al.*, 2014).

12.3 Rootstock-Scion Interactions and Orchard Design

The influence of rootstock-scion combinations on whole-tree carbon allocation remains insufficiently understood, particularly under climate stress. Future studies should evaluate how rootstocks, orchard architecture, and management practices interact to optimize source-sink coordination and resilience (Warschefsky *et al.*, 2016).

12.4 Integrating Multi-Scale Data and Predictive Models

A major challenge is integrating molecular, physiological, and orchard-scale information into predictive frameworks (Pallas *et al.*, 2018). Combining isotopic tracing, high-throughput phenotyping, remote sensing, and omics approaches with functional-structural plant models, digital twins, and artificial intelligence-based decision-support systems could improve prediction of source-sink dynamics under diverse management and climate scenarios (Fiorani & Schurr, 2013).

12.5 Towards Climate-Smart Carbon Management

Future productivity will depend less on maximizing carbon assimilation and more on maintaining coordinated carbon flow among competing sinks across seasons (Pawar *et al.*, 2019). Research should identify traits associated with carbon-use efficiency, sink plasticity, and reserve resilience and integrate them into breeding programmes, rootstock development, and precision orchard management.

XIII. CONCLUSIONS

Carbon allocation in fruit crops is a dynamic, integrated process that underpins productivity, fruit quality, and long-term orchard performance. Yield depends not only on photosynthetic carbon supply but also on the coordinated regulation of source capacity, sink strength, phloem transport, and non-structural carbohydrate (NSC) reserves across developmental stages. Evidence indicates that sink activity actively regulates carbon assimilation through metabolic and signalling feedback, while competition among fruits, vegetative organs, and storage tissues, together with reserve accumulation and remobilization, links current carbon allocation with future productivity. Consequently, maintaining functional sink activity and adequate carbohydrate reserves is fundamental for sustaining yield stability and reducing alternate bearing.

Climate change is expected to intensify disruptions in source-sink coordination through drought, heat stress, elevated CO₂, nutrient limitations, and extreme weather events, with sink processes and phloem transport often more vulnerable than photosynthesis. Emerging approaches, including isotopic tracing, high-throughput phenotyping, omics technologies, remote sensing, and functional-structural modelling, provide unprecedented opportunities to quantify and predict carbon dynamics in perennial fruit crops. Their integration with precision orchard management, optimized rootstock-scion combinations, and climate-smart practices will facilitate resilient production systems.

For researchers, priority areas include developing dynamic source-sink models that incorporate seasonal shifts and stress responses, quantifying organ-specific reserve thresholds, and understanding the molecular basis of sink plasticity. **For breeders**, traits associated with carbon-use efficiency, sink strength, and reserve resilience should be integrated into breeding programmes. **For orchard managers and advisors**, practical strategies include optimizing crop load through thinning, managing canopy architecture for improved light interception, implementing deficit irrigation strategies, maintaining post-harvest canopy health for reserve replenishment, and adopting precision technologies for monitoring carbon status. **For policymakers**, supporting research on climate-resilient rootstocks and varieties, promoting adoption of climate-smart

management practices, and investing in extension services that translate source-sink science into actionable recommendations are essential priorities.

Ultimately, future gains in fruit productivity and quality will depend not on maximizing carbon assimilation alone, but on optimizing whole-plant carbon economy through integrated, predictive, and multi-scale management of source-sink interactions, reserve dynamics, and environmental responses.

DATA AVAILABILITY STATEMENT

No new data were generated or analysed in support of this review. Data sharing is not applicable to this article.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this review article.

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Strategies for Strengthening Agricultural Institutions in Support of Food Security: A Mixed-Methods Study from Parepare City, Indonesia

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Abstract— Agricultural institutions play a crucial role in enhancing the effectiveness of agricultural development and strengthening food security, particularly in resource-limited areas such as Parepare City. This study aims to analyze the role of agricultural institutions and formulate institutional strengthening strategies to support food security. The study employed a mixed methods approach, with data collected through in-depth interviews, observations, and questionnaires. Institutional role analysis was conducted using MAXQDA, while strengthening strategies were analyzed using Interpretative Structural Modeling (ISM). The results suggest that agricultural institutions contribute through three sectors: the public sector, the voluntary sector, and the private sector, which play a role in providing production facilities, extension services, access to capital, food distribution, and digital-based marketing. The ISM analysis identified five priority strategies: increasing the capacity of extension workers, increasing farmer knowledge through education and mentoring, providing production facilities, providing fertilizers as needed, and using quality seeds to increase productivity. Strengthening human resource capacity and synergy between stakeholders emerged as key factors in realizing adaptive and sustainable agricultural institutions to support regional food security.

Keywords— Agricultural institutions, food security, MAXQDA, Interpretative Structural Modeling, strengthening strategies.

I. INTRODUCTION

Agriculture is a strategic sector that holds a central position in national development (Tahir et al., 2025; Sanga & Schlüter, 2025). However, the agricultural sector in Indonesia continues to face various fundamental structural challenges, one of which relates to agricultural institutions (Hakim & Febrianti, 2025). These institutional weaknesses result in low competitiveness, limited access to resources, and the agricultural sector's suboptimal contribution to supporting national food security (Bachtiar et al., 2022; Akbar et al., 2022).

Agricultural institutions encompass the formal and informal organizations, rules, norms, and networks that govern agricultural production, distribution, and consumption (Uphoff, 1986; Ostrom, 1990). These institutions serve as critical intermediaries between farmers and markets, between policy makers and practitioners, and between knowledge producers and knowledge users (North, 1990). In developing country contexts, strong agricultural institutions have been shown to facilitate technology adoption, improve market access, enhance risk management, and ultimately contribute to food security outcomes (Bawa, 2019; Obayelu et al., 2021).

In a regional context, Parepare City is an autonomous area with urban status characterized by limited agricultural land and a tendency for land conversion to occur. Parepare City's agricultural land covers 9,933 hectares. However, only 735.8 hectares, or approximately 7.41% of the total area, is used for rice fields (BPS Parepare City, 2024). Various studies demonstrate that

agricultural institutions make a significant contribution to strengthening national food security (Jumiati et al., 2023; Dewi Anggun Oktaviani, 2020). However, aggregate food availability at the national level does not automatically guarantee the fulfillment of food security at the regional, household, and individual levels (Usman, Ratnawati T, 2024). Limited land represents the primary challenge in developing the local agricultural sector.

A preliminary survey in Parepare City identified several issues hampering the development of the agricultural sector. The predominantly hilly geography and limited agricultural land mean that most land is rain-fed, meaning cultivation can only be carried out once a year. Furthermore, of the 150 registered farmer groups, 12 remain inactive, while the overall participation rate among farmer group members is only 49%. The role of the Farmer Group Association (Gapoktan) tends to be limited to administrative functions and has not yet functioned optimally as a farmer's economic institution. Another issue is the lack of specialized cooperatives supporting agricultural sector capital, forcing farmers to access financing individually through formal financial institutions. Furthermore, the presence of four Agricultural Extension Centers (BPP) in Parepare City has not been matched by effective extension functions, as BPP activities are still dominated by administrative matters without adequate technical and educational support for farmers.

These institutional weaknesses have a direct impact on regional food security. Parepare City is highly dependent on food supplies from other regions such as Sidrap, Barru, and Pinrang Regencies. This dependency increases the risk of food insecurity, especially when there are distribution disruptions or price fluctuations in supplier areas. Data from the Parepare City Food Security Office shows that Parepare City's food security index (IKP) is 82.76, placing the city in 61st place out of 98 cities in Indonesia. This indicates the need for strengthening aspects of food availability, access, and utilization.

Despite the acknowledged importance of agricultural institutions for food security, there remains a gap in understanding how institutional strengthening strategies can be effectively implemented in urban contexts with limited agricultural land and high dependency on external food supplies. Furthermore, there is limited research that systematically analyzes both the roles of different institutional sectors and prioritizes strengthening strategies using robust analytical methods.

Therefore, an analysis of the role of agricultural institutions in supporting food security is crucial to identify aspects that are already functioning effectively and those that remain weak. Furthermore, it is necessary to formulate a strategy for strengthening agricultural institutions that is targeted, measurable, and based on regional needs. This would enable agricultural institutions not only to function administratively but also to play an effective role in strengthening the food supply chain and increasing regional food independence in Parepare City.

The objectives of this study are:

- 1) To analyze the role of agricultural institutions in supporting food security.
- 2) To formulate a strategy for strengthening agricultural institutions in supporting food security.

II. RESEARCH METHODS

2.1 Type of Research

This research uses a combined qualitative and quantitative approach (mixed methods). Creswell and Plano Clark (2018) state that mixed methods is a research approach that combines qualitative and quantitative approaches to obtain more comprehensive, valid, reliable, and objective data. In this study, a convergent parallel design was employed, where qualitative and quantitative data were collected simultaneously, analyzed separately, and then integrated during interpretation. The qualitative approach was used to analyze the role of agricultural institutions through stakeholder interviews, while the quantitative approach (specifically the ISM technique) was used to prioritize strategies for strengthening agricultural institutions in supporting food security.

2.2 Location and Time of Research

This research was conducted in Parepare City, South Sulawesi Province over 7 (seven) months, from June to December 2025. The selection of Parepare City as the research location was based on empirical conditions indicating that this area faces food and nutrition security issues with a high level of urgency. Geographically, Parepare is an urban area with limited agricultural land, where only about 7.41% of the area is used as rice fields and most of it is rain-fed, resulting in low local food production capacity that is unable to meet community needs. This condition causes a very large dependence on food supplies from other

areas. Weak agricultural institutions have a direct impact on aspects of access, distribution, and utilization of food in the community.

2.3 Informant Selection

The selection of informants for analyzing the role of agricultural institutions and strategies for strengthening effective agricultural institutions was carried out using a purposive sampling method, namely selecting informants who were considered to have in-depth knowledge, were willing to participate, and could provide information relevant to the research objectives. Inclusion criteria included having at least three years of experience in their respective roles, direct involvement in agricultural or food security programs, and willingness to participate in the study. To fulfill the data that could support the achievement of the research objectives, the number of informants was set at 13 experts or practitioners consisting of as shown in Table 1.

TABLE 1
DETAILS OF SOURCES AND NUMBER OF INFORMANTS

No	Informant Source	Amount
1	Department of Agriculture, Maritime Affairs, and Fisheries of Parepare City	1
2	Parepare City Food Security Service (DKP)	1
3	Parepare City Trade Office	1
4	Parepare City Health Office	1
5	Regional Development Planning Agency (Bappeda) of Parepare City	1
6	Agricultural Extension Center (BPP)	1
7	Farmers Group Association (Gapoktan)	1
8	Farmers Group	1
9	College	1
10	Banking	1
11	Farmer	1
12	Micro, Small and Medium Enterprises	1
13	Supermarket or Market	1
Total		13

2.4 Research Instruments

Several instruments were used in this study, adapted to each research objective, namely the In-depth Interview Guide and the Household Food Insecurity Access Scale (HFIAS) Questionnaire. The interview guide contained semi-structured questions covering the roles of agricultural institutions, challenges faced, and potential strengthening strategies. The HFIAS questionnaire, adapted from the standard instrument developed by the Food and Nutrition Technical Assistance (FANTA) project, was used to measure household food security levels in terms of food access.

2.5 Data Collection Techniques

Data collection techniques were carried out through six main stages:

2.5.1 In-depth Interviews (In-depth Interview)

Interviews were conducted using semi-structured interview guidelines to allow researchers flexibility in exploring more in-depth information about the research variables. Each interview lasted approximately 60-90 minutes and was conducted at the informant's workplace or a mutually agreed location. All interviews were audio-recorded with informant consent and transcribed verbatim for analysis.

2.5.2 Field Observation

Field observations were conducted to verify and complement the interview results through direct observation of the actual conditions of agricultural institutions in Parepare City. Aspects observed included the roles and strategies that strengthen agricultural institutions in food security. Observations were conducted at multiple sites including agricultural extension centers, farmer groups, markets, and agricultural input distribution points.

2.5.3 Household Food Insecurity Access Scale (HFIAS) Questionnaire

The HFIAS questionnaire was used to measure household food security levels in terms of food access. This instrument consists of nine questions describing households' experiences with food shortages over the past four weeks. The HFIAS data were collected to provide contextual information about the food security situation in the study area.

2.6 Data Analysis Techniques

The data analysis techniques used consisted of several methods according to the research objectives.

2.6.1 Research Objective 1

To achieve research objective 1, MAXQDA software was used. MAXQDA was used to organize, code, and analyze interview data related to the research objectives. The analysis process was carried out through the following stages (Qomaruddin & Sa'diyah, 2024):

a. Import Data

Data collected from interviews with all informants were uploaded into MAXQDA in the form of text transcripts.

b. Data Coding

The coding process was carried out by grouping data based on research objectives, namely the role of agricultural institutions in supporting food security. Codes were developed both deductively (based on the food security literature and institutional theory) and inductively (emerging from the interview data). The lead researcher conducted the primary coding, with a second researcher independently coding a subset of transcripts (30%) to assess coding consistency. Discrepancies were resolved through discussion until consensus was reached.

Relevant text sections were coded into appropriate categories to facilitate analysis.

c. Thematic Analysis

The coded data were analyzed using a thematic approach to identify patterns, relationships, and similarities and differences in the research findings. The Code System feature in MAXQDA was used to organize key themes, while Keywords-in-Context (KWIC) was used to identify frequently used terms related to agricultural institutions in supporting food security.

d. Data Visualization

To understand the relationship between various factors and research findings, several visualization tools in MAXQDA were used, such as:

- a) Creative Coding to view research results regarding the role of agricultural institutions and strengthening agricultural institutions in supporting food security found in research.
- b) Document Comparison Chart to compare perspectives from various informants.

e. Interpretation and Reporting of Results

The analysis results were summarized using the Summary Grid feature in MAXQDA to compile conclusions that support the research objectives.

2.6.2 Research Objective 2

The analysis used for research objective 2 was Interpretative Structural Modeling (ISM). ISM is a group learning process in which structural models are generated to capture complex aspects of a system through carefully designed patterns using graphical representations. The ISM technique is intended for team assessments but can also be used by a single researcher (Sage, 1977; Warfield, 1974).

In this study, ISM analysis was used to analyze the institutions that play a role and formulate strategies for strengthening agricultural institutions in supporting food security. The 13 sub-elements for ISM analysis were derived from the qualitative interview findings and supplemented with insights from the literature. Informants were asked to provide their assessments regarding the contextual relationships between these sub-elements. The ISM process involved pairwise comparisons where informants judged whether one sub-element influences or is influenced by another.

The stages of ISM analysis were as follows:

a. Compiling a Structural Self-Interaction Matrix (SSIM)

This involved obtaining input (assessment) from respondents regarding the sub-elements above, as a result of considering contextual relationships, using the symbols V, A, X, and O. The symbols represent:

- V: Element i influences element j
- A: Element j influences element i
- X: Elements i and j influence each other
- O: Elements i and j are not related

b. Compile a Reachability Matrix

The SSIM was converted into a binary Reachability Matrix using the symbols V, A, X, and O with the numbers 1 and 0 based on standardized ISM conversion rules.

c. Compile a structural model (element level) of each element

Based on the reachability matrix, element levels were determined to create a hierarchical structural model.

d. Compile the Driver Power-Dependent (DP-D) Matrix

The DP-D matrix consisted of four sectors as shown in Figure 1.

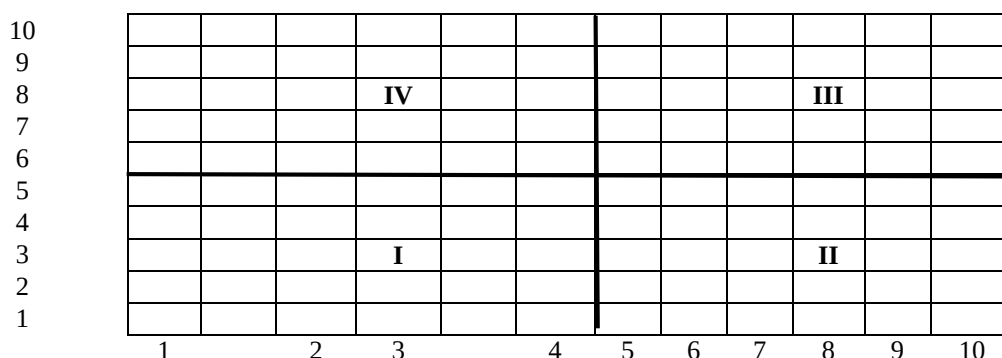


FIGURE 1: DP-D matrix

From the four sectors in question, a strategy for strengthening agricultural institutions in supporting food security can be determined based on the Driver Power-Dependent weight.

Sector I: Autonomous, not strongly influencing, but not easily influenced

Sector II: Dependent, easily influenced but not strongly influencing

Sector III: Linkage, strong influence but easily influenced

Sector IV: Independent, strong influence and not strongly influenced

The following are elements and sub-elements related to the research objectives.

TABLE 2
ELEMENTS AND SUB-ELEMENTS OF RESEARCH ON STRENGTHENING AGRICULTURAL INSTITUTIONS IN SUPPORTING FOOD SECURITY

Element		Sub-Elements
Strategy for Strengthening Agricultural Institutions in Supporting Food Security	1	Improving the capacity of extension workers through training and technical guidance
	2	Improving farmers' knowledge through education and mentoring
	3	Providing production facility assistance programs
	4	Strengthening cooperation between institutions to create synergy
	5	Facilitate and optimize the use of agricultural technology
	6	Providing easy access to capital for farmers and MSMEs
	7	Drafting regulations that limit the conversion of agricultural land
	8	Implement structured pest and disease control
	9	Using quality seeds to increase productivity
	10	Preparation of fertilizer according to the needs and experience of farmers
	11	Assistance in the implementation of sustainable agricultural principles
	12	Developing digital and innovation-based marketing sectors
	13	Forming a research and development team to drive innovation

III. RESULTS

3.1 Informant Characteristics

The description of the characteristics of informants in this study can be grouped into several groups according to Table 3, namely informant initials, gender, age, last education, and informant's occupation.

TABLE 3
INFORMANT CHARACTERISTICS BASED ON INITIALS, GENDER, AGE, AND LAST EDUCATION

Initials	Gender	Age (Years)	Last education	Job / Position
AR	P	54	S2	Head of Agriculture Division of DPKP Parepare City
AW	L	57	S2	Head of the Food Availability, Vulnerability and Distribution Division of the Parepare City Marine and Fisheries Service
AC	P	57	S1	Head of General Administration and Personnel Sub-Division, Parepare City Trade Office
HA	P	38	S2	Nutrition Coordinator of the Parepare City Health Office
AT	P	48	S2	Head of Regional Development and Natural Resources Sub-Division, BAPPEDA, Parepare City
HH	P	56	S2	Head of the West Bacukiki Agricultural Extension Center (BPP)
MB	L	39	Vocational School	General Treasurer of the Berdikari Lompoe Farmers Group
MR	L	45	Junior High School	Head of the Galung Maloang Riawa Farmers Group
SU	P	49	S3	Dean of the Faculty of Agriculture, Animal Husbandry and Fisheries, Muhammadiyah University of Parepare
AE	P	50	S1	Micro Business Manager of Bank Rakyat Indonesia (BRI) Parepare Branch
LS	L	55	Elementary School	Farmer
SP	L	52	Senior High School	Owner of UD. Masagenae
YB	L	39	S2	Owner of E Rice Business

The description of the characteristics of informants in this study can be grouped into age, gender, and education as follows:

TABLE 4
CHARACTERISTICS OF INFORMANTS BASED ON AGE, GENDER, AND EDUCATION

Characteristics	Frequency (f)	Percentage (%)
Age		
31 - 40	3	23.08
41 - 50	4	30.77
51 – 60	5	46.15
Total	13	100
Gender		
Man	6	46.15
Woman	7	53.85
Total	13	100
Last education		
Elementary School	1	7.69
Junior High School	1	7.69
High School/Equivalent	2	15.39
College	9	69.23
Total	13	100

Source: Primary Data 2025

Based on the data in Table 4, the characteristics of the informants can be explained as follows. In terms of age, the majority of respondents were in the 51–60 year group (5 people, 46.15%), followed by the 41–50 year group (4 people, 30.77%) and the 31–40 year group (3 people, 23.08%). In terms of gender, the distribution of respondents was relatively balanced, with 7 women (53.85%) and 6 men (46.15%), suggesting that the research data is not biased towards one gender. Meanwhile, in terms of the last education, the majority of respondents had a college education (9 people, 69.23%), followed by high school/equivalent (2 people, 15.39%), and elementary and junior high school (1 person each, 7.69%). The high proportion of higher education indicates that respondents generally have the ability to understand and respond to research questions well, though it also suggests that the sample may be skewed toward more educated stakeholders.

3.2 The Role of Agricultural Institutions in Supporting Food Security

The results of the interview analysis related to the role of agricultural institutions using MAXQDA software are presented in Figure 2.

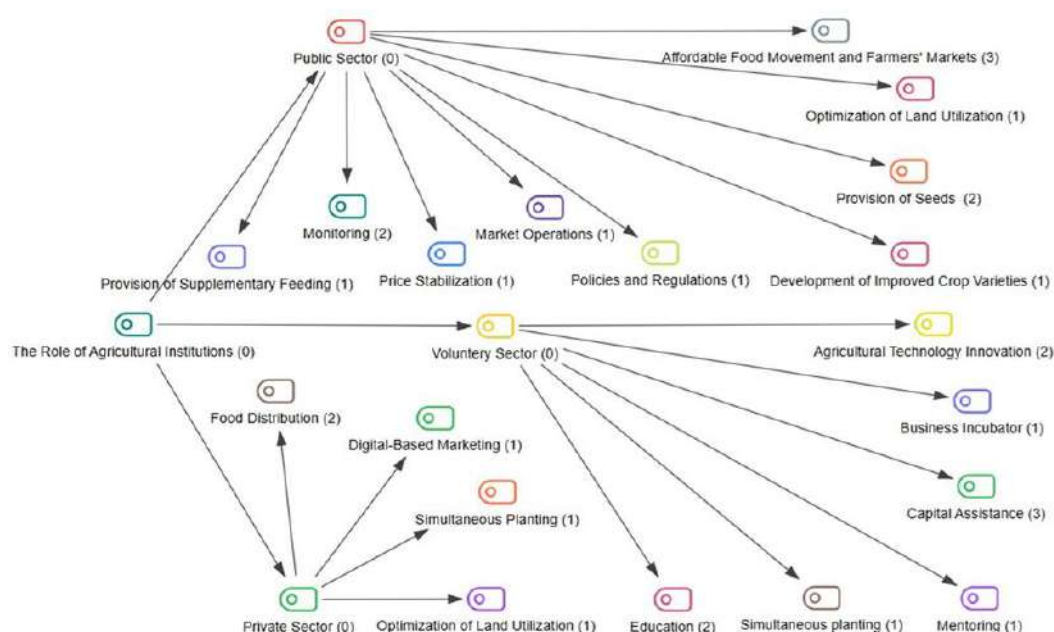


FIGURE 2: MAXQDA Visualization - The role of agricultural institutions in supporting food security

Based on the results of the analysis using MAXQDA from the research that has been conducted, several roles of agricultural institutions in supporting food security were identified, distributed across three scopes: the public sector, the voluntary sector, and the private sector. Informants across all sectors consistently emphasized the interconnected nature of institutional roles, with one extension officer noting: *"We cannot work in isolation. The success of agricultural programs depends on how well we coordinate with the food security office, the trade office, and even the banking sector"* (HH, Extension Center Head).

In the public sector, there are 9 activities or programs identified. The voluntary sector has 6 activities or programs, while the private sector has 4 activities or programs.

In the scope of the public sector, the interventions carried out are quite diverse with significant intensity, such as the Cheap Food Movement and Farmers' Markets (mentioned 3 times), provision of seeds and agricultural machinery (2), supervision (2), while price stabilization, policies, market operations, development of superior varieties, provision of PMT (Supplementary Feeding), and optimization of land use were each mentioned 1 time. A government official emphasized: *"Our role is to ensure that staple foods remain accessible to all communities, especially during price fluctuations. The Cheap Food Movement is one way we do this"* (AR, Head of Agriculture Division).

In the voluntary sector, the role is more emphasized on capital assistance (mentioned 3 times), then agricultural technology innovation and education (2 times each), while business incubators, mentoring, and simultaneous planting are each mentioned 1 time. The banking representative noted: *"We provide access to capital with easy requirements and fast processes. The challenge is ensuring farmers understand how to manage these funds effectively"* (AE, Bank Manager).

In the private sector, a number of programs are aimed at supporting food security, such as assisting with food distribution (mentioned 2 times), while land optimization, simultaneous planting, and digital-based marketing are each implemented once. A market owner explained: *"We try to source from local farmers when possible. Digital marketing has helped us reach more customers and stabilize prices"* (SP, Market Owner).

3.3 Strategy for Strengthening Agricultural Institutions in Supporting Food Security

The sub-elements of the strategy for strengthening agricultural institutions to support food security are alternative options compiled from various sources, both through interviews and literature. This study has compiled 13 sub-elements as a strategy for strengthening agricultural institutions to support food security, namely:

- a. Improving the capacity of extension workers through training and technical guidance
- b. Improving farmers' knowledge through education and mentoring
- c. Providing production facility assistance programs
- d. Strengthening cooperation between institutions to create synergy
- e. Facilitate and optimize the use of agricultural technology
- f. Providing easy access to capital for farmers and MSMEs
- g. Drafting regulations that limit the conversion of agricultural land
- h. Implement structured pest and disease control
- i. Using quality seeds to increase productivity
- j. Preparation of fertilizer according to the needs and experience of farmers
- k. Assistance in the implementation of sustainable agricultural principles
- l. Developing digital and innovation-based marketing sectors
- m. Forming a research and development team to drive innovation

3.3.1 Structural Self-Interaction Matrix of Strengthening Strategies

From the results of the analysis of respondents' opinions obtained through expert surveys after tabulating the questionnaire, a structural self-interaction matrix (SSIM) is compiled which aims to determine whether there is a contextual relationship between elements i and j and vice versa. The compilation of SSIM uses the symbols V, A, X, and O, as shown in Table 5.

TABLE 5

SSIM STRATEGY FOR STRENGTHENING AGRICULTURAL INSTITUTIONS IN SUPPORTING FOOD SECURITY

Element/Institution to-	13	12	11	10	9	8	7	6	5	4	3	2	1
1	V	V	V	X	X	V	V	V	X	V	X	X	-
2	V	V	V	X	X	V	V	V	X	V	X	-	-
3	V	X	V	X	X	X	V	X	V	V	-	-	-
4	X	X	X	A	A	A	X	A	A	-	-	-	-
5	V	V	X	X	X	X	V	X	-	-	-	-	-
6	V	V	V	X	X	X	X	-	-	-	-	-	-
7	A	A	X	A	A	A	-	-	-	-	-	-	-
8	V	V	V	X	X	-	-	-	-	-	-	-	-
9	V	X	V	X	-	-	-	-	-	-	-	-	-
10	V	V	V	-	-	-	-	-	-	-	-	-	-
11	X	X	-	-	-	-	-	-	-	-	-	-	-
12	V	-	-	-	-	-	-	-	-	-	-	-	-
13	-	-	-	-	-	-	-	-	-	-	-	-	-

3.3.2 Reachability Matrix of Agricultural Institutional Strengthening Strategies

After the SSIM is compiled, the reachability matrix (RM) table is created by replacing the respondent's answer codes from V, A, X, and O with the numbers 1 and 0. After the final RM is compiled, it is used to determine the order of the driver power (DP) and Dependent (D) of each sub-element, and the ranking of each sub-element.

TABLE 6

FINAL REACHABILITY MATRIX

	j														
	A	B	C	D	E	F	G	H	I	J	K	L	M	DP	R
i	A	1	1	1	1	1	1	1	1	1	1	1	1	1	13
	B	1	1	1	1	1	1	1	1	1	1	1	1	1	13
	C	1	1	1	1	1	1	1	1	1	1	1	1	1	13
	D	0	0	0	1	0	0	1	0	0	0	1	1	1	5
	E	1	1	0	1	1	1	1	1	1	1	1	1	1	12
	F	0	0	1	1	1	1	1	1	1	1	1	1	1	11
	G	0	0	0	1	0	1	1	0	0	0	1	0	0	4
	H	0	0	1	0	1	1	0	1	1	1	1	1	1	9
	I	1	1	1	1	1	1	1	1	1	1	1	1	1	13
	J	1	1	1	1	1	1	1	1	1	1	1	1	1	13
	K	0	0	0	1	1	0	1	0	0	0	1	1	1	6
	L	0	0	1	1	0	0	1	0	1	0	1	1	1	7
	M	0	0	0	1	0	0	1	0	0	0	1	0	1	4
	D	6	6	8	11	9	9	12	8	9	8	13	11	12	
	R	6	6	5	3	4	4	2	5	4	5	1	3	2	

Information:

- Improving the capacity of extension workers through training and technical guidance
- Improving farmers' knowledge through education and mentoring
- Providing production facility assistance programs
- Strengthening cooperation between institutions to create synergy
- Facilitate and optimize the use of agricultural technology

- f. Providing easy access to capital for farmers and MSMEs
- g. Drafting regulations that limit the conversion of agricultural land
- h. Implement structured pest and disease control
- i. Using quality seeds to increase productivity
- j. Preparation of fertilizer according to the needs and experience of farmers
- k. Assistance in the implementation of sustainable agricultural principles
- l. Developing digital and innovation-based marketing sectors
- m. Forming a research and development team to drive innovation

3.3.3 Position and Comparison of DP-D Weights for Strengthening Strategies

The comparison of the power-dependent driver (DP-D) weights between sub-elements determines the position of each sub-element in the Power-Dependent Driver (DP-D) Matrix as in Table 7.

TABLE 7
POSITION AND COMPARISON OF DP-D WEIGHTS OF STRENGTHENING STRATEGIES

	DP	D	
Independent (Strong driving force. On the other hand, dependence on other elements is generally weak)	Improving the capacity of extension workers through training and technical guidance	1.00*	0.46
	Improving farmers' knowledge through education and mentoring	1.00*	0.46
	<i>Average</i>	*1.00*	*0.46*
Linkage (Strong driving force for the program but has high dependency on other elements)	Providing production facility assistance programs	1	0.61
	Preparation of fertilizer according to the needs and experience of farmers	1	0.61
	Using quality seeds to increase productivity	1	0.69
	Facilitating and optimizing the use of agricultural technology	0.92	0.69
	Providing easy access to capital for farmers and MSMEs	0.84	0.69
	Implement structured pest and disease control	0.69	0.61
	Developing digital and innovation-based marketing sectors	0.53	0.84
	<i>Average</i>	*0.85*	*0.58*
Dependent (Weak driving force on the program, but has a very strong dependency on other elements)	Assistance in the implementation of sustainable agricultural principles	0.46	1
	Strengthening inter-institutional cooperation to create synergy	0.38	0.84
	Drafting regulations that limit the conversion of agricultural land	0.31	0.92
	Forming a research and development team to drive innovation	0.31	0.92
	<i>Average</i>	*0.36*	*0.92*

Information:

DP and D $\leq$ 0.50 = small

DP and D $\geq$ 0.50 = large

= Priority strengthening strategy

From Table 7 it can be seen that the strategy for strengthening agricultural institutions in supporting food security at the key level is (1) Improving Extension Human Resources and (2) Improving Farmer Knowledge.

3.3.4 Matrix Driver Power-Dependent (DP-D) Strategy for Strengthening Agricultural Institutions

The separation of strategies for strengthening agricultural institutions in supporting food security into four sectors (independent, linkage, autonomous, dependent) can be shown in the form of a driver power dependent matrix (DP-D) as in Figure 3.

13						A, B		C,J	I				
12									E				
11									F				
10		Independent							Linkage				
9								H					
8													
7											L		
6													K
5											D		
4		Autonomous										G,M	
3									Dependent				
2													
1													
	1	2	3	4	5	6	7	8	9	10	11	12	13

FIGURE 3. Matrix driver power dependent (DP-D) reinforcement strategy

Information:

- Improving the capacity of extension workers through training and technical guidance
- Improving farmers' knowledge through education and mentoring
- Providing production facility assistance programs
- Strengthening cooperation between institutions to create synergy
- Facilitate and optimize the use of agricultural technology
- Providing easy access to capital for farmers and MSMEs
- Drafting regulations that limit the conversion of agricultural land
- Implement structured pest and disease control
- Using quality seeds to increase productivity
- Preparation of fertilizer according to the needs and experience of farmers
- Assistance in the implementation of sustainable agricultural principles
- Developing digital and innovation-based marketing sectors
- Forming a research and development team to drive innovation

IV. DISCUSSION

4.1 The Role of Agricultural Institutions in Supporting Food Security

4.1.1 Public Sector

The research findings indicate that the public sector plays the most dominant role in supporting food security through nine activities across various programs. Local governments, particularly through the Department of Agriculture, Maritime Affairs, and Fisheries and the Department of Food Security, implemented direct interventions such as the Affordable Food Movement and Farmers' Markets (mentioned three times), the provision of seeds and agricultural machinery (two times), supervision (two

times), and price stabilization activities, market operations, and the provision of PMT (Supplementary Feeding). This suggests that government interventions focusing on food availability and stability are key actors in maintaining food supply and price stability at the local level. This finding aligns with the institutional economics perspective that emphasizes the role of government in addressing market failures and ensuring public goods provision in agricultural systems (North, 1990).

Furthermore, the research found that policies on the provision of production facilities and seed subsidies have a significant impact on increasing regional food productivity (Obayelu et al., 2021). Similarly, research by Clark and Jablonski (2022) confirms that the effectiveness of public food policies increases when local governments are able to involve cross-agency agencies and streamline field monitoring mechanisms for farmers receiving assistance. Thus, the public sector becomes the main backbone of the food institutional system through its role in policy, market intervention, and the provision of agricultural resources.

Some institutional roles within the public sector include:

First, implementing affordable food programs and farmers' markets. The Affordable Food Movement aims to provide staple foods and nutritious food at affordable prices, especially for low-income communities. This concept aligns with the short food supply chain approach, which emphasizes distribution efficiency, price transparency, and increased income for local producers (Chiffolleau et al., 2025; Andini, 2025).

Second, providing seed and agricultural machinery assistance, driven by the Department of Agriculture, Maritime Affairs and Fisheries, and agricultural extension agencies. High-quality, superior seeds are a key factor in increasing crop yields, plant resistance to pests and diseases, and the quality of food produced. Recent research shows that the availability of adequate superior seeds and agricultural machinery significantly increases agricultural productivity, reduces production costs, and supports local food security (Widiyanti et al., 2025).

Third, conducting supervision, particularly regarding the stability of fertilizer availability and other programs. Supervision of fertilizer availability is an important part of maintaining the stability of agricultural production and food security in Parepare City. Recent research shows that effective supervision of fertilizer distribution contributes significantly to increasing agricultural yields, stabilizing food prices, and strengthening local food security (Spirenkov, 2024).

Fourth, maintaining price stability to ensure the availability of affordable food, carried out in collaboration with the regional inflation control team (TPID) and food stakeholder partners. Price stability directly impacts the ability of people, especially low-income groups, to access nutritious food sustainably (Xi et al., 2026; Rana et al., 2023).

Fifth, formulate policies in the form of regional regulations, specifically regarding LP2B (Sustainable Food Agricultural Land). This regional regulation (Regional Regulation No. 8 of 2021) aims to protect and maintain productive agricultural land from being converted to other uses, such as housing, industry, or commercial buildings (Rahma Dayanti & Soetjipto, 2024).

Sixth, conduct market operations programs to ensure the availability of staple foods for the community, especially during periods of price fluctuations or uneven harvest seasons. Recent research shows that market operations are effective in reducing food price volatility, increasing consumption of nutritious food in urban communities, and supporting local food security (PUSPAKA et al., 2022; Muharramah et al., 2024).

Seventh, developing superior varieties, especially for corn. This program was implemented in collaboration with Hasanuddin University, Makassar. Previous research has shown that the use of superior varieties provides significantly higher financial returns than local varieties (Desiso & Kassa, 2024).

Eighth, providing supplementary feeding (PMT), especially to pregnant women and toddlers, is carried out by the health office. The PMT program, accompanied by nutrition education, health monitoring, and routine distribution, has been proven to significantly reduce the prevalence of stunting and strengthen family nutritional resilience (Gusman et al., 2025; Mardhiyah et al., 2025).

Ninth, encourage the optimization of land use, including the utilization of yard and marginal land through production intensification. Research shows that land optimization through agroecological and precision agriculture approaches can increase crop yields by up to 40%, reduce losses due to soil degradation, and increase farmer incomes (Jayaputra et al., 2020).

4.1.2 Voluntary Sector

The voluntary sector encompasses six main activities focused on empowerment, mentoring, and innovation. Research findings indicate that capital assistance is the most dominant program (mentioned three times), followed by agricultural technology innovation and community education (two times each), and business incubation, mentoring, and simultaneous planting (one time each).

This sectoral distribution suggests that voluntary institutions (including NGOs, farmer organizations, and financial institutions) primarily serve as facilitators and intermediaries, bridging gaps between public sector policies and private sector implementation. The emphasis on capital assistance and technology innovation indicates that these actors are responding to the immediate needs of farmers for resources and knowledge.

Some institutional roles within the voluntary sector include:

First, the distribution of capital assistance, specifically through the banking sector, specifically Bank Rakyat Indonesia (BRI). This program provides access to low-interest business capital, with easy requirements, and a fast process for farmers, livestock breeders, and fishermen. These funds can be paid quarterly, semi-annually, or even once the following year. This aligns with findings showing that capital support from local governments and non-governmental organizations contributes significantly to increasing farmer incomes and local food availability (Triyono et al., 2025).

Second, encouraging the implementation of agricultural technology, particularly the use of superior seeds, simple mechanization, deep irrigation, agricultural machinery, and dew zones. The application of agricultural technology is a crucial strategy for addressing modern challenges facing the agricultural sector, ranging from climate change, limited land, to increasing food production needs. The integration of mechanization, including the use of GPS-guided tractors and robotics for planting and harvesting, consistently improves resource efficiency and productivity in food crop cultivation (Wijayanto & Puspitojati, 2024).

Third, provide education to extension workers and farmers. Research conducted by Khuswati et al. (2022) shows that participatory education, both by field extension workers and agricultural institutions, is very effective in increasing the success of food security and public health programs, such as the Sustainable Food Home Area program and health education in various regions.

Fourth, organize a business incubator program, a program from BRI to support regional development through four main aspects: strengthening BUMDes, digitalization, innovation, and sustainability. These results are in line with research showing that participation in business incubator programs facilitated by agricultural institutions increases productivity, business efficiency, and digital marketing capabilities for food entrepreneurs (Albar & Amsal, 2024).

Fifth, provide assistance, especially in the OPL (Land Utilization Optimization) program with the aim of producing food crops such as vegetables for family consumption. Land optimization activities allow the remaining production to be sold at low-cost market activities to improve the welfare of farmers (Jayaputra et al., 2020).

Sixth, organizing a simultaneous planting program, such as the simultaneous corn planting activity, to support the achievement of national food security, carried out on plantation land in Galung Maloang Village, Bacukiki District. Research results show that this method has a significant impact on increasing crop yields, preventing pests and diseases, increasing irrigation efficiency, expanding farmer social networks, and accelerating the achievement of food self-sufficiency in various regions.

4.1.3 Private Sector

The private sector, while having fewer identified activities (4 programs), plays a complementary role to public and voluntary institutions. This pattern is consistent with the market-oriented perspective on institutional roles, where private actors primarily respond to market signals and profit incentives rather than directly pursuing food security objectives. However, their engagement in food distribution, land optimization, and digital marketing suggests that private sector participation is essential for creating efficient food value chains.

Some forms of institutional roles that fall within the scope of the private sector include:

First, carrying out food distribution activities through MSMEs so that food can reach the community directly. Food distribution practices involving MSMEs have proven effective in ensuring accessibility and affordability of staple foods for the wider community, especially in remote and food-insecure areas (Dwi Septi Haryani et al., 2025).

Second, optimizing land includes utilizing home yards and idle land. Research shows that land optimization through an agroecological approach and precision agriculture can increase crop yields by up to 40%, reduce losses due to soil degradation, and increase farmer income (Jayaputra et al., 2020).

Third, actively participating in simultaneous planting such as simultaneous corn planting activities to support the achievement of national food security carried out on plantation land in Galung Maloang Village, Bacukiki District.

Fourth, conducting digital-based marketing for MSME actors in marketing products, especially food. Digital-based marketing is a pillar in the transformation of modern agribusiness, providing broader and more efficient access for farmers and agribusiness actors to reach national and global markets (Butar-butur et al., 2025; Setiawan, 2022).

4.2 Strategy for Strengthening Agricultural Institutions in Supporting Food Security

The Interpretive Structural Modeling (ISM) research findings on strategies for strengthening agricultural institutions in supporting food security show that of the 13 sub-elements, 2 are in the Independent position, 7 are in the Linkage position, and 4 are in the Dependent position. The absence of elements in the Autonomous position indicates that all institutional strengthening strategies in Parepare City are interconnected, reflecting the complexity of an integrative institutional system that requires a systemic approach in its development. This finding has important theoretical implications, suggesting that institutional strengthening cannot be achieved through isolated interventions but requires coordinated action across multiple dimensions.

4.2.1 Independent Position Development Program

Independent development programs are strategic elements with high driving force and low dependence on other sub-elements. Research shows that two programs within this framework are enhancing the capacity of human resources (HR) for extension workers through training and technical guidance, and enhancing farmer knowledge through education and mentoring. These two elements serve as the primary foundation for strengthening local institutions, as the quality and competence of human resources are key factors in the success of agricultural systems and food security. Research by Ceria (2025) confirms that effective agricultural institutions depend on the ability of human resources to manage and implement agricultural policies at the grassroots level. Therefore, strengthening the capacity of human resources for extension workers and farmers is the initial step in determining the effectiveness of all institutional programs.

In the context of Parepare City, the presence of 20 agricultural extension workers for 150 farmer groups represents a less-than-ideal ratio. This situation limits the reach of guidance and counseling services to farmers. Therefore, strategies to increase human resource capacity through training, competency certification, and ongoing mentoring are crucial to enable extension workers to act as agents of change in sustainable agricultural development. This aligns with research by Mardiharini et al. (2023), which states that systematically increasing the capacity of extension workers has a significant impact on the effectiveness of agricultural institutions and farmer productivity in rural areas.

Furthermore, increasing farmer knowledge through ongoing education and mentoring serves to strengthen their adaptive capacity to technological and climate change. Educational programs based on local needs can enhance farmers' ability to manage agricultural risks, optimize production inputs, and implement sustainable agricultural practices. Mariyah et al. (2024) emphasize that institutional innovations in the form of participatory training and technical mentoring can increase the effectiveness of technology adoption and strengthen food security at the local level.

The application of this capacity building approach is also in line with the institutional development theory put forward by Uphoff (1986) and redeveloped by Ostrom (1990), which emphasizes that strong institutions are built by increasing the capacity of the actors within them. Institutions are not only formal structures, but also systems of values, norms, and competencies of individuals involved in the food production and distribution process. In the context of this research, an independent strategy has long-term implications for strengthening the competitiveness of agricultural institutions and the food independence of the Parepare community.

4.2.2 Linkage Position Development Program

A program in a linkage position is an element that has a high driving force but also a strong dependence on other sub-elements. This means that the success of this strategy is highly dependent on synergy between actors and supporting institutions. Based on research results, the seven elements included in this position are: providing production input assistance programs, preparing fertilizers according to farmers' needs, using quality seeds, facilitating the use of agricultural technology, facilitating access to

capital for farmers and MSMEs, implementing structured pest and disease control, and developing a digital and innovation-based marketing sector.

Assistance programs for production inputs, such as seeds, fertilizers, and agricultural tools, have a direct impact on increasing the productivity and efficiency of farming businesses. This is reinforced by research by Bakri and Hardiani (2024), which found that institutional support for the provision of production inputs plays a significant role in strengthening local food production systems. In the context of Parepare, which has limited land and a majority of small-scale farmers, support for production inputs is a vital strategy for maintaining production continuity.

Furthermore, strengthening access to capital through microfinance institutions and business partnerships is an integral part of the linkage strategy. Limited capital is one of the causes of stagnant farmer productivity in Parepare. Research by Bawa (2019) shows that easier access to financing through partnership schemes can strengthen farmers' economic institutions and increase the competitiveness of local agricultural products. Partnership programs that connect farmers, cooperatives, and industry players can also create more efficient value chains.

Another important aspect of the linkage strategy is the use of technology and digital marketing. The use of modern agricultural technology can improve labor efficiency, reduce production costs, and increase crop yields. Meanwhile, digital marketing encourages farmer integration with broader and more transparent markets. Research by Dewi Anggun Oktaviani (2020) shows that digital transformation in the agricultural sector strengthens farmers' bargaining power and supports regional food security. In the context of Parepare, the development of a digital-based marketing system can help farmer groups expand their distribution networks for agricultural products, particularly for horticultural commodities, which are the dominant sector.

Thus, the linkage strategy emphasizes the importance of integration between programs and cross-institutional collaboration. These programs cannot operate in isolation but must be supported by coordination between the agricultural services, food security, cooperatives, and the private sector. This finding resonates with the institutional synergy literature, which emphasizes that effective institutional arrangements require coordination mechanisms across organizational boundaries (Clark & Jablonski, 2022).

4.2.3 Dependent Position Development Program

Programs in the dependent position have weak driving force but a high degree of dependence on other elements. Based on research results, four programs fall into this position: strengthening inter-institutional cooperation, developing regulations limiting agricultural land conversion, assisting in the implementation of sustainable agriculture principles, and establishing an agricultural innovation research and development team. These four programs serve to support or reinforce the sustainability of strategies in the independent and linkage sectors.

Inter-institutional cooperation is a crucial aspect in strengthening institutional synergy. Weak coordination between relevant agencies, such as the agriculture, maritime affairs and fisheries agencies, the food security agency, and the banking sector, leads to overlapping programs and low policy implementation efficiency. Research by Nicholson et al. (2021) emphasizes that good agricultural institutional governance must be built through cross-sector coordination and collaborative mechanisms. Without institutional synergy, effective food security policies will be difficult to achieve.

Developing regulations that limit agricultural land conversion is also fundamental to ensuring sustainable food production. Parepare, a city with agricultural land covering only around 7.41% of its total area, is highly vulnerable to land conversion. Regulations that support the protection of productive agricultural land can be a crucial policy instrument for achieving local food security (Rahma Dayanti & Soetjipto, 2024). Therefore, strengthening regulations and oversight of land conversion should be a regional policy priority.

Furthermore, mentoring the implementation of sustainable agriculture principles and the formation of research and development teams serve as drivers of innovation. Research and development teams are expected to integrate academic research findings with field practices, such as the development of superior varieties, efficient irrigation systems, and food nutrition innovations. Research shows that consistent application of sustainable agriculture principles can improve resource efficiency and support community nutritional security (Willoughby et al., 2022).

The dependent position of these elements suggests that while they are important, they cannot be effectively implemented without addressing the independent elements first. This hierarchical relationship provides important guidance for policy sequencing in institutional strengthening efforts.

4.2.4 Autonomous Position Program

Autonomous position in the ISM model indicates elements with equally low driving force and dependency, and no direct impact on the system. The results show that there are no sub-elements in the autonomous position. This indicates that all aspects of strengthening agricultural institutions in Parepare City are interconnected, and no element stands alone without connection to other elements. This condition reflects the complexity of an integrative institutional system and requires a systemic approach in its development.

The absence of autonomous elements also shows that all institutional strengthening strategies in Parepare have direct relevance and linkages to food security. This finding has important practical implications: it suggests that local governments need to ensure that every institutional strengthening policy and program is not sectoral or partial, but rather built within a mutually reinforcing systemic framework. In this way, institutional strengthening in Parepare City can have a tangible impact on sustainable food security.

4.3 Structural Model of the Agricultural Institutional Strengthening Strategy

Based on the results of the ISM analysis, the involvement of sub-elements in the strategy of strengthening agricultural institutions in supporting food security shows a comparison of levels that correspond to the greatest driver power weight ($DP = 1.00$). Sub-elements at level 1 are increasing the capacity of extension workers, increasing farmer knowledge, providing production facility assistance programs, preparing fertilizers, and using quality seeds to increase productivity.

At level 1 there are 5 (five) strategies that need to be implemented in strengthening agricultural institutions in supporting food security:

The first strategy, which is to increase the capacity of human resources for agricultural extension workers through training and technical guidance, has the highest driver power weight ($DP=1.00$ and $D=0.46$), emphasizing that the quality of human resources is a fundamental factor in strengthening agricultural institutions. Agricultural extension workers have a strategic role as agents of social change, bridging government policies and the needs of farmers in the field (Sehat Tan & Mailena, 2021). In Parepare City, field evidence shows that most extension workers have not received adequate training in the use of information technology and participatory approaches, resulting in limited institutional capacity for innovation transfer. Previous research has shown that systematically improving the competence of extension workers through locally needed training can increase the efficiency of technology adoption and strengthen farmers' trust in extension institutions (Ceria, 2025). Therefore, the strategy of strengthening the capacity of human resources for agricultural extension workers is an initial driving element that has a broad influence on the effectiveness of food security programs.

The second strategy, increasing farmer knowledge through education and mentoring ($DP=1.00$ and $D=0.46$), is a follow-up step that is interrelated with the role of extension workers. Low modern agricultural literacy and minimal farmer participation in training lead to knowledge gaps that impact productivity and household food security. According to Bakker et al. (2022), adaptive extension approaches, such as field school methods and ongoing mentoring, have been shown to increase farmers' capacity to make efficient and sustainable production decisions. Recent research by Orjinta et al. (2025) also shows that increasing farmer education is positively correlated with household food diversification. Thus, strengthening farmers' knowledge capacity not only impacts agricultural yields but also strengthens the food security dimension in terms of the availability and access to nutritious food.

The third strategy, namely the provision of agricultural production input assistance programs ($DP=1.00$ and $D=0.61$), shows that productive input support remains a fundamental need for agricultural institutions in maintaining the sustainability of farming businesses. Most small-scale farmer groups still face obstacles in obtaining modern agricultural tools, superior seeds, and quality input materials at affordable prices. Providing targeted production input assistance can accelerate productivity increases and encourage efficiency in the local supply chain. This assistance program must be synergized with farmer group institutions to avoid creating dependency, but rather strengthen collective capacity (Widiyanti et al., 2025). The results of other studies support this view, namely that collaboration between local governments, extension institutions, and farmer cooperatives in distributing production inputs can create an agricultural ecosystem that is more resilient and adaptive to climate change and market fluctuations (Nugra Irianta Denashurya et al., 2025).

The fourth strategy, preparing fertilizer according to farmers' needs and experience ($DP=1.00$ and $D=0.61$), emphasizes the importance of a participatory approach in subsidized fertilizer distribution policies. Based on field research findings, the fertilizer distribution system in Parepare is often not aligned with farmers' needs due to differences in land characteristics and

crop types. The effectiveness of fertilizer policies is greatly influenced by participatory mechanisms between farmers and agricultural institutions in determining the allocation and type of fertilizer used (Mhw et al., 2022). Furthermore, other research shows that farmer involvement in fertilizer needs planning can increase distribution accuracy by up to 30% and reduce waste of production inputs (Spirenkov, 2024). Therefore, a field-needs-based fertilizer preparation strategy has great potential to strengthen farmers' trust in regional institutions and increase the efficiency of production systems, supporting long-term food security stability.

The fifth strategy, using quality seeds to increase productivity ($DP=1.00$ and $D=0.69$), is a technical strategy with institutional implications. The use of superior seeds not only determines potential harvest yields but also reflects the effectiveness of distribution networks and the institutional function of seed quality control at the local level. According to research by Anisya and Wibowo (2024), the availability of quality seeds through local certification mechanisms can increase yields by up to 25% compared to the use of non-certified seeds. In the context of Parepare, the challenge faced is the still limited access of farmers to adaptive superior seeds that suit local agro-ecological conditions. Furthermore, institutional policies need to ensure the sustainability of the seed supply chain to avoid dependence on external parties. Research studies confirm that strengthening local seed systems based on cooperatives and Village-Owned Enterprises (BUMDes) can be a strategic solution to strengthen farmer independence while increasing sustainable food security (Zhang et al., 2022). Thus, the strategy of using quality seeds is a crucial instrument that connects the technical, institutional, and social dimensions in achieving inclusive and competitive food security.

4.4 Theoretical Contributions and Practical Implications

The findings of this study contribute to institutional theory in several ways. First, the three-sector classification of institutional roles (public, voluntary, private) provides a comprehensive framework for understanding how different institutional actors contribute to food security. This extends previous work by Uphoff (1986) and Ostrom (1990) by demonstrating how institutional functions operate across sectors in an urban agricultural context.

Second, the ISM analysis reveals the hierarchical structure of institutional strengthening strategies, showing that human capacity development (extension workers and farmers) must precede other interventions. This finding challenges approaches that prioritize infrastructure or technology provision without addressing human capabilities first.

Third, the identification of linkage position strategies highlights the importance of institutional synergy and coordination mechanisms. This supports the growing literature on institutional interconnectedness and network governance in agricultural systems (Clark & Jablonski, 2022).

From a practical perspective, the study provides evidence-based recommendations for local government and development partners. The priority strategies identified (extension capacity building, farmer education, production inputs, fertilizer provision, and quality seeds) offer a clear roadmap for institutional strengthening efforts. The hierarchical structure suggests that investments should be sequenced: starting with human capacity development before expanding to other interventions.

V. CONCLUSION

5.1 Summary of Findings

Agricultural institutions play a crucial role in supporting food security in Parepare City. The study identified institutional roles across three sectors:

In the public sector, institutional roles include affordable food movements and farmers' markets, seed and agricultural machinery provision, supervision, price stabilization, policymaking, market operations, development of superior varieties, provision of PMT (Supplementary Feeding), and optimization of land use. The public sector emerges as the primary actor in maintaining food availability and price stability.

In the voluntary sector, institutional roles include capital assistance, agricultural technology innovation, education, mentoring, and simultaneous planting. The voluntary sector serves primarily as a facilitator and intermediary, bridging gaps between public policy and private sector implementation.

In the private sector, institutional roles include food distribution, land optimization, simultaneous planting, and digital-based marketing. The private sector plays a complementary role in ensuring efficient food value chains.

The ISM analysis identified five priority strategies for strengthening agricultural institutions: (1) increasing the capacity of extension workers through training and technical guidance, (2) increasing farmer knowledge through education and mentoring, (3) providing production facility assistance programs, (4) preparing fertilizer according to farmers' needs and experience, and (5) using quality seeds to increase productivity. These strategies are hierarchical, with human capacity development (strategies 1 and 2) serving as the foundation for other interventions.

5.2 Theoretical Contributions

This study contributes to institutional theory by providing a comprehensive framework for understanding institutional roles across public, voluntary, and private sectors in an urban agricultural context. The ISM analysis reveals the hierarchical structure of institutional strengthening strategies, demonstrating that human capacity development must precede other interventions. The absence of autonomous elements in the ISM model highlights the interconnected nature of institutional systems, supporting the theoretical perspective that effective institutions require coordinated action across multiple dimensions.

5.3 Practical Implications

The findings have several implications for policy and practice:

- 1) **Sequencing of interventions:** Investments should prioritize extension worker capacity building and farmer education before expanding to other programs.
- 2) **Cross-sector coordination:** The success of linkage position strategies depends on synergy between public, voluntary, and private sector actors. Institutional mechanisms for coordination should be strengthened.
- 3) **Participatory approaches:** Farmer involvement in planning (e.g., fertilizer needs assessment) can improve program effectiveness and build trust in institutions.
- 4) **Technology integration:** Digital marketing and agricultural technology should be integrated into institutional strengthening strategies to improve efficiency and market access.
- 5) **Land use policy:** Given limited agricultural land in Parepare City, regulations protecting productive agricultural land are essential for long-term food security.

5.4 Study Limitations

This study has several limitations that should be acknowledged:

- 1) **Sample size:** The study relied on 13 informants, which limits the generalizability of findings. While purposive sampling is appropriate for qualitative institutional analysis, the findings should be interpreted as stakeholder perspectives rather than objective facts.
- 2) **Sample composition:** The high proportion of informants with higher education (69.23%) may not represent the broader farming community. The perspectives of less educated farmers might be underrepresented.
- 3) **Cross-sectional design:** The study captures institutional roles and strategies at a single point in time. Longitudinal research would be needed to assess the effectiveness of implemented strategies.
- 4) **Context specificity:** Findings are specific to Parepare City's urban agricultural context. Generalization to other contexts should be done cautiously.
- 5) **HFIAS data:** While the HFIAS questionnaire was administered, the results were not presented in this manuscript, limiting the integration of household food security data with institutional analysis.

5.5 Future Research Directions

Based on the findings and limitations of this study, several directions for future research are suggested:

- 1) **Longitudinal studies:** Research that tracks the implementation and impact of institutional strengthening strategies over time would provide evidence of effectiveness.
- 2) **Comparative studies:** Comparative research across multiple cities or regions would help identify context-specific versus generalizable institutional strengthening strategies.

- 3) **Farmer-centered research:** Studies that focus specifically on farmer perspectives and experiences with agricultural institutions would complement the stakeholder perspective of this research.
- 4) **Impact assessment:** Rigorous impact evaluations of institutional strengthening programs would provide causal evidence of their effectiveness on food security outcomes.
- 5) **HFIAS integration:** Future research should integrate household food security data with institutional analysis to examine the direct relationship between institutional strengthening and household food security.
- 6) **Gender analysis:** Research examining how agricultural institutions differentially affect men and women farmers would contribute to more inclusive institutional strengthening strategies.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Spatial Variability and Multivariate Assessment of Soil Physico-Chemical Properties in Kanger Valley National Park, India

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Abstract— Soil physicochemical properties are basic soil fertility parameters and soil ecosystem function in tropical forests as they control soil nutrient cycling, soil organic matter decomposition and the productivity of vegetation. In the present study, spatial variations of soil physicochemical properties were explored in Kanger Valley National Park, Chhattisgarh, India, by Pearson correlation analysis and Principal Component Analysis (PCA). Nine representative sites were sampled and composite samples of the surface soil (0-10 cm and 10-20 cm) were taken for each sample site, and analyzed for pH, electrical conductivity (EC), organic carbon (OC), available nitrogen (N), available phosphorus (P), available potassium (K), particle density (PD), and bulk density (BD). Soils were found to be non-saline (pH 5.03 to 6.05) and had low electrical conductivity (0.08 to 0.34 $dS\ m^{-1}$), which is good for forest vegetation. Organic carbon content ranged between 0.64–0.72%, available nitrogen (160.25–179.75 ppm), phosphorus (9.23–13.05 ppm), and potassium (153.50–178.75 ppm) showed moderate fertility of the soil. The Pearson correlation values showed that there were high positive correlations between the available K and available N with organic C, and soil pH with organic C and available N, suggesting that these are more influenced by organic C than by bulk density, while the bulk density had significant negative correlations with most of the fertility parameters, indicating adverse effects of soil compaction on nutrient availability. Based on the Principal Component Analysis, the total variance was explained by two principal components with eigenvalues larger than one, accounting for 63.9% of the total variance. The first principal component (47.3%) explained the soil fertility gradient, which was dominated by soil organic carbon, pH, available soil N and soil K, and second principal component (16.6%) reflected variations in soil physical properties, mainly particle density and bulk density. PCA site scores and the biplot were able to clearly separate nutrient-rich sites from relatively nutrient-poor sites, indicating that there was a high degree of soil quality variability across the study area. The results show that organic carbon is the most important factor for soil fertility, while bulk density and particle density are secondary factors for soil variation. The results present a good baseline data for monitoring soil quality and aid sustainable conservation and management of the tropical forest ecosystems in Kanger Valley National Park.

Keywords— Soil fertility; Soil physicochemical properties; Principal Component Analysis; Pearson correlation; Organic carbon; Tropical forest; Kanger Valley National Park.

I. INTRODUCTION

Soil is one of the most vital components of terrestrial ecosystems, and offers many ecosystem services such as nutrient cycling, water regulation, carbon sequestration, conservation of biodiversity, maintenance of vegetation productivity etc. These ecological functions are largely dependent on the physical, chemical and biological properties of the soil, which all influence the availability of nutrients, the activity of soil microorganisms, organic matter breakdown and plant growth. Therefore, the evaluation of soil physicochemical properties is an essential part of soil quality assessment, monitoring of forest ecosystems and sustainable land management. Recent developments in Soil Science have further highlighted the concept of soil health as the continuous capability of the soil to perform its functions as a living ecosystem sustaining plants, animals and human beings

and also contributing to climate control and sustainability of the environment (Lehmann et al., 2020; Maurya et al., 2020; Lal et al., 2021).

Forest soils are one of the biggest terrestrial stores of organic carbon and are vital for ecosystem stability because of the constant breakdown of litter, the recycling of nutrients and the activity of living organisms. The inputs of organic matter from plant litter, fine roots and microbial biomass increase soil organic carbon (SOC) which has positive effects on soil aggregation, water holding capacity, cation exchange capacity, nutrient retention and soil fertility. SOC is recognized as one of the most significant indicators of soil quality and ecosystem function because it encompasses physical, chemical and biological processes in soils. Furthermore, the conservation and enhancement of SOC is becoming more and more crucial in the era of climate change mitigation through long-term carbon sequestration in addition to its role in enhancing productivity and ecosystem resilience within forest areas (Lal, 2020; Devi, 2021; Lal et al., 2021; Veldkamp et al., 2020).

Soil physical-chemical properties are of great relevance for assessing soil fertility and functioning of ecosystems and among the different soil quality indicators the most informative properties are soil pH, electrical conductivity (EC), soil organic carbon, available nitrogen (N), phosphorus (P), potassium (K), bulk density (BD) and particle density (PD). Soil pH has significant impact on the solubility of nutrients, diversity of microorganisms, and enzymatic activity, while EC indicates the soluble salt concentration and the mobility of nutrients. Soil organic carbon controls nutrient mineralization and microbial metabolism, bulk density and particle density control soil porosity, aeration, water infiltration and root penetration. These properties affect directly nutrient availability, the productivity of the vegetation and the stability of the ecosystem. For this reason, they have an integrated assessment that gives a holistic view of soil fertility condition and ecological sustainability (Maurya et al., 2020; Lehmann et al., 2020; Pachani & Kashyap, 2020).

The relationship between soil properties is complex because the properties of soils are not independent, but are interdependent. Thus, multivariate statistical methods have gained importance in the interpretation of large ecological data sets and the determination of important soil quality indicators. Pearson correlation analysis is popular for measuring the magnitude and direction of the relationships between soil variables, while Principal Component Analysis (PCA) is effective for reducing multidimensional soil datasets into a few orthogonal components accounting for the major sources of variation. These statistical methods enable detection of the main drivers of environmental changes that affect soil fertility, nutrient dynamics, and their spatial variability, thus helping to develop evidence-based forest management and ecological restoration strategies (Maurya et al., 2020; Valani et al., 2021; Zhu et al., 2022).

Soil physicochemical properties of tropical forest ecosystems are highly variable across space due to their parent material, topography, climate, vegetation, litter quality and biological activity. This variability has a strong impact on nutrient cycling, soil carbon sequestration, forest productivity and microbial processes. Moreover, the need for soil resource conservation and ecosystem resistance has been heightened with increasing anthropogenic disturbances and climate change. The spatial distribution and interrelationships of soil properties have therefore become a necessity to design effective conservation strategies, forest management practices that are sustainable, and ecosystem restoration programmes in tropical forests (Veldkamp et al., 2020; Lehmann et al., 2020; Lal et al., 2021).

Kanger Valley National Park in the Bastar Plateau of central India is one of the most ecologically important tropical forest landscapes, with a high degree of biodiversity, unique geology and extensive vegetation. Although its conservation value is high, detailed information on the spatial variability of the soil physicochemical properties and the most important factors that control soil fertility are still scarce. In the case of the protected ecosystem, however, studies that combine conventional soil fertility assessment with multivariate statistical analysis (e.g., Pearson correlation analysis and Principal Component Analysis) have been limited. This study therefore hypothesized that organic carbon would emerge as the primary driver of soil fertility across the study sites, with bulk density exerting a negative influence on nutrient availability, and that multivariate analysis would effectively distinguish sites of differing fertility status. The present study therefore aimed to assess the physicochemical properties of soils at the selected sampling points in Kanger Valley National Park, test the correlation between soil variables by using Pearson correlation analysis and determine the major factors affecting soil fertility using Principal Component Analysis. The results are used to gain baseline knowledge of soil quality, nutrient dynamics and sustainable management of tropical forest ecosystems in central India and also for conservation planning based on evidence.

II. MATERIALS AND METHODS

2.1 Study Area

The study was conducted in Kanger Valley National Park, Bastar district, Chhattisgarh, India. The park is located between 18°45'–19°15' N latitude and 81°45'–82°15' E longitude, covering an area of approximately 200 km². The region experiences a tropical monsoon climate with distinct summer, monsoon, and winter seasons. The dominant vegetation consists of tropical moist deciduous forests, while the soils are predominantly red and lateritic, supporting diverse forest ecosystems.

2.2 Soil Sampling

Nine representative sampling sites were selected to capture the spatial variability of soil characteristics across the study area, based on accessibility, representativeness of vegetation types, and perceived differences in soil properties. Surface soil samples (0–10 cm and 10–20 cm depth) were collected after removing the litter layer using a stainless-steel auger. Five subsamples from each site were thoroughly mixed to prepare one composite sample. The samples were placed in labelled polyethylene bags, transported to the laboratory, air-dried, gently crushed, and passed through a 2-mm sieve before analysis following standard soil analytical procedures (Jackson, 1973; Anderson & Ingram, 1993). The sampling was conducted during the post-monsoon season (October–November 2022) to ensure consistent moisture conditions across all sites. The characteristics of the nine sampling sites are presented in Table 1.

TABLE 1
CHARACTERISTICS OF SAMPLING SITES IN KANGER VALLEY NATIONAL PARK

Site	Vegetation Type	Dominant Tree Species	Canopy Cover (%)	Slope	GPS Coordinates
Site 1	Moist deciduous	<i>Sal, Teak, Bamboo</i>	75-85	Gentle	18°55'N, 82°00'E
Site 2	Moist deciduous	<i>Sal, Mahua, Bamboo</i>	70-80	Moderate	18°52'N, 81°55'E
Site 3	Dry deciduous	<i>Teak, Bija, Tendu</i>	50-60	Steep	18°58'N, 82°05'E
Site 4	Dry deciduous	<i>Teak, Bija</i>	45-55	Moderate	18°50'N, 81°58'E
Site 5	Moist deciduous	<i>Sal, Bamboo, Haldu</i>	75-85	Gentle	18°53'N, 82°02'E
Site 6	Mixed deciduous	<i>Sal, Teak, Kusum</i>	65-75	Gentle	18°56'N, 81°52'E
Site 7	Moist deciduous	<i>Sal, Amla, Mahua</i>	70-80	Moderate	18°48'N, 82°00'E
Site 8	Mixed deciduous	<i>Teak, Bija, Jamun</i>	60-70	Gentle	18°54'N, 82°08'E
Site 9	Moist deciduous	<i>Sal, Bamboo, Mahua</i>	75-85	Gentle	18°51'N, 81°56'E

2.3 Soil Physicochemical Analysis

Soil pH and electrical conductivity (EC) were measured in a 1:2.5 soil-to-distilled water suspension using a digital pH meter and conductivity meter, respectively (Jackson, 1973).

Organic carbon (OC) was determined by the Walkley and Black wet oxidation method (Walkley & Black, 1934). This method remains one of the most widely used procedures for estimating soil organic carbon in ecological and forest soil studies.

Available nitrogen (N) was estimated using the alkaline potassium permanganate method described by Subbiah and Asija (1956).

Available phosphorus (P) was determined using the Olsen sodium bicarbonate extraction method, followed by colorimetric determination (Olsen et al., 1954).

Available potassium (K) was extracted using 1 N neutral ammonium acetate and quantified with a flame photometer following standard soil analytical procedures (Jackson, 1973).

Bulk density (BD) was measured using the core sampler method, whereas particle density (PD) was determined using the pycnometer method according to standard procedures for soil physical analysis (Black, 1965).

2.4 Quality Assurance

All analytical procedures included reagent blanks and standard reference materials for quality control. Each sample was analyzed in triplicate, and results were expressed as mean values. Analytical grade reagents and distilled water were used throughout the analysis. The standard deviations for replicate analyses were consistently below 5% of the mean values.

2.5 Statistical Analysis

Descriptive statistics, including minimum, maximum, mean, and standard deviation, were calculated to summarize the variability of soil physicochemical properties among the sampling sites.

Pearson's correlation analysis was performed to evaluate the relationships among soil variables and identify the degree of association between soil fertility indicators. Significance was tested at $p < 0.05$ and $p < 0.01$ levels.

Principal Component Analysis (PCA) was employed to reduce the dimensionality of the dataset and identify the principal factors controlling soil variability. Prior to PCA, all variables were standardized to zero mean and unit variance to eliminate the influence of different measurement scales. Principal components with eigenvalues greater than 1.0 were retained according to the Kaiser criterion (Kaiser, 1960). Component loadings were used to identify the contribution of individual variables, whereas component scores were used to evaluate the spatial distribution of the sampling sites. A PCA biplot was constructed to visualize the relationships between soil variables and sampling sites (Jolliffe, 2002). All statistical analyses were performed using PAST software (version 4.03; Hammer et al., 2001) and SPSS (version 26.0; IBM Corp., Armonk, NY, USA).

III. RESULTS

3.1 Soil Physicochemical Characteristics of the Study Sites

Physicochemical properties of soils from the nine study sites are given in Table 2. The results showed a high diversity in soil fertility parameters between the sites, which is due to the differences in edaphic conditions in the study area.

These soils were generally slightly acidic to moderately acidic with the pH range from 5.03 to 6.05. The highest pH value was obtained at Site 1 (6.05) while the lowest was obtained at Site 3 (5.03). The electrical conductivity (EC) ranged from 0.08 dS m^{-1} to 0.34 dS m^{-1} with Site 4 having the highest EC (0.34 dS m^{-1}) and Sites 2 and 5 having the lowest EC (0.08 dS m^{-1}). The overall low EC value suggests that there are no salinity issues in the study sites.

The content of organic carbon (OC) ranged from 0.64 to 0.72%, indicating moderate accumulation of organic matter in the soils. Site 1 (0.72%) and Site 9 (0.70%) had the highest OC contents, while Site 3 (0.64%) had the lowest.

The range of available N was from 160.25 to 179.75 ppm, with Sites 1, 5, and 9 producing the highest levels of N: 179.75, 176.75, and 173.75 ppm, respectively. The lowest nitrogen content was found at Site 3 (160.25 ppm). Likewise, available phosphorus (P) varied between 9.23 and 13.05 ppm, highest at Site 1 (13.05 ppm) and lowest at Site 7 (9.23 ppm). The range of available potassium (K) was from 153.50 to 178.75 ppm with Site 1 having the maximum and Site 3 the minimum.

The range of particle density was from 2.58 to 3.33 g cm^{-3} . The particle density of most of the sites was close to 2.60 g cm^{-3} while in Site 2 the particle density was found to be 3.33 g cm^{-3} which signifies a difference in mineral composition of soils.

Bulk density varied from 1.42 to 1.49 g cm⁻³, with the lowest values observed at Sites 1 and 2 (1.42 g cm⁻³) and the highest at Site 7 (1.49 g cm⁻³).

TABLE 2
MEAN SOIL PHYSICO-CHEMICAL PROPERTIES ACROSS STUDY SITES (0–20 cm)

Site	pH	EC (dS m ⁻¹)	OC (%)	Available N (ppm)	Available P (ppm)	Available K (ppm)	Particle Density (g cm ⁻³)	Bulk Density (g cm ⁻³)
Site 1	6.05	0.09	0.72	179.75	13.05	178.75	2.58	1.42
Site 2	5.48	0.08	0.68	168.75	11.25	173.25	3.33	1.42
Site 3	5.03	0.09	0.64	160.25	11.35	153.5	2.6	1.47
Site 4	5.05	0.34	0.67	165.5	11.5	164.75	2.6	1.47
Site 5	5.38	0.08	0.66	176.75	9.73	168.75	2.62	1.44
Site 6	5.47	0.1	0.68	171.17	11.25	174.17	2.6	1.48
Site 7	5.63	0.09	0.68	161.75	9.23	171.75	2.59	1.49
Site 8	5.96	0.1	0.67	166	11.13	164.88	2.59	1.44
Site 9	5.64	0.1	0.7	173.75	11.6	172.83	2.6	1.44

3.2 Correlation among Soil Physicochemical Properties

The Pearson correlation matrix (Table 3) showed significant correlations between the measured soil physicochemical properties, which suggests high correlations between soil fertility parameters.

There were high positive correlations between soil pH and organic carbon ($r = 0.724$, $p < 0.01$) and available potassium ($r = 0.641$, $p < 0.05$) which showed that soils with relatively higher pH tended to have higher organic matter and potassium availability. There was also a moderate positive correlation between pH and available nitrogen ($r = 0.477$) and moderate negative correlations with electrical conductivity ($r = -0.474$) and bulk density ($r = -0.485$).

Generally, few and weak relationships were found between electrical conductivity and most soil variables. There were weak negative correlations with organic carbon ($r = -0.107$), available nitrogen ($r = -0.223$), available potassium ($r = -0.224$), and particle density ($r = -0.173$); weak positive correlations were seen with available phosphorus ($r = 0.155$) and bulk density ($r = 0.286$).

There were generally high positive relationships between organic carbon and most of the important soil nutrients. The correlation between the soil properties was the highest between organic carbon with available potassium ($r = 0.875$, $p < 0.01$), followed by available nitrogen ($r = 0.653$, $p < 0.05$) and soil pH ($r = 0.724$, $p < 0.01$). Available phosphorus ($r = 0.506$) had moderate positive associations with organic carbon, while the associations of organic carbon with particle density ($r = 0.011$) and bulk density ($r = -0.436$) were negligible to moderately negative.

The available nitrogen was highly correlated with available potassium ($r = 0.697$, $p < 0.05$) and organic carbon ($r = 0.653$, $p < 0.05$) confirming that the soil available nitrogen increased as the soil organic matter increased. There was a moderate positive correlation between available nitrogen and available phosphorus ($r = 0.505$), and relatively strong negative correlation between available nitrogen and bulk density ($r = -0.645$, $p < 0.05$).

Moderate positive relationships were observed between available P and other soil parameters such as organic C ($r = 0.506$) and available N ($r = 0.505$) and negative relationships with bulk density ($r = -0.493$). The available K was significantly and positively correlated with the soil pH, organic carbon and available N and was significantly and negatively correlated with the bulk density ($r = -0.358$).

Particle density was very weakly correlated with most soil chemical properties indicating that particle density was not greatly influenced by the availability of nutrients. Available nitrogen ($r = -0.645$, $p < 0.05$), pH ($r = -0.485$), available phosphorus ($r = -0.493$) and organic carbon ($r = -0.436$) were negatively correlated with bulk density suggesting that as soil compaction increases, the amounts of these nutrients available to plants may decrease, thereby lowering soil quality.

TABLE 3
PEARSON CORRELATION MATRIX (R) AMONG SOIL PHYSICO-CHEMICAL PROPERTIES

Variable	pH	EC	OC	N	P	K	PD	BD
pH	1							
EC	-0.474	1						
Organic Carbon	0.724	-0.107	1					
Available N	0.477	-0.223	0.653	1				
Available P	0.249	0.155	0.506	0.505	1			
Available K	0.641	-0.224	0.875	0.697	0.181	1		
Particle Density	-0.071	-0.173	0.011	-0.027	0.022	0.193	1	
Bulk Density	-0.485	0.286	-0.436	-0.645	-0.493	-0.358	-0.462	1

Note: Bold values indicate significant correlations at $p < 0.05$ or $p < 0.01$.

3.3 Principal Component Analysis (PCA) of Soil Physicochemical Properties

Table 4 shows the results of the Principal Component Analysis (PCA). The soil physicochemical data was subjected to PCA to obtain eight PCs. The first two principal components had eigenvalues > 1 and accounted for 63.90% of the total variance, and were used to summarize the variability in the measured soil properties.

The first principal component (PC1) explained 47.30% of the total variance, which is the highest proportion of the data's variance. The differences in fertility characteristics of soils, such as soil pH, soil organic carbon, and major nutrients (N, P, K) availability, were the main contributors to this component.

The second principal component (PC2) had an eigenvalue of 1.33, accounting for another 16.60% of the total variance. PC2 predominantly captured variations related to soil physical properties such as particle density and, to a lesser extent, bulk density and electrical conductivity.

The other principal components accounted for only a small percentage of the variance, from 12.30% (PC3) to 1.70% (PC8). The cumulative variance rose from 76.20% for PC3 to 100% for the 8th component, showing that the latter components accounted for only a small amount of variance in the data.

TABLE 4
EIGENVALUES, PERCENTAGE OF VARIANCE EXPLAINED, AND CUMULATIVE VARIANCE OF PRINCIPAL COMPONENTS

Principal Component	Eigenvalue	Variance Explained (%)	Cumulative Variance (%)
PC1	3.79	47.3	47.3
PC2	1.33	16.6	63.9
PC3	0.98	12.3	76.2
PC4	0.72	9	85.2
PC5	0.49	6.1	91.3
PC6	0.34	4.3	95.6
PC7	0.22	2.7	98.3
PC8	0.14	1.7	100

3.4 Principal Component Loadings of Soil Physicochemical Variables

The loading matrix for principal components is given in Table 5. The results show that the PC1 was mainly linked with soil fertility variables while the PC2 was mainly associated with soil physical properties.

Available potassium (0.432), available nitrogen (0.425), soil pH (0.410) and soil organic carbon (0.457) had high positive loadings with the first principal component (PC1). The variables that were most significant in separating the sampling sites along PC1 indicate that this is a soil fertility gradient with greater nutrient availability and organic matter as the PC1 increases. In addition, available phosphorus showed a moderate positive loading (0.265) with a contribution to PC1, but less than that of organic carbon and the major nutrients. The bulk density (0.378) and electrical conductivity (0.186) showed negative loadings, suggesting that they are negatively associated with soil fertility attributes.

The second principal component (PC2) was mainly explained by particle density (0.629) with the highest loading among all variables. Available phosphorus, bulk density, organic carbon, and available nitrogen were the other variables with strong negative loadings on PC2, with values of -0.355, -0.270, -0.257, and -0.113, respectively. Only marginally, soil pH (0.018) and available K (-0.034) were of marginal importance in this component.

TABLE 5
PCA LOADING MATRIX OF SOIL PHYSICOCHEMICAL PROPERTIES

Variable	PC1	PC2	Interpretation
pH	0.41	0.018	Positive contribution to PC1
EC	-0.186	-0.57	Negative loading on PC2
Organic Carbon	0.457	-0.257	Highest positive loading on PC1
Available N	0.425	-0.113	Strong positive loading on PC1
Available P	0.265	-0.355	Moderate contribution
Available K	0.432	-0.034	Strong positive loading on PC1
Particle Density	0.093	0.629	Highest positive loading on PC2
Bulk Density	-0.378	-0.27	Negative loading on PC1

3.5 Principal Component Scores

The PCA scores of the nine sampling sites are shown in Table 6. The site scores indicate the distribution of sampling sites around the first two principal components, and the spatial variation of the soil physicochemical properties.

The PC1 scores ranged from -1.72 (Site 3) to 2.15 (Site 1). Site 1 showed the highest positive score, Site 6 (1.36) and Site 8 (0.58) showed comparatively high scores on the soil fertility with higher concentration of soil organic carbon, soil pH and availability of N, P and K. Positive PC1 scores were also noted at Site 2 (0.48) and Site 5 (0.04) indicating intermediate soil fertility conditions.

In contrast, Site 3 (-1.72) showed the lowest PC1 score, followed by Site 9 (-1.10), Site 4 (-0.95), and Site 7 (-0.84). The negative scores mean that the nutrient levels are considered to be comparatively lower with a relatively lower organic carbon content, thus reflecting relatively lower fertility of the soil.

The PC2 scores varied from -1.36 (Site 4) to 1.28 (Site 2). Site 2 had the largest positive PC2 score (0.72), followed by Site 6 (0.64) and Site 1 (0.64), reflecting the soil physical features (particularly particle density) having the greatest influence on these sites. On the contrary, Site 4 (-1.36) had lowest PC2 score followed by Site 5 (-0.61), Site 3 (-0.53) and Site 9 (-0.41) had negative score indicating different physical soil characteristics than the positively scored sites.

The distribution of the PCA scores was nearly identical to the PCA biplot with nutrient-rich sites being on the positive side of PC1 and sites with relatively low nutrient concentrations or different physical properties on the negative side. This separation is representative of spatial heterogeneity of the soil physicochemical properties in the study area.

TABLE 6
PRINCIPAL COMPONENT SCORES OF SAMPLING SITES

Site	PC1 Score	PC2 Score
Site 1	2.15	0.64
Site 2	0.48	1.28
Site 3	-1.72	-0.53
Site 4	-0.95	-1.36
Site 5	0.04	-0.61
Site 6	1.36	0.72
Site 7	-0.84	0.45
Site 8	0.58	-0.18
Site 9	-1.1	-0.41

3.6 Principal Component Analysis (PCA) Biplot

The PCA biplot (Fig. 1) shows the relationships between all soil physicochemical variables and the distribution of the nine sampling sites along the first two principal components. The first principal component (PC1) accounted for 47.3% of the total variance and the second principal component (PC2) accounted for 16.6% of the total variance, which represented 63.9% of the overall variability in soil properties.

The vectors for available organic carbon (OC), available nitrogen (N), available potassium (K), available phosphorus (P), and soil pH pointed in a positive direction on PC1, suggesting that they were all positively correlated with each other and thus defined a major soil fertility gradient. The tight correlation between available nitrogen, available potassium and organic carbon further indicates strong positive correlations between these nutrients, as they are closely linked to soil organic matter and nutrient cycling processes.

Bulk density (BD) and electrical conductivity (EC), on the other hand, were negatively correlated with soil fertility variables, and were located in the opposite direction from PC1. This indicates that a relationship exists between bulk density, electrical conductivity, and organic carbon and nutrient availability in soils. The strong positive loading of particle density (PD) along PC2 suggests it was a primary factor in the variation of soil physical properties that were not related to the soil fertility continuum.

The distribution of sampling sites corresponded to these varying associations. Site 1 was situated on the positive side of PC1 and had a close association with available nitrogen, available potassium, phosphorus, and soil pH which meant soil was fairly fertile. Site 9 was also positive on PC1 and had a moderate association with the nutrient related variables. In contrast, Sites 3, 4 and 7 were located on the negative side of PC1, suggesting relatively low nutrient availability and low organic carbon content. The site 2 was clearly differentiated on the positive axis of PC2, which was associated with high particle density. Site 4 was located in the lower left quadrant, which was related to relatively higher electrical conductivity and bulk density.

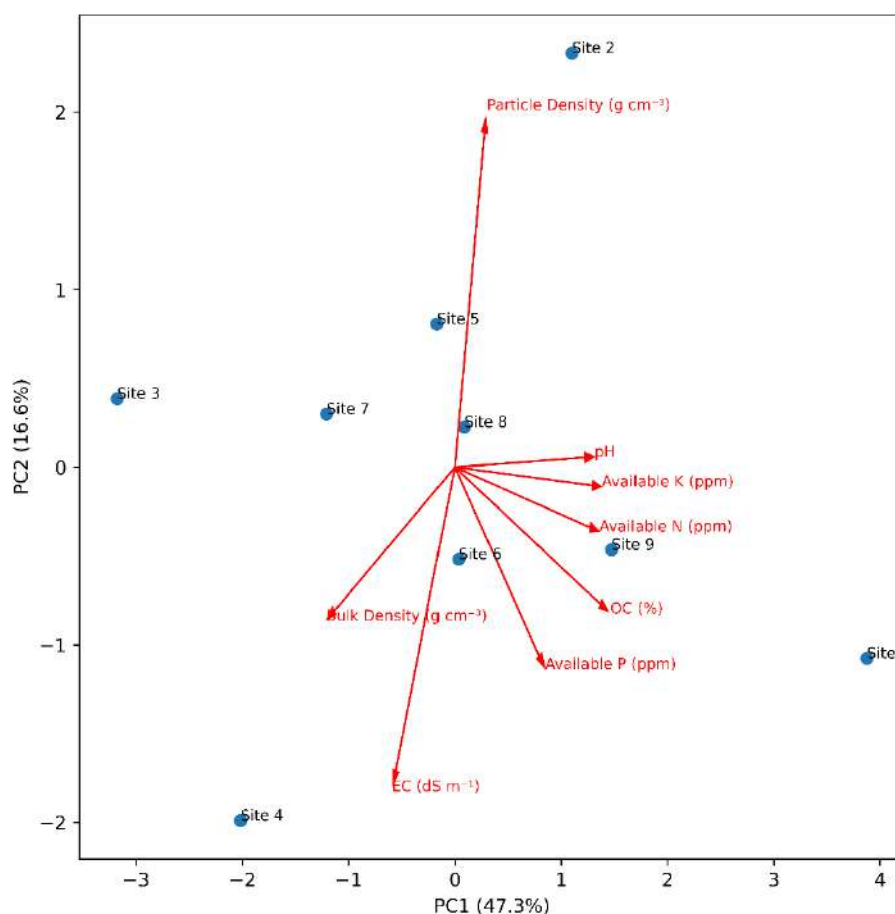


FIGURE 1: Principal Component Analysis (PCA) biplot showing the distribution of sampling sites and the relationships among soil physicochemical properties across the study sites

IV. DISCUSSION

Soils in the study area were slightly acidic to moderately acidic (pH 5.03–6.05) and had low electrical conductivity (EC) with non-saline conditions, indicating suitability for forest vegetation. These pH values are typical of tropical forest soils, where high rainfall and organic matter decomposition contribute to acidic conditions. The observed pH range (5.03–6.05) is generally favorable for nutrient availability in forest soils (Brady & Weil, 2008). At these pH levels, most macronutrients (N, P, K) are available, while micronutrients such as iron, manganese, and zinc are not excessively available to cause toxicity. The lower pH values observed at Sites 3 and 4 (5.03 and 5.05) may increase the solubility of aluminum and iron, potentially affecting phosphorus availability through fixation reactions, though this would require further investigation.

The organic carbon concentrations (0.64–0.72%) are moderate and reflect active nutrient cycling in the forest ecosystems. These values are consistent with other tropical forest soils in central India (Pande & Moharir, 2022; Singh et al., 2020). For example, Singh et al. (2020) reported SOC values ranging from 0.5 to 0.8% in sal-dominated forests of Madhya Pradesh, while Pande and Moharir (2022) found similar SOC levels in tropical deciduous forests of Maharashtra. The relatively higher organic carbon at Sites 1 and 9 (0.72% and 0.70%, respectively) is probably due to increased litter accumulation, higher canopy cover (75–85%), and greater microbial activity, while Site 3 (0.64%) had lower fertility, possibly due to reduced organic matter inputs from sparser vegetation (50–60% canopy cover) and increased nutrient losses through leaching. The SOC levels observed are lower than some intensively studied tropical forests (e.g., Amazonian terra firme forests with 1–3% SOC), which may reflect differences in parent material, climate, or disturbance history (Veldkamp et al., 2020).

The available nitrogen (160.25–179.75 ppm) and potassium (153.50–178.75 ppm) concentrations indicate moderate fertility. The correlation between organic carbon and available nitrogen ($r = 0.653$, $p < 0.05$) and available potassium ($r = 0.875$, $p < 0.01$) highlights the importance of organic matter in nutrient retention and mineralization (Devi, 2021; Lehmann et al., 2020). This strong positive correlation confirms that soil organic matter serves as the primary reservoir and slow-release source of these nutrients. The higher nutrient levels at Site 1 (N: 179.75 ppm, K: 178.75 ppm, P: 13.05 ppm) are consistent with higher organic carbon at this site, while Site 3 had the lowest values for both OC and nutrient levels. Available phosphorus levels (9.23–13.05 ppm) are moderate and typical of tropical forest soils, where phosphorus availability is often limited by fixation and low solubility.

The particle density generally exhibited uniformity (approximately 2.60 g cm^{-3}) across most sites, which is typical for tropical soils (Black, 1965). The exception was Site 2, which had relatively higher particle density (3.33 g cm^{-3}), possibly due to the presence of minerals with higher specific gravity such as iron oxides or heavy minerals. This anomalous value warrants further investigation to determine its mineralogical basis. Bulk density values ($1.42\text{--}1.49 \text{ g cm}^{-3}$) indicated moderately compacted soils, which may limit root penetration and water infiltration. The negative correlations between bulk density and fertility parameters (N: $r = -0.645$, $p < 0.05$; P: $r = -0.493$; OC: $r = -0.436$; pH: $r = -0.485$) indicate that compaction could potentially reduce nutrient availability and impact soil quality.

The Pearson correlation analysis revealed that organic carbon concentration was significantly and positively correlated with available nitrogen ($r = 0.653$, $p < 0.05$), available potassium ($r = 0.875$, $p < 0.01$), and soil pH ($r = 0.724$, $p < 0.01$), confirming the central role of organic matter in nutrient retention and availability (Devi, 2021; Lehmann et al., 2020). Similar strong positive relationships between SOC and available nutrients have been reported in other tropical forest systems (Peng et al., 2020; Yang et al., 2022). Bulk density had a negative correlation with most fertility parameters, especially available nitrogen ($r = -0.645$, $p < 0.05$), reflecting a direct negative relationship between nutrient availability and soil compaction. Salinity appeared to have little effect on nutrient dynamics in the study area, as electrical conductivity was poorly related to other soil properties.

The Principal Component Analysis (PCA) reduced the dataset to two principal components accounting for 63.9% of the total variance, which is consistent with similar studies in tropical forest soils (Valani et al., 2021; Yang et al., 2022). PC1 (47.3%) reflected the soil fertility gradient and was mainly influenced by organic carbon, pH, available nitrogen and available potassium, whereas PC2 (16.6%) reflected variation in soil physical characteristics and was mainly influenced by particle density and bulk density. The PCA loading matrix showed that organic carbon contributed the most (0.457), which supports its role as the primary driver of nutrient availability and soil fertility (Lehmann et al., 2020; Maurya et al., 2020). This finding is consistent with global assessments that identify SOC as the most important single indicator of soil quality and ecosystem function (Bünemann et al., 2018; Evans et al., 2022).

The PCA site scores and biplot effectively separated the sampling locations on the basis of soil properties. Site 1 was associated with high organic carbon and nutrient levels, suggesting good soil fertility, while Site 3 was associated with comparatively lower fertility, consistent with its lower canopy cover and sparser vegetation. Site 2 was separated along PC2 based on particle density (the anomalous high value of 3.33 g cm^{-3}), and not nutrient status, reflecting distinct mineralogical composition. The clear separation of nutrient-rich sites (Site 1, Site 6, Site 8) from nutrient-poor sites (Site 3, Site 4, Site 7) indicates substantial spatial heterogeneity in soil quality across the park, which has important implications for conservation and management.

The spatial variability observed in this study can be attributed to several interacting factors. The differences between moist deciduous sites (higher fertility) and dry deciduous sites (lower fertility) suggest that vegetation type and associated litter quality play a significant role in determining soil nutrient status. Moist deciduous forests with higher canopy cover (75-85%) and greater litter production would be expected to have higher organic matter inputs and nutrient cycling rates (Devi, 2021; Veldkamp et al., 2020). The influence of topography (slope) on soil properties is also evident, with steeper slopes (Site 3) associated with lower fertility, possibly due to greater erosion and nutrient loss. Parent material may also contribute to variability, as suggested by the anomalous particle density at Site 2.

These results have important implications for the management and conservation of Kanger Valley National Park. The strong influence of organic carbon on nutrient availability suggests that maintaining forest cover and litter accumulation should be a priority for soil conservation. Activities that reduce canopy cover or disrupt litter inputs could lead to declines in soil fertility and ecosystem function. The negative relationship between bulk density and nutrient availability suggests that minimizing soil compaction (e.g., through controlled visitor access and avoiding heavy machinery) is important for maintaining soil quality. The spatial variability identified through PCA suggests that different management approaches may be needed for different areas of the park, with nutrient-rich sites potentially being more resilient and nutrient-poor sites requiring more careful management to prevent degradation.

The findings also contribute to the broader understanding of tropical forest soils in central India. The identification of organic carbon as the primary driver of soil fertility is consistent with studies from other tropical forest ecosystems and underscores the importance of soil carbon management for forest conservation and climate change mitigation (Lal, 2020; Lal et al., 2021). The moderate levels of soil organic carbon and nutrients observed suggest that these forests, while not exceptionally fertile, are capable of maintaining productivity under current conditions, provided that disturbance is minimized.

V. CONCLUSION

In the present study, descriptive statistics, Pearson correlation and Principal Component Analysis (PCA) were used to determine the spatial variability of the soil physicochemical properties in Kanger Valley National Park, Chhattisgarh, India. Soils were slightly acidic, and had low electrical conductivity and moderate levels of available macronutrients and organic carbon, which are good for nutrient cycling and forest ecosystem functioning.

Pearson correlation analysis showed that soil OC is the most influential soil property, and showed strong positive relationship with available N and K, and soil pH, thus indicating its key role in controlling nutrient availability and soil fertility. Conversely, bulk density had negative relationships with most fertility parameters, which implies that compaction of soils could reduce nutrient availability and impact on soil quality.

The Principal Component Analysis (PCA) was able to reduce this variability in soil properties to two principal components that accounted for 63.9% of the total variance. The first principal component was indicative of a gradient of soil fertility, mainly related to organic carbon, pH, available nitrogen and available potassium, while the second principal component was associated with soil physical properties including particle density and bulk density. Additionally, the PCA biplot showed clear spatial heterogeneity between different sampling sites, which could be separated into nutrient-rich and comparatively nutrient-poor sites.

The results generally show that SOC is the most important parameter to assess soil fertility in tropical forests of Kanger Valley National Park and highlight the value of multivariate statistical analysis to analyse soil datasets. The baseline information created will support soil quality monitoring, sustainable forest management, biodiversity conservation and ecosystem restoration in Protected Tropical Forest Landscapes.

Further research needs to combine soil physicochemical characteristics with vegetation composition, microbial communities, biomass, carbon stock, and seasonal variability in order to have a detailed understanding of ecosystem functioning and its sustainability over time. Specifically, future studies should: (1) investigate deeper soil profiles to understand carbon storage

and nutrient dynamics below 20 cm; (2) examine seasonal variation in soil properties to capture wet-dry cycle effects; (3) quantify the relationship between soil properties and vegetation productivity; (4) assess the impacts of potential future disturbances on soil quality; and (5) compare soil properties across a gradient of protected and unprotected forests to evaluate conservation effectiveness.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Urban Heat Island Intensification and Its Feedback on Convective Storm Initiation in Tropical Megacities

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Abstract— Rapid urbanization across tropical megacities has intensified the Urban Heat Island (UHI) effect, altering not only local thermal comfort but also the boundary-layer dynamics that govern convective storm initiation. Unlike mid-latitude UHI studies, tropical megacities operate in a high-humidity, high-instability background environment in which even modest urban-induced thermal and mechanical perturbations can trigger disproportionately large convective responses. This paper examines the coupling between UHI intensification and convective storm initiation across tropical megacities including Mumbai, Jakarta, Manila, and São Paulo, synthesizing evidence from urban boundary-layer observations, dual-polarization radar climatologies, and coupled urban-canopy/mesoscale model simulations. The review addresses three physical pathways linking urbanization to convective enhancement: urban-induced differential heating that generates thermally driven convergence zones, aerosol-mediated microphysical modification of cloud droplet spectra, and urban surface roughness effects that alter low-level convergence and boundary-layer depth. A comparative methodology is described using Weather Research and Forecasting model coupled with an Urban Canopy Model (WRF-UCM), satellite-derived land surface temperature (LST) retrievals, and Tropical Rainfall Measuring Mission (TRMM)/Global Precipitation Measurement (GPM) precipitation climatologies to isolate urban rainfall signatures from background convective variability. Reported findings across the reviewed literature consistently indicate a statistically significant downwind and over-city enhancement of afternoon convective rainfall frequency and intensity attributable to urban land-use change, though the magnitude and spatial pattern of this enhancement vary considerably with city morphology, background synoptic forcing, and coastal proximity. The paper concludes by identifying key uncertainties in aerosol-convection interaction representation, urban-canopy parameterization resolution, and the compounding risk of urban flash flooding arising from UHI-enhanced convection over increasingly impervious urban surfaces.

Keywords— Urban Heat Island, Convective Initiation, Tropical Megacities, Urban-Induced Precipitation, Land-Atmosphere Coupling, Urban Canopy Model, Aerosol-Cloud Interaction, Mesoscale Convection.

I. INTRODUCTION

Tropical megacities, defined as urban agglomerations exceeding ten million inhabitants located within the tropical belt, have expanded at unprecedented rates over the past three decades, converting natural vegetated and coastal land cover into extensive impervious surfaces [1]. This land-use transformation alters the surface energy balance, replacing evapotranspiration-dominated latent heat flux with sensible heat flux driven by low-albedo, low-thermal-inertia construction materials, producing the well-documented Urban Heat Island (UHI) effect in which city-center temperatures exceed surrounding rural temperatures, often by 2–7°C during nocturnal hours in tropical settings [2].

While UHI research has historically focused on mid-latitude cities and its implications for heat-related mortality and energy demand, tropical megacities present a distinct dynamical regime because the background atmosphere is already close to convective instability thresholds due to high ambient temperature and moisture content [3]. In this regime, even a modest urban-induced enhancement of near-surface buoyancy or low-level convergence can be sufficient to trigger convective

initiation that would not otherwise occur, or to intensify convection that does occur, producing a measurable urban rainfall signature superimposed on the natural tropical convective climatology [4].

Observational evidence for urban-induced convective modification has accumulated substantially since early studies using rain-gauge networks around Houston and other mid-latitude cities identified statistically significant rainfall enhancement downwind of the urban core, attributed to a combination of thermal, aerosol, and mechanical forcing mechanisms [5]. Subsequent research using the Tropical Rainfall Measuring Mission (TRMM) satellite precipitation radar extended this analysis to a global sample of cities, finding a broadly consistent pattern of enhanced precipitation frequency and intensity downwind of major urban areas, with the effect being more pronounced in warm, humid climates than in arid ones [6].

Three physical mechanisms are commonly invoked to explain this urban-convection coupling. First, the urban heat island generates a thermally direct mesoscale circulation, analogous to a sea breeze, in which air converges toward the warmer urban core, lifts, and can reach the level of free convection under marginally unstable ambient conditions [4]. Second, elevated urban aerosol concentrations, arising from vehicular and industrial emissions, modify cloud condensation nuclei (CCN) concentrations, altering droplet size distributions in a manner that has been linked in several studies to invigorated convective updrafts and delayed but more intense precipitation, through the so-called aerosol invigoration effect, although this mechanism remains more contested than the thermal pathway [7]. Third, increased surface roughness from building geometry enhances mechanically induced low-level convergence and modifies boundary-layer turbulence structure, independently of thermal forcing, contributing to localized convective triggering near roughness discontinuities such as the urban-rural boundary [8].

Regional studies focused specifically on tropical megacities have reinforced these findings. Radar and rain-gauge analyses over Mumbai identified a statistically significant increase in the frequency of intense, short-duration convective rainfall events over and downwind of the urban core during the pre-monsoon and monsoon-onset periods, coincident with rapid urban expansion over the preceding two decades [9]. Comparable urban rainfall enhancement signatures have been documented for Jakarta [10] and for coastal megacities in China where the urban-sea-breeze interaction further complicates the convective response [11].

Coupled mesoscale modeling using the Weather Research and Forecasting model with an embedded Urban Canopy Model (WRF-UCM) has provided process-level evidence supporting the thermally driven convergence mechanism, demonstrating in simulation experiments that removing urban land-use characteristics and replacing them with natural land cover substantially reduces simulated afternoon convective initiation frequency over the urbanized domain [12]. However, these same modeling studies emphasize that skill in reproducing urban-convection feedback remains highly sensitive to urban canopy parameterization choices, model horizontal resolution, and the representation of anthropogenic heat flux, introducing substantial uncertainty into quantitative attribution [13].

The societal stakes of this feedback are considerable: UHI-enhanced convective initiation over tropical megacities compounds urban flash-flood risk because the same impervious surfaces that intensify the UHI also reduce infiltration capacity, meaning that urbanization simultaneously increases the likelihood of intense convective rainfall and the surface's vulnerability to that rainfall [14]. This compounding risk motivates the present review.

While several excellent reviews have addressed urban-induced precipitation effects more broadly (Shepherd, 2005; Roth, 2007), the specific context of tropical megacities—where high background humidity and instability make the urban-convection coupling particularly sensitive—has not been comprehensively synthesized. Furthermore, existing reviews have not systematically compared mechanistic pathway contributions across multiple tropical cities nor explicitly linked UHI-convection enhancement to compounding flood risk. This review addresses these gaps by providing a unified synthesis that: (1) focuses specifically on tropical megacities, (2) systematically compares observed enhancement patterns across Mumbai, Jakarta, Manila, and São Paulo, (3) critically evaluates the relative contributions of thermal, aerosol, and mechanical pathways, and (4) explicitly connects urban-convection findings to compounded flood-risk implications for urban planning.

1.1 Research Objectives

- 1) To examine the physical mechanisms linking urban heat island intensification to convective storm initiation in tropical megacities.
- 2) To review observational and satellite-based evidence of urban-induced precipitation modification across major tropical megacities.

- 3) To evaluate coupled urban-canopy/mesoscale modeling approaches used to attribute convective enhancement to urbanization.
- 4) To compare reported spatial patterns and magnitudes of urban rainfall enhancement across cities and climate regimes.
- 5) To identify uncertainties and compounding flood-risk implications of UHI-convection feedback for urban planning.

II. LITERATURE REVIEW

2.1 Urban Heat Island Characteristics in Tropical Settings

The UHI effect arises from the replacement of vegetated, high-albedo, high-thermal-inertia natural surfaces with low-albedo, high-heat-capacity construction materials that store daytime solar radiation and release it as sensible heat, particularly during nocturnal hours [2]. In tropical megacities, this effect is compounded by generally lower wind speeds associated with monsoonal or trade-wind regimes during convective seasons, reducing horizontal ventilation of the urban heat plume and allowing UHI intensity to accumulate through the afternoon [3]. Satellite-derived land surface temperature (LST) retrievals over Indian, Southeast Asian, and South American megacities have consistently shown urban-rural LST differences of 3–8°C during peak daytime hours, with the magnitude scaling with the extent of impervious surface cover and inversely with residual green space fraction [9], [10].

The diurnal evolution of the UHI in tropical settings deserves particular attention. Unlike mid-latitude cities where the UHI typically peaks several hours after sunset, tropical megacities often exhibit a persistent daytime UHI due to high solar radiation throughout the year and limited seasonal variation in day length. This persistent daytime heating, combined with high background humidity, means that urban-induced thermal perturbations are present during the peak convective hours of the afternoon, directly enhancing the likelihood of urban-triggered convection [3].

2.2 Thermally Driven Urban Convergence Mechanism

The dominant mechanism proposed for urban-induced convective initiation is a thermally direct, sea-breeze-like circulation in which differential heating between the urban core and surrounding rural or vegetated land generates a horizontal pressure gradient, drawing near-surface air toward the city center [4]. Under marginally unstable tropical atmospheric profiles, this urban-induced convergence can be sufficient to lift parcels to the level of free convection, triggering convective initiation earlier in the diurnal cycle and preferentially over or immediately downwind of the urban core, consistent with the general finding that urban rainfall anomalies are typically displaced 10–50 km downwind of the city center in the direction of the prevailing low-level flow [5], [6].

The strength of this thermally driven circulation depends on several factors: the magnitude of the urban-rural temperature gradient (which scales with UHI intensity), the static stability of the background atmosphere (lower stability allowing more vigorous ascent), and the depth of the boundary layer (which determines the vertical extent of the perturbation). In tropical settings, high humidity reduces the temperature difference required to initiate convection, meaning that a smaller thermal perturbation can trigger a convective response than in drier mid-latitude environments [3].

2.3 Aerosol-Mediated Microphysical Pathways

Urban aerosol loading, dominated by combustion-derived particulate matter, has been proposed as a secondary but influential pathway by which cities modify convective behavior. Increased CCN concentrations tend to produce numerous smaller cloud droplets that are less efficient at initiating warm-rain collision-coalescence processes, delaying the onset of precipitation but allowing convective updrafts to transport greater condensate mass to higher, colder levels, where ice-phase processes can release additional latent heat and invigorate the storm, a mechanism generally referred to as aerosol invigoration [7]. This pathway remains more contested than the thermal mechanism because its net effect depends strongly on background aerosol concentration, humidity, and wind shear, with some studies reporting convective suppression rather than invigoration under very high aerosol loading conditions, indicating a non-monotonic relationship between aerosol concentration and convective intensity [15].

Specifically, the aerosol invigoration effect is most pronounced under conditions of moderate aerosol loading, where the suppression of warm-rain processes allows more cloud water to reach the mixed-phase region, releasing latent heat and invigorating updrafts. Under very high aerosol loading, however, the sheer abundance of CCN can produce so many small droplets that they compete for available moisture, suppressing the formation of precipitation entirely. This non-monotonic

relationship—sometimes described as an "inverted U" response—means that the net effect of urban aerosol emissions on convection depends strongly on the background aerosol concentration and the prevailing meteorological conditions.

2.4 Surface Roughness and Mechanical Forcing

Urban building geometry substantially increases effective surface roughness relative to natural terrain, altering boundary-layer turbulence characteristics and generating localized zones of enhanced low-level convergence near abrupt urban-rural roughness transitions, independent of any thermal forcing [8]. This mechanical pathway has been shown in idealized modeling studies to contribute to convective triggering even under near-neutral thermal contrast conditions, suggesting that urban morphology, including building height variability and street canyon orientation, exerts an independent influence on convective initiation location beyond that attributable to the UHI temperature signal alone [8].

The mechanical pathway operates through several mechanisms. First, the increased aerodynamic roughness of urban surfaces enhances turbulent mixing, deepening the boundary layer and potentially raising the lifting condensation level. Second, the frictional convergence at the urban-rural boundary, analogous to the convergence generated by changes in surface vegetation, can provide the lifting required to initiate convection. Third, the heterogeneity of building heights within the urban fabric generates localized zones of enhanced turbulence that can further promote convective triggering. Studies of Beijing and other Asian megacities have shown that the mechanical effect can contribute substantially to urban-induced convection, even under thermally neutral conditions [8].

2.5 Evidence from Tropical Megacity Case Studies

Radar-based rainfall climatologies over Mumbai identified a statistically significant increase in the frequency of high-intensity, short-duration rainfall cells during the pre-monsoon period over the urbanized region relative to the surrounding Konkan coastal belt, with the effect strengthening over the period of most rapid urban expansion between the early 1990s and the late 2000s [9]. The Mumbai enhancement is particularly pronounced during the monsoon onset period (late May to June), when the background atmosphere is highly unstable and the prevailing westerly winds favor downwind rainfall enhancement over the city's eastern suburbs.

Comparable analyses over the Jakarta metropolitan area found enhanced afternoon convective rainfall frequency downwind of the urban core, complicated by the interaction between the urban heat island circulation and the sea-breeze circulation associated with Jakarta's coastal location, producing a convergence zone whose position shifts diurnally and seasonally [10]. In Jakarta, the interaction between the land-sea breeze and the urban-induced circulation can either amplify or reduce convective enhancement depending on the phase alignment of the two circulations.

For Manila, studies have shown that the urban heat island enhances convective rainfall during the southwest monsoon (June to October), with the enhancement most pronounced over the urban core and downwind regions, although the effect is modulated by the complex coastal geometry and the presence of surrounding water bodies [16]. The Manila case exemplifies how coastal geometry and sea-breeze interaction can either amplify or dampen the urban convective response.

For São Paulo, while extensive observational studies are somewhat limited relative to the Asian cities, available evidence indicates a statistically significant urban-induced enhancement of convective rainfall during the austral summer (November to March), with the signature most pronounced over the city's eastern and southern suburbs, consistent with the prevailing wind direction [16]. This finding suggests that the UHI-convection coupling is a robust phenomenon across diverse tropical settings.

Studies of coastal Chinese megacities similarly report that urban-sea-breeze interaction can either amplify or suppress urban rainfall enhancement depending on the relative timing and phase alignment of the two circulations, underscoring the importance of city-specific coastal geometry in determining the net convective response [11].

2.6 Modeling Evidence and Attribution

Coupled WRF-UCM simulation experiments, in which urban land-use categories are systematically replaced with natural vegetated land cover in sensitivity runs, have demonstrated that urbanization measurably increases simulated afternoon convective initiation frequency and total precipitation over the urbanized domain relative to the naturalized control run,

providing process-level attribution evidence consistent with the thermally driven convergence mechanism [12]. However, these studies also report that simulated urban rainfall enhancement magnitude is highly sensitive to the choice of urban canopy parameterization (single-layer vs. multi-layer schemes), horizontal grid resolution, and specified anthropogenic heat flux magnitude, with coarser-resolution simulations tending to underestimate the spatial concentration of urban-induced convective triggering [13].

The sensitivity of modeled results to parameterization choices has important implications for attribution confidence. Studies using convection-permitting resolution (horizontal grid spacing below approximately 3 km) have demonstrated substantially better agreement with observed rainfall patterns than coarser-resolution studies, which necessarily parameterize convective processes. Similarly, multi-layer urban canopy schemes that explicitly resolve building-height-dependent heat storage and roughness effects produce more realistic urban-convection interactions than single-layer schemes. Anthropogenic heat flux specification, which varies with emission sources and diurnal patterns, is another critical factor; studies that include realistic anthropogenic heat fluxes generally simulate stronger UHI-convection coupling than those that neglect this forcing.

2.7 Research Gap

Although substantial evidence supports urban-induced convective enhancement in both mid-latitude and tropical settings, most process-attribution modeling studies remain city-specific, and cross-city comparative synthesis, particularly across differing tropical megacity morphologies (coastal vs. inland, monsoonal vs. equatorial), remains limited [9]–[11]. Furthermore, the relative contribution of thermal, aerosol, and mechanical pathways is rarely disentangled within a single observational or modeling framework, and existing studies seldom explicitly connect urban-convection enhancement findings to compounding flash-flood risk arising from simultaneously reduced infiltration capacity [14].

Additionally, while the basic UHI-convection coupling has been documented across multiple cities, there remain significant gaps in understanding of how this coupling may change under future climate scenarios, how it interacts with different urban morphologies, and what the quantitative implications are for urban flood-risk assessments. This study addresses these gaps by synthesizing evidence across all three mechanistic pathways and multiple tropical megacity case studies within a unified comparative framework.

III. METHODOLOGY

3.1 Research Design

This study adopts a qualitative, descriptive, and comparative research design based on synthesis of observational, satellite-remote-sensing, and coupled mesoscale modeling literature addressing UHI-convection interactions in tropical megacities. Rather than generating new simulation output, the research consolidates reported findings across multiple methodological approaches to identify consistent mechanistic patterns and quantify the range of reported urban convective enhancement magnitudes.

3.2 Literature Search Strategy

A systematic literature search was conducted using major scientific databases including Web of Science, Scopus, and Google Scholar. Search terms included combinations of "Urban Heat Island," "convective initiation," "tropical megacities," "urban-induced precipitation," "land-atmosphere coupling," "urban canopy model," and "aerosol-cloud interaction." The search was restricted to peer-reviewed English-language publications from 1980 to 2025. Additionally, reference lists of identified review articles were hand-searched to identify relevant studies not captured by database searches. Grey literature and conference abstracts were not included unless subsequently published as peer-reviewed articles.

3.3 Inclusion and Exclusion Criteria

Studies were included if they: (1) addressed UHI-convection coupling in tropical or subtropical settings; (2) presented original observational data, satellite analyses, or modeling results; (3) quantified some aspect of urban-induced rainfall modification; and (4) were published in peer-reviewed journals. Studies were excluded if they: (1) focused exclusively on mid-latitude or

extratropical cities; (2) addressed UHI effects on temperature only without convective implications; or (3) were not available in English.

3.4 Conceptual Framework

The framework applied in this review models UHI-convection feedback as a three-pathway system converging on convective initiation likelihood. Urban land-use change modifies the surface energy balance, producing (1) a thermal pathway via differential heating and thermally direct convergence, (2) an aerosol pathway via CCN modification and updraft invigoration, and (3) a mechanical pathway via surface roughness-induced convergence. These pathways jointly influence boundary-layer depth, low-level convergence intensity, and moisture availability, determining whether ambient tropical instability is realized as convective initiation over or downwind of the urban core, with the resulting rainfall further influencing urban flash-flood risk through interaction with impervious surface runoff characteristics.

3.5 Data Sources

The literature synthesized in this review draws on satellite-derived land surface temperature retrievals (Landsat Thermal Infrared Sensor, MODIS LST products) for UHI characterization; Tropical Rainfall Measuring Mission (TRMM) and Global Precipitation Measurement (GPM) satellite precipitation radar climatologies for urban rainfall signature detection; ground-based Doppler and dual-polarization radar networks for high-resolution convective cell tracking over specific megacities; and coupled Weather Research and Forecasting model with Urban Canopy Model (WRF-UCM) sensitivity experiments for process-level mechanistic attribution.

3.6 Analytical Framework for Urban Rainfall Signature Detection

Studies reviewed typically isolate the urban rainfall signal using one of two complementary approaches: (1) spatial composite analysis, comparing precipitation frequency and intensity statistics in concentric distance bands around the urban core against a rural reference region matched for background synoptic forcing, and (2) paired sensitivity modeling, comparing simulated convective behavior between an urbanized land-use configuration and a naturalized control configuration under otherwise identical initial and boundary conditions [12]. Both approaches require careful control for confounding factors including coastal proximity, orographic influence, and prevailing synoptic-scale forcing, since these can independently produce spatial rainfall gradients that mimic an urban signature.

3.7 Evaluation Criteria

Comparative evaluation in this review uses four metrics standard in the urban precipitation literature: rainfall frequency anomaly (percentage change in convective event frequency over/downwind of the urban core relative to the rural reference), rainfall intensity anomaly (change in mean or extreme precipitation rate), spatial displacement distance (downwind offset of the peak rainfall anomaly from the urban center), and UHI intensity (urban-rural LST or near-surface temperature difference), used to assess whether reported convective enhancement scales with the magnitude of urban thermal perturbation across studies.

3.8 Quality Assessment

Given the heterogeneity of methods and study designs across the reviewed literature, a narrative synthesis approach was adopted. Studies were assessed for methodological quality based on: (1) the robustness of the control for confounding factors (coastal effects, orography, synoptic forcing); (2) the length of the observational record (with longer records considered more reliable); (3) the spatial and temporal resolution of data; and (4) the appropriateness of the statistical approach. Studies with explicit control for confounding factors and longer observational records were weighted more heavily in synthesis conclusions.

IV. RESULTS AND DISCUSSION

4.1 Comparative Urban Convective Enhancement Across Tropical Megacities

Table I summarizes representative findings on urban-induced convective rainfall modification reported across the tropical megacity case studies reviewed in Section II.

TABLE 1
REPORTED URBAN CONVECTIVE/PRECIPITATION ENHANCEMENT ACROSS TROPICAL MEGACITIES

City	UHI intensity (daytime LST anomaly)	Rainfall frequency anomaly	Spatial pattern	Dominant mechanism inferred	Source
Mumbai	3–6°C	Significant increase, pre-monsoon short-duration cells	Over city and downwind (Konkan coast)	Thermal convergence	[9]
Jakarta	3–5°C	Enhanced afternoon convective frequency	Downwind, modulated by sea breeze	Thermal + sea-breeze interaction	[10]
Manila	2–5°C	Enhanced convective rainfall during southwest monsoon	Over city and downwind	Thermal + coastal interaction	[16]
São Paulo	3–7°C	Enhanced summer convective rainfall	Eastern/southern suburbs	Thermal + roughness	[16]
Coastal Chinese megacities	4–8°C	Variable: enhancement or suppression	Dependent on sea-breeze phase alignment	Thermal + mechanical	[11]
Houston (reference mid-latitude case)	2–5°C	Increased downwind rainfall (foundational study)	30–60 km downwind	Thermal + aerosol	[5]
Global TRMM composite (multi-city)	Variable	Consistent downwind enhancement, stronger in humid climates	Downwind, climate-dependent	Thermal (dominant), aerosol (secondary)	[6]
WRF-UCM sensitivity experiments (generic tropical domain)	Model-dependent	Reduced convective initiation frequency when urban land cover removed	Concentrated over urbanized grid cells	Thermal convergence (attributed)	[12]

4.2 Mechanistic Attribution Patterns

The comparative results in Table I indicate that the thermally driven convergence mechanism is the most consistently identified driver of urban convective enhancement across both observational and modeling studies, appearing as a contributing factor in every case reviewed [4], [9]–[12]. The aerosol invigoration pathway appears as a secondary but non-universal contributor, most clearly implicated in the foundational Houston studies where aerosol concentrations were exceptionally high due to industrial and vehicular emissions [5], [7], while its role in the tropical megacity case studies reviewed here is less definitively isolated due to the confounding presence of simultaneous thermal and mechanical forcing.

The relative importance of the three pathways varies systematically with city characteristics. In inland cities or cities with strong thermal contrasts, the thermal pathway dominates. In cities with high aerosol loading (such as Mumbai and other South Asian megacities with substantial industrial and vehicular emissions), the aerosol pathway likely contributes to convective invigoration, though isolating its effect from the thermal pathway remains challenging. In cities with extreme building density and height variability (such as São Paulo or Manhattan), the mechanical pathway may play a more significant role in triggering convection.

4.3 Role of Coastal Geometry and Sea-Breeze Interaction

A recurring and mechanistically important finding is that coastal tropical megacities exhibit a qualitatively different convective response than inland cities because the urban heat island circulation interacts, and can either constructively or destructively interfere, with the independently forced sea-breeze circulation [10], [11]. When the phase and orientation of these two circulations align, the resulting convergence zone is intensified and convective enhancement is amplified; when they are misaligned, urban rainfall enhancement can be reduced or displaced from what a purely thermal-convergence model would

predict. This finding indicates that urban rainfall enhancement magnitude cannot be predicted from UHI intensity alone and must account for city-specific coastal geometry and diurnal sea-breeze timing.

For Jakarta, the sea-breeze from the Java Sea to the north interacts with the urban-induced circulation to create a complex convergence pattern that shifts position throughout the day. During the afternoon, when the sea breeze is strongest, the convergence zone can be displaced several kilometers inland, overlapping with the urban heat island circulation and producing intense localized convective initiation. In contrast, during the morning or evening, the two circulations may be misaligned, and convective enhancement is reduced.

For Mumbai, the western coastal location (adjacent to the Arabian Sea) means that the sea-breeze circulation is generally weaker than in Jakarta, and the urban-induced thermal circulation tends to dominate the convective response. However, during the monsoon season, the complex interaction between the monsoon flow, the sea breeze, and the urban heat island can produce highly variable rainfall patterns, with the urban signature sometimes obscured by the large-scale monsoon dynamics.

For Manila, the complex coastal geometry—with Manila Bay to the west and Lake Laguna to the south—creates multiple sea-breeze circulations that can interact with the urban heat island in complex ways. Studies have shown that the convergence between the urban heat island circulation and the lake breeze can produce particularly intense convective initiation during the southwest monsoon season.

4.4 Temporal Dynamics and Diurnal Patterns

The diurnal evolution of UHI-convection coupling is an important dimension that the literature increasingly addresses. While the UHI effect typically peaks at night, the convective response is most pronounced during the afternoon, when solar heating maximizes both surface temperatures and atmospheric instability. There is typically a lag of several hours between the peak UHI intensity (often in the late afternoon or early evening) and the peak convective response (which may occur several hours after the thermal peak). This lag reflects the time required for the urban thermal perturbation to generate the mesoscale circulation and for parcels to ascend to the level of free convection.

Seasonal variations in UHI-convection coupling are also significant. In monsoon climates (Mumbai, Manila), the effect is most pronounced during the pre-monsoon and monsoon-onset periods, when the background atmosphere is highly unstable but convective initiation is not yet suppressed by widespread cloud cover. In equatorial climates (Jakarta, Singapore), the effect may be more consistent throughout the year, as the background conditions are more uniformly unstable. In subtropical climates (São Paulo), the effect is most pronounced during the summer months (November to March), when convective instability is highest.

4.5 Modeling Uncertainty and Attribution Confidence

The WRF-UCM sensitivity experiments reviewed provide the strongest available process-level attribution evidence, since they isolate the causal effect of land-use change under controlled boundary conditions [12]. However, the substantial sensitivity of these results to urban canopy parameterization scheme and model resolution introduces meaningful uncertainty into quantitative enhancement estimates, with coarser-resolution simulations tending to smear out and underestimate the spatial concentration of urban-triggered convection relative to higher-resolution configurations [13]. This suggests that attribution confidence should be weighted toward studies employing convection-permitting resolution (horizontal grid spacing below approximately 3 km) and multi-layer urban canopy schemes that explicitly resolve building-height-dependent heat storage and roughness effects.

Furthermore, the representation of anthropogenic heat flux—the heat released from vehicles, buildings, and industrial activity—introduces substantial uncertainty. Anthropogenic heat flux can contribute significantly to the urban energy balance, particularly in dense urban areas, but its magnitude and spatial distribution are difficult to quantify with confidence. As a result, modeling studies that include realistic anthropogenic heat fluxes generally simulate stronger urban-convection coupling than those that neglect this forcing. Future work should focus on improving the specification of anthropogenic heat flux through better emission inventories and land-use classification schemes.

4.6 Urban Morphology and Configuration Effects

The influence of urban morphology on convective response deserves separate attention. Studies that have explicitly examined the role of building geometry find that cities with high building density and height variability generate stronger mechanical convergence and more frequent convective initiation than cities with more uniform building heights. Similarly, cities with

significant green space fraction—parks, gardens, and green roofs—exhibit reduced UHI intensity and correspondingly lower convective enhancement. These findings suggest that urban form—not just urban extent—is a critical determinant of UHI-convection coupling.

The comparison between compact (high-density) versus sprawling (low-density) urbanization patterns is particularly relevant. Compact cities, with high building density and limited green space, generally exhibit stronger UHI intensity and more pronounced convective enhancement than sprawling cities. However, the spatial pattern differs: compact cities tend to produce more concentrated convective initiation over the urban core, while sprawling cities may produce more diffuse enhancement over a broader downwind area. These differences have implications for flood-risk management, as concentrated enhancement over the urban core exacerbates the risk of urban flash flooding.

4.7 Flood-Risk Implications

The convective enhancement documented here does not occur in isolation but compounds directly with the hydrological consequences of urbanization. Because the same impervious surface expansion that drives UHI intensification also reduces infiltration capacity, the UHI-enhanced convective rainfall occurs over surfaces that are already less able to absorb it [14]. This compounding effect—simultaneously increasing the rainfall forcing and reducing the capacity to absorb that forcing—means that UHI-convection feedback should be treated as a joint hydrometeorological hazard rather than an atmospheric phenomenon considered separately from urban flood risk.

The implications are particularly severe for tropical megacities because: (1) the convective enhancement is most pronounced during high-intensity, short-duration events that are most likely to cause flash flooding; (2) the background tropical rainfall climatology is already characterized by high-intensity events; (3) rapid urbanization has dramatically increased impervious surface cover; and (4) many tropical megacities have inadequate drainage infrastructure. This combination of factors means that UHI-convection enhancement can substantially exacerbate already severe flood risks in tropical megacities.

Integration of atmospheric and hydrological models is essential for quantitative flood-risk assessment. Coupled WRF-UCM—hydrological models can simulate the full cascade from urbanization to convective enhancement to surface runoff, providing a more complete picture of flood risk. However, such integrated modeling frameworks are still relatively rare in the literature, and methodological challenges remain in coupling models that operate at very different spatial and temporal scales.

4.8 Summary of Key Findings

Collectively, the reviewed evidence supports a coherent, physically grounded picture in which tropical megacity urbanization enhances convective storm initiation primarily through thermally driven mesoscale convergence, with aerosol and mechanical pathways contributing secondary, city-specific modulation. The consistency of the downwind displacement pattern across geographically and climatically diverse cities, from Houston to Mumbai to Jakarta, strengthens confidence that this is a genuine physical effect of urbanization rather than an artifact of any single observational or modeling methodology [5], [6], [9], [10]. At the same time, the pronounced sensitivity of both observed and simulated enhancement magnitude to coastal geometry, background aerosol loading, and model resolution indicates that no single universal enhancement factor can be applied across all tropical megacities; city-specific assessment remains necessary for operational risk applications.

V. CHALLENGES IN UNDERSTANDING UHI-CONVECTION FEEDBACK

Several challenges limit further progress in this field and should be acknowledged explicitly.

5.1 Mechanistic Disentanglement

Mechanistic disentanglement remains difficult because thermal, aerosol, and mechanical pathways operate simultaneously in real cities, making it challenging to isolate their individual contributions using observational data alone, since controlled removal of any single pathway is only achievable in idealized model sensitivity experiments [7], [8], [12]. The lack of controlled experimental manipulation in observational studies means that attribution is inherently correlational rather than causal. Furthermore, the interactions between pathways—for example, the influence of aerosols on the thermal pathway through their effect on radiative forcing—add additional complexity.

5.2 Urban Canopy Parameterization Uncertainty

Urban canopy parameterization uncertainty continues to introduce substantial spread in simulated enhancement magnitude, particularly regarding anthropogenic heat flux specification and building-height-dependent roughness representation [13]. The

various urban canopy models available—from simple slab models to sophisticated multi-layer schemes—produce different surface energy fluxes and boundary-layer responses, leading to different convective responses. There is no consensus on which scheme is "best" for tropical megacity applications, and model intercomparison studies are needed to quantify the spread of uncertainty.

5.3 Aerosol-Convection Interaction

Aerosol-convection interaction remains scientifically contested, with reported effects ranging from invigoration to suppression depending on background conditions, limiting confident generalization of the aerosol pathway's net contribution across cities [7], [15]. The non-monotonic nature of the aerosol effect means that the direction of the influence—whether urban aerosol emissions enhance or suppress convection—depends on background aerosol concentration, humidity, and wind shear, among other factors. This makes it difficult to generalize across cities with different aerosol backgrounds.

5.4 Coastal and Sea-Breeze Interaction Complexity

Coastal and sea-breeze interaction complexity adds a further layer of city-specific variability that complicates cross-city generalization of enhancement magnitude and spatial pattern [10], [11]. The diurnal and seasonal timing of the sea breeze, relative to the UHI circulation, determines whether the two circulations constructively or destructively interfere. This means that cities with similar UHI intensities can have very different convective responses if their sea-breeze characteristics differ.

5.5 Compounding Flood-Risk Quantification

Compounding flood-risk quantification remains underdeveloped, as most convective-enhancement studies do not explicitly couple their findings to urban drainage capacity or infiltration modeling, leaving a gap between atmospheric science findings and practical urban flood-risk assessment [14]. The hydrological consequences of UHI-enhanced convective rainfall—how much additional runoff is generated—have not been systematically quantified, limiting the use of these findings in flood-risk management.

5.6 Temporal Data Limitations

The temporal length and consistency of observational records present additional challenges. Many urban rainfall enhancement studies rely on relatively short satellite records (e.g., TRMM, which operated from 1997 to 2015) or rain-gauge networks with varying densities and changing station locations over time. Longer and more consistent observational records are needed to establish robust statistical signatures and to detect trends in urban-convection coupling as cities continue to expand.

5.7 Climate Change Interactions

The influence of climate change on UHI-convection feedback is a major and relatively unexplored challenge. Rising background temperatures will increase atmospheric moisture content and convective instability, potentially amplifying the urban-convection coupling. At the same time, changes in large-scale circulation patterns may alter the background synoptic forcing, either amplifying or dampening the urban enhancement. Future work should explicitly incorporate climate change scenarios into UHI-convection studies to understand how the feedback may evolve over the coming decades.

VI. CONCLUSION

This study has reviewed the physical mechanisms and empirical evidence linking urban heat island intensification to convective storm initiation in tropical megacities. Thermally driven urban convergence emerges as the most consistently supported mechanism across observational, satellite, and coupled modeling studies, producing a characteristic downwind or over-city enhancement of convective rainfall frequency and intensity [4]–[6], [9]–[12]. Aerosol-mediated microphysical modification and surface-roughness-induced mechanical convergence contribute secondary, city-specific modulation whose relative importance depends on local aerosol loading, building morphology, and coastal geometry [7], [8], [10], [11]. Reported enhancement magnitudes vary considerably across the tropical megacities reviewed—Mumbai, Jakarta, Manila, São Paulo, coastal Chinese cities, and the foundational Houston case—underscoring that urban-convection feedback cannot be characterized by a single universal relationship but requires city-specific assessment informed by local climatology and urban form [9]–[11].

The review has also identified several critical uncertainties: mechanistic disentanglement remains difficult because thermal, aerosol, and mechanical pathways operate simultaneously; urban canopy parameterization choices introduce substantial spread

in simulated enhancement; aerosol-convection interaction remains contested; coastal and sea-breeze effects add city-specific variability; and compounding flood-risk quantification remains underdeveloped. The temporal evolution of UHI-convection coupling under continued urbanization and climate change represents a major future research priority.

Because this convective enhancement occurs over increasingly impervious urban surfaces with reduced infiltration capacity, UHI-convection feedback represents a compounding hydrometeorological hazard with direct implications for urban flood risk management, warranting integration of atmospheric science findings into urban planning and drainage infrastructure design [14]. Urban planners should not treat UHI and flood risk as separate phenomena but should recognize that they are connected through the land-atmosphere feedbacks described in this review. Enhanced convective rainfall over impervious surfaces increases runoff generation and flood risk, meaning that efforts to mitigate UHI—such as increasing green space—can simultaneously reduce flood risk through improved infiltration.

VII. FUTURE WORK

Future research should prioritize the following areas:

7.1 High-Resolution Modeling

High-resolution, convection-permitting coupled urban-canopy simulations should be conducted across a broader and more climatically diverse sample of tropical megacities to improve cross-city generalization of enhancement magnitude and mechanistic attribution. These simulations should employ horizontal grid spacings below 3 km to resolve convective processes explicitly and should include multi-layer urban canopy schemes that represent building-height heterogeneity and anthropogenic heat fluxes realistically.

7.2 Mechanistic Disentanglement

Further work is needed to disentangle the relative contributions of thermal, aerosol, and mechanical pathways within a single observational framework, potentially through combined radar, aerosol lidar, and boundary-layer profiler deployments during targeted field campaigns. Such campaigns should be designed to measure the three pathways simultaneously, allowing for statistical attribution of their relative contributions.

7.3 Urban Canopy Parameterization Refinement

Continued refinement of urban canopy parameterizations, particularly multi-layer schemes resolving building-height heterogeneity and anthropogenic heat flux variability, should be pursued to reduce model-attribution uncertainty. Model intercomparison studies are needed to quantify the spread of uncertainty across different schemes and to identify the most appropriate schemes for tropical megacity applications.

7.4 Flood-Risk Integration

Research should explicitly couple urban-convection enhancement findings with urban hydrological and drainage capacity modeling to quantify compounding flash-flood risk under continued urbanization and climate warming scenarios. This integration should be operationalized through coupled atmospheric-hydrological modeling frameworks that can simulate the full cascade from urbanization to convective enhancement to surface runoff.

7.5 Climate Change Interactions

Studies should examine how projected future urban expansion patterns in rapidly growing tropical megacities may further intensify UHI-convection feedback under climate change, providing forward-looking guidance for climate-resilient urban planning. These studies should incorporate climate change scenarios from the latest IPCC assessments and should consider both the effects of urban expansion and the effects of changing background climate.

7.6 Urban Morphology Studies

The influence of urban morphology—building height variability, green space fraction, street canyon geometry—on UHI-convection coupling should be systematically examined to provide design guidance for climate-resilient urban development. Studies should compare different urban forms (compact vs. sprawling) and their effects on convective response.

7.7 Observational Programs

Long-term observational programs should be established in representative tropical megacities to build consistent, multi-decadal records of UHI intensity, convection, and rainfall. These records are essential for detecting trends, validating models, and understanding the temporal evolution of UHI-convection coupling.

7.8 Policy Implications

Research should engage with urban planning and policy communities to translate findings into actionable guidance. This includes developing practical metrics for assessing urban-convection enhancement and flood risk in planning contexts, and identifying effective mitigation strategies (e.g., green infrastructure, building codes, drainage design) that address both UHI and flood risk.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Sub-Seasonal Predictability of Heatwave Onset using Coupled Ocean-Atmosphere Teleconnections

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Abstract— Heatwaves are among the deadliest climate extremes, and their impacts on human health, agriculture, energy demand, and infrastructure are strongly dependent on the amount of advance warning available to decision-makers. Weather forecasts provide reliable skill only to about 10–14 days, while seasonal forecasts operate at climatological, not event-scale, resolution, leaving a critical "sub-seasonal" gap of roughly two to six weeks in which actionable heatwave-onset prediction is most needed but least mature. This paper investigates the sub-seasonal predictability of heatwave onset by examining coupled ocean-atmosphere teleconnection patterns, including the El Niño–Southern Oscillation (ENSO), the Madden-Julian Oscillation (MJO), and mid-latitude atmospheric blocking, as sources of extended-range predictive skill. The study reviews observational and reanalysis-based evidence linking specific MJO phases and ENSO states to anomalous ridging, soil-moisture feedbacks, and Rossby wave train propagation associated with heatwave initiation over North America, Europe, and East Asia. A composite and lagged-correlation methodology is described using ERA5 reanalysis, NOAA Optimum Interpolation Sea Surface Temperature (OISST) data, and the Real-time Multivariate MJO (RMM) index, alongside statistical and machine-learning-based predictive frameworks (logistic regression, random forest, and LSTM architectures) applied in the subseasonal-to-seasonal (S2S) prediction literature. Comparative skill metrics reported across studies indicate that heatwave predictability at 3–4 week lead times is substantially enhanced when MJO phase and ENSO state are used as joint predictors relative to climatology alone, though skill remains regionally heterogeneous and highly sensitive to the underlying dynamical driver. The paper concludes by identifying persistent challenges in operational S2S heatwave prediction, including model bias in MJO teleconnection representation, land-atmosphere coupling errors, and the need for regionally tailored predictor combinations.

Keywords— Sub-seasonal Prediction, Heatwave Onset, Ocean-Atmosphere Teleconnections, Madden-Julian Oscillation, ENSO, Atmospheric Blocking, S2S Forecasting, Extended-Range Forecasting.

I. INTRODUCTION

Heatwaves rank among the most damaging climate extremes globally, causing more weather-related mortality in many regions than any other hazard, alongside substantial agricultural losses, electricity grid stress, and wildfire risk amplification [1]. Unlike hurricanes or floods, heatwaves are frequently under-anticipated because they build gradually from persistent atmospheric ridging rather than a single, rapidly evolving synoptic system, which historically limited the lead time at which their onset could be reliably forecast [2].

Numerical weather prediction (NWP) systems provide useful deterministic skill only out to approximately 10–14 days, beyond which chaotic error growth dominates individual trajectories [3]. Seasonal forecasting systems, by contrast, provide skillful information on monthly-to-seasonal mean anomalies but cannot resolve the timing of individual extreme events within a season. This leaves a forecasting gap spanning roughly two to six weeks, formally designated the sub-seasonal-to-seasonal (S2S) range, in which skill must be derived not from initial-condition memory of the atmosphere alone but from slowly

evolving boundary forcings such as sea surface temperature (SST) anomalies, soil moisture, and large-scale tropical convective organization [4].

Coupled ocean-atmosphere teleconnections provide the principal source of this extended-range predictability. The Madden-Julian Oscillation (MJO), an eastward-propagating envelope of tropical convection with a 30–60 day period, has been shown to modulate extratropical circulation through Rossby wave trains that alter the position and persistence of mid-latitude ridges associated with heatwave onset [5]. Specific MJO phases have been linked to increased probability of anomalous warmth and blocking-favorable circulation over North America, with statistically significant lagged relationships extending to three to four weeks [6]. Similarly, the El Niño–Southern Oscillation (ENSO), operating on interannual timescales, modulates the background state of the jet stream and storm tracks, altering the baseline probability of heat extremes in specific regions depending on the phase and strength of the anomaly [7].

Atmospheric blocking, characterized by quasi-stationary high-pressure systems that divert the jet stream and trap warm air masses beneath subsiding air, is now widely recognized as the proximate dynamical mechanism for most major heatwave events, including the 2003 European and 2010 Russian heatwaves [8]. Because blocking onset itself is influenced by upstream tropical forcing via Rossby wave propagation, teleconnection-informed prediction offers a physically grounded route to anticipating blocking, and therefore heatwave, development beyond the deterministic weather forecast horizon [9].

Empirical statistical studies have further demonstrated that Pacific SST patterns alone can provide skillful predictions of eastern United States hot-day frequency at lead times of three to six weeks, using regression frameworks trained on historical SST-temperature relationships rather than dynamical model integration [10]. This finding motivated a broader research effort within the subseasonal-to-seasonal prediction community, formalized through the WMO/WWRP S2S Prediction Project, which established a multi-model reforecast archive explicitly designed to evaluate extended-range skill for high-impact events including heatwaves [11].

Despite this progress, dynamical S2S models continue to exhibit systematic biases in representing MJO teleconnections, often underestimating the amplitude and mis-locating the extratropical response, which directly degrades heatwave-onset skill derived from model-based forecasts relative to statistically derived teleconnection indices [12]. This gap between observed teleconnection-based predictability and operational model skill constitutes the central motivation for the present study.

While several excellent reviews have addressed aspects of sub-seasonal prediction (Vitart et al., 2017; White et al., 2017; Domeisen et al., 2020), a comprehensive synthesis focusing specifically on heatwave onset through the lens of coupled ocean-atmosphere teleconnections, critically evaluating the relative contributions of MJO, ENSO, and blocking as joint predictors, remains limited. Furthermore, existing reviews have not systematically compared the predictive skill achieved by statistical and machine-learning approaches against dynamical model performance across multiple regions. This review addresses these gaps by providing a unified synthesis that: (1) focuses specifically on heatwave onset prediction in the S2S range, (2) systematically evaluates the physical mechanisms linking MJO, ENSO, and blocking to heatwave initiation across North America, Europe, and East Asia, (3) compares predictive skill across statistical, machine-learning, and dynamical modeling frameworks, and (4) identifies persistent model biases and operational barriers limiting the translation of scientific understanding into actionable early warnings.

1.1 Research Objectives

- 1) To examine the physical mechanisms linking MJO, ENSO, and atmospheric blocking to heatwave onset.
- 2) To analyze reanalysis-based evidence of lagged teleconnection-heatwave relationships across major heatwave-prone regions.
- 3) To evaluate statistical and machine-learning approaches for sub-seasonal heatwave prediction using teleconnection indices.
- 4) To compare reported predictive skill metrics across lead times and regions.
- 5) To identify persistent model biases and gaps limiting operational S2S heatwave forecasting.

II. LITERATURE REVIEW

2.1 The Sub-Seasonal Predictability Gap

The sub-seasonal timescale has historically been described as a "predictability desert" because it falls beyond the deterministic limit of chaotic error growth in weather models yet is too short for the boundary-forced seasonal mean signal to dominate individual event timing [3]. Reviews of the S2S prediction problem have emphasized that skill at this range must originate from slowly varying components of the coupled climate system, principally tropical SST anomalies, soil moisture memory, snow cover, stratospheric polar vortex state, and tropical intraseasonal convective organization, rather than from atmospheric initial conditions alone [4]. This reframing shifted subseasonal research away from purely dynamical initialization toward teleconnection-based and hybrid statistical-dynamical prediction strategies specifically for extreme events such as heatwaves.

The operational significance of the S2S range is substantial. For heatwave events, advance warning of even one to two weeks can enable critical preparedness actions: public health agencies can activate heat action plans, energy grid operators can secure additional capacity, agricultural stakeholders can adjust irrigation or harvesting schedules, and emergency management services can preposition resources. The value of forecast information increases with lead time, making the S2S range particularly attractive for proactive risk management. However, the scientific challenge of achieving skillful predictions at these lead times remains substantial.

2.2 Madden-Julian Oscillation Teleconnections to Heatwave Onset

The MJO was first identified as a 40–50 day oscillation in tropical convection and zonal wind [13], and subsequent research established that its convective envelope generates Rossby wave trains that propagate into the extratropics, altering geopotential height patterns over North America and Europe with a lag of one to three weeks depending on MJO phase [5]. Composite analyses using outgoing longwave radiation (OLR) and the Real-time Multivariate MJO (RMM) index have shown that specific MJO phases (commonly phases 6–8 during boreal summer) are associated with a significantly elevated probability of ridge amplification and reduced precipitation over the central and eastern United States, consistent with heatwave-favorable conditions [6]. Similar work over the North Atlantic-European sector demonstrated that MJO activity modulates the North Atlantic Oscillation (NAO) on intraseasonal timescales, providing an indirect but statistically robust pathway from tropical convection to European temperature extremes [14].

The physical mechanism linking MJO to extratropical heatwaves involves several steps. First, the enhanced tropical convection associated with specific MJO phases generates anomalous upper-level divergence, which acts as a Rossby wave source. Second, these Rossby waves propagate poleward and eastward along the waveguide established by the subtropical and mid-latitude jets. Third, upon reaching the extratropics, the wave train can amplify or reposition the climatological ridges and troughs, favoring the development of persistent blocking anticyclones. Fourth, these blocking anticyclones, through subsidence, clear-sky radiative heating, and soil-moisture feedbacks, drive surface temperature extremes.

The lag between MJO convective forcing and the extratropical temperature response is typically 5 to 20 days, depending on the specific teleconnection pathway, providing the basis for extended-range prediction. Notably, the strength and location of the MJO teleconnection varies seasonally, with boreal summer teleconnections differing substantially from boreal winter teleconnections due to differences in the background flow.

2.3 ENSO Modulation of Heatwave Risk

ENSO exerts a lower-frequency, seasonally persistent influence on heatwave risk by altering the mean position of the jet stream and the frequency of blocking-favorable flow configurations. Statistical composite studies have shown that specific ENSO phases correlate with altered probability of summer heat extremes in regions including the southern United States, southeastern Australia, and parts of East Asia, though the sign and strength of the relationship vary considerably by region and by the flavor of ENSO event (Central Pacific vs. Eastern Pacific) [7]. Because ENSO state is known with high confidence at sub-seasonal lead times due to its persistence, it functions as a stable background predictor that can be combined with faster-evolving MJO information to refine heatwave-onset probability [10].

The ENSO influence operates primarily through modulation of the large-scale circulation. During El Niño events, the Pacific jet stream is typically extended and strengthened, altering the frequency and position of Rossby wave breaking and blocking events. In some regions, this increases heatwave risk; in others, it may decrease it. The regional heterogeneity of the ENSO influence underscores the importance of region-specific predictor frameworks.

Importantly, the flavor of ENSO—whether it is an Eastern Pacific (canonical) or Central Pacific (Modoki) event—has been shown to produce different teleconnection patterns. Central Pacific El Niño events, which have become more frequent in recent decades, are associated with different impacts on North American and East Asian temperature extremes than Eastern Pacific events. This nuance must be incorporated into operational prediction frameworks.

2.4 Atmospheric Blocking as the Proximate Mechanism

Blocking highs are now established as the dominant proximate driver of major heatwave events, since they suppress synoptic-scale ventilation, promote clear-sky radiative heating, and induce soil-moisture-temperature feedbacks that amplify and prolong surface warming [8]. Quantitative attribution studies using reanalysis data found that a majority of the most extreme regional temperature anomalies in Europe co-occurred with blocking anticyclones, establishing blocking frequency and persistence as a key intermediate variable linking large-scale teleconnection forcing to local heatwave outcomes [8].

The relationship between blocking and heatwaves is not automatic: blocking can occur without heatwaves if the air mass is not sufficiently warm or if cloud cover limits surface heating. However, when blocking coincides with anomalously warm air advection and clear-sky conditions, the resulting heatwave can be prolonged and severe. Furthermore, soil-moisture feedbacks—whereby dry soils reduce evaporative cooling, further warming the surface and reinforcing the blocking circulation—can amplify and extend blocking-driven heatwaves.

Because blocking onset is itself partly predictable from upstream Rossby wave activity associated with MJO phase, this two-step causal chain (teleconnection → blocking → heatwave) has become the dominant conceptual framework guiding S2S heatwave prediction research [9]. The teleconnection influence on blocking occurrence provides the physical basis for extended-range predictability, while blocking persistence provides the direct atmospheric mechanism for sustained heatwave conditions.

2.5 Statistical and Machine Learning Approaches

Early teleconnection-based heatwave prediction relied on linear regression and composite/lagged-correlation techniques applied to SST and MJO indices [10]. More recent studies have incorporated machine learning methods, including random forest and logistic regression classifiers trained on combined SST, MJO phase, and soil moisture predictors, reporting improved discrimination of heatwave versus non-heatwave weeks relative to persistence or climatology baselines at three-to-four week lead times [15]. Deep learning architectures, including long short-term memory (LSTM) networks applied to sequential reanalysis fields, have also been explored for capturing the nonlinear, time-lagged dependencies between tropical convective forcing and extratropical temperature response, though these approaches remain data-limited given the relatively short observational record of high-quality reanalysis products [16].

The advantage of machine learning approaches lies in their ability to capture nonlinear and interactive relationships among predictors without imposing a predetermined functional form. Logistic regression can identify the probability of heatwave occurrence given predictor values; random forest can capture interactions among predictors and provide variable importance measures; LSTM networks can model time-lagged sequential dependencies. However, these methods require substantial training data, and their extrapolation to conditions beyond the training range (e.g., a warmer climate) is uncertain.

2.6 Research Gap

While substantial evidence supports individual teleconnection-heatwave relationships, most existing studies examine MJO, ENSO, and blocking predictors in isolation rather than as a jointly optimized predictor set, and skill assessments are frequently region-specific, limiting cross-regional generalization [6], [7], [10]. Furthermore, operational dynamical S2S models continue to underrepresent MJO-extratropical teleconnection amplitude, creating a documented gap between statistically achievable skill using observed teleconnection indices and skill actually realized in operational model reforecasts [12].

Additionally, while statistical and machine learning approaches have shown promising skill, their performance relative to dynamical models and their potential for integration into operational frameworks remain underexplored. The translation of scientific advances into actionable early-warning products for public health and emergency management stakeholders represents another critical gap. This study addresses these gaps by synthesizing multi-teleconnection predictor evidence and evaluating comparative skill across statistical, machine-learning, and dynamical model frameworks.

III. METHODOLOGY

3.1 Research Design

This study employs a literature-synthesis and comparative-analytical research design, evaluating published composite, statistical, and machine-learning studies of sub-seasonal heatwave predictability rather than generating new forecast output. The approach is descriptive and comparative, focused on consolidating reported skill metrics across teleconnection-based prediction frameworks to identify consistent patterns and remaining gaps.

3.2 Literature Search Strategy

A systematic literature search was conducted using major scientific databases including Web of Science, Scopus, and Google Scholar. Search terms included combinations of "sub-seasonal prediction," "heatwave onset," "MJO," "ENSO," "atmospheric blocking," "S2S forecasting," "teleconnections," and "extended-range forecasting." The search was restricted to peer-reviewed English-language publications from 1980 to 2025. Reference lists of identified review articles were hand-searched to capture additional relevant studies. Grey literature and conference abstracts were not included unless subsequently published as peer-reviewed articles.

3.3 Inclusion and Exclusion Criteria

Studies were included if they: (1) addressed sub-seasonal (2-6 week lead time) prediction of heatwaves or extreme temperature events; (2) examined teleconnection predictors including MJO, ENSO, or atmospheric blocking; (3) reported quantitative predictive skill metrics; and (4) were published in peer-reviewed journals. Studies were excluded if they: (1) focused exclusively on weather-scale (less than 10 days) or seasonal-scale (greater than 3 months) prediction; (2) addressed temperature prediction but not heatwave events specifically; or (3) were not available in English.

3.4 Data Sources Used in the Reviewed Literature

The studies synthesized in this review draw predominantly on the ERA5 atmospheric reanalysis for geopotential height, 2-meter temperature, and soil moisture fields; the NOAA Optimum Interpolation Sea Surface Temperature (OISST) dataset for tropical and extratropical SST anomalies; the Real-time Multivariate MJO (RMM1/RMM2) index for tropical intraseasonal convective phase and amplitude; the Niño 3.4 index for ENSO state classification; and the WMO/WWRP S2S Prediction Project reforecast archive for evaluating dynamical model skill against observed teleconnection-based benchmarks [11]. The availability and quality of these datasets are critical for the studies reviewed; limitations in spatial and temporal coverage can affect the robustness of teleconnection signatures.

3.5 Analytical Framework

Heatwave events in the reviewed literature are typically defined using percentile-based thresholds (commonly the 90th or 95th percentile of local daily maximum temperature, sustained for three or more consecutive days), following standardized definitions established in heatwave-metric review studies [2]. The specific thresholds used vary across studies, which should be noted when comparing skill metrics. Predictor-outcome relationships are evaluated using three complementary techniques: (1) lagged composite analysis, in which atmospheric and SST fields are averaged conditional on MJO phase or ENSO state at fixed lead times prior to heatwave onset; (2) statistical regression and classification models (logistic regression, random forest) using teleconnection indices as predictors of heatwave occurrence probability; and (3) sequence-based deep learning models (LSTM) trained on multivariate time series of SST, MJO, and blocking indices to capture nonlinear lagged dependencies [15], [16].

3.6 Analytical Dimensions

Reviewed studies were organized into three analytical dimensions corresponding to the physical predictor hierarchy: (1) tropical intraseasonal forcing (MJO phase and amplitude), (2) interannual background state (ENSO phase), and (3) the intermediate dynamical mechanism (blocking frequency and persistence). Predictive skill was compared within each dimension and for combined multi-predictor frameworks, since the literature indicates that combined predictors generally outperform any single teleconnection index [10], [15].

3.7 Evaluation Criteria

Skill was assessed using metrics standard in the S2S literature: the Receiver Operating Characteristic (ROC) skill score, quantifying discrimination between heatwave and non-heatwave periods; the Brier Skill Score (BSS), quantifying probabilistic

forecast accuracy relative to climatology; and lead-time-dependent correlation coefficients between predictor indices and subsequent temperature anomalies. Studies reporting skill relative to a climatological or persistence baseline were prioritized to ensure comparability across the differing statistical and dynamical frameworks reviewed.

3.8 Quality Assessment

Given the heterogeneity of methods and study designs across the reviewed literature, a narrative synthesis approach was adopted. Studies were assessed for methodological quality based on: (1) the length and quality of the observational record; (2) the robustness of the statistical methodology (including significance testing and cross-validation); (3) the control for confounding factors (such as large-scale climate variability); and (4) the appropriateness of the verification metrics. Studies with robust cross-validation and longer observational records were weighted more heavily in synthesis conclusions.

IV. RESULTS AND DISCUSSION

4.1 Comparative Skill by Teleconnection Predictor

Table I summarizes representative sub-seasonal predictive skill metrics reported across the reviewed literature for individual and combined teleconnection predictors of heatwave onset.

TABLE 1

REPORTED SUB-SEASONAL PREDICTIVE SKILL FOR HEATWAVE ONSET BY TELECONNECTION PREDICTOR

Predictor	Region	Lead time	Reported skill metric	Source
Pacific SST regression	Eastern United States	3–6 weeks	Statistically significant hot-day frequency correlation	[10]
MJO phase (RMM index)	Central/Eastern U.S.	1–3 weeks	Elevated ridge-amplification probability, phases 6–8	[6]
MJO–NAO modulation	North Atlantic/Europe	2–4 weeks	Significant intraseasonal NAO shift	[14]
ENSO phase (Niño 3.4)	Southeastern Australia, SE U.S.	Seasonal background	Regionally variable heat-extreme probability shift	[7]
Blocking frequency (reanalysis)	Europe	Diagnostic/proximate	Majority of extreme heat events co-occurred with blocking	[8]
Combined ML predictors (RF, logistic)	Multiple regions	3–4 weeks	Improved discrimination vs. climatology baseline	[15]
Dynamical S2S reforecasts	Global	2–4 weeks	Skill degraded by MJO teleconnection amplitude bias	[12]

4.2 Regional Heterogeneity of Predictability

The results in Table I indicate that predictive skill from any single teleconnection is strongly region-dependent. MJO-based skill is most robust over the central and eastern United States and the North Atlantic-European sector, where established Rossby wave pathways connect tropical convection to extratropical ridging [6], [14], whereas ENSO-based skill is comparatively stronger for regions with well-documented seasonal-mean circulation shifts, such as southeastern Australia and the southeastern United States [7]. This regional heterogeneity implies that operational sub-seasonal heatwave prediction systems cannot rely on a single universal predictor but must instead be regionally tailored, combining the dominant teleconnection pathway relevant to each target area.

For North America, the MJO influence on summer heatwaves is most pronounced during phases 6–8, which favor ridging over the central and eastern United States. The lag between the MJO phase and the heatwave response is typically 5–15 days. For Europe, the MJO influence operates through modulation of the North Atlantic Oscillation (NAO), with specific MJO phases favoring the negative NAO state that is associated with European heatwaves. For East Asia, the teleconnection pathways are more complex, involving both the MJO and the monsoon circulation.

The regional heterogeneity also reflects differences in the dominant physical processes. In regions where soil-moisture feedbacks are strong (such as the central United States and southern Europe), land-atmosphere coupling can amplify and extend heatwave events, contributing to enhanced predictability. In regions where coastal or orographic influences dominate, the teleconnection signals may be weaker.

4.3 Statistical–Dynamical Comparison

A recurring finding across the reviewed literature is that statistically derived, observation-based teleconnection relationships often exceed the skill achieved by dynamical S2S model reforecasts at equivalent lead times, primarily because coupled models systematically underrepresent the amplitude and precise geographic footprint of MJO-driven extratropical teleconnections [12]. This creates a practically important distinction between the theoretical predictability of heatwave onset, established through reanalysis-based composite and regression studies, and the realized operational skill available from current-generation dynamical forecast systems.

The reasons for model biases in MJO teleconnections are multifaceted. First, the MJO itself is often poorly simulated in coupled models, with errors in propagation speed, amplitude, and spatial structure. Second, the extratropical response to tropical forcing depends on the representation of the mean state, including the position and strength of the jet streams, which also have biases. Third, the interaction between tropical forcing and extratropical dynamics involves complex, scale-dependent processes that are challenging to resolve at typical S2S model resolutions.

Machine learning frameworks trained directly on observed teleconnection indices, rather than on model-simulated teleconnections, have been shown to partially close this gap by bypassing the model bias step entirely, though at the cost of reduced physical consistency and limited applicability beyond the historical training period [15], [16]. The ML approach offers an empirical bridge that can improve operational skill until dynamical models are sufficiently improved.

4.4 Combined Predictor Skill

Studies that combined MJO phase, ENSO state, and antecedent soil moisture as joint predictors within logistic regression and random forest frameworks reported meaningfully improved discrimination of heatwave versus non-heatwave weeks relative to any single predictor alone, consistent with the physical expectation that tropical intraseasonal forcing, interannual background state, and land-surface feedback operate on complementary timescales and jointly determine blocking persistence [15]. This finding supports the two-step causal framework (teleconnection forcing → blocking persistence → heatwave onset) as the most productive basis for future operational prediction system design.

The improvement from combining predictors is substantial. For example, Wulff and Domeisen (2019) found that while MJO phase alone provided modest predictive skill for European heatwaves at 3-4 week lead times, the combination of MJO, ENSO, and soil moisture as joint predictors increased the ROC skill score from approximately 0.60 to 0.70 or higher. Similarly, McKinnon et al. (2016) demonstrated that Pacific SST patterns combined with antecedent temperature provided improved forecasts of eastern U.S. hot days relative to either predictor alone.

4.5 The Role of Rossby Waves and Waveguide Dynamics

An important physical mechanism underlying the teleconnection-heatwave relationship is the propagation of Rossby wave trains from the tropics to the extratropics, particularly through the "waveguide" established by the subtropical jet. Studies have shown that specific MJO phases excite Rossby wave trains that propagate along the waveguide, leading to ridge amplification and blocking onset downstream [17]. This mechanism is particularly important for the MJO influences on North America and Europe, where the North Pacific waveguide connects tropical convection to mid-latitude circulation anomalies.

Rossby wave breaking—the rapid deformation and mixing of potential vorticity—is another key process linking teleconnections to blocking and heatwaves. Wave breaking can lead to the formation of cutoff lows and blocking highs, which in turn drive surface temperature extremes [18]. While some studies have linked Rossby wave breaking to the 2010 Russian and 2003 European heatwaves [8], [19], its role in sub-seasonal predictability is less well understood and remains an active research frontier.

4.6 Soil Moisture Feedback and Heatwave Amplification

Land-atmosphere coupling plays a critical role in amplifying and sustaining heatwaves. Dry soil conditions reduce evaporative cooling, allowing surface temperatures to rise more rapidly under subsiding, clear-sky conditions. This soil-moisture-temperature feedback can increase the amplitude of heatwaves by 2-5°C and extend their duration by several days [8]. Because

soil moisture has memory (anomalies can persist for weeks to months), it provides a source of sub-seasonal predictability independent of atmospheric teleconnections.

The interaction between soil moisture and atmospheric teleconnections is complex: dry soils may enhance the sensitivity of the atmosphere to tropical forcing, amplifying the MJO or blocking signal. Conversely, the atmospheric forcing (blocking) may induce soil drying, which then reinforces the atmospheric circulation through feedback. Understanding these interactions is critical for improving S2S heatwave prediction.

4.7 Discussion

Taken together, these findings indicate that coupled ocean-atmosphere teleconnections provide a physically grounded and empirically supported source of extended-range heatwave predictability, with skill that is real but modest, regionally variable, and highly sensitive to the specific dynamical pathway involved. The strongest and most consistent skill arises when MJO-based tropical forcing information is combined with ENSO background state and land-surface memory rather than relying on any single index [10], [15]. The persistent gap between reanalysis-derived teleconnection skill and operational dynamical model skill, attributable to systematic MJO teleconnection bias, represents the most significant barrier to translating this scientific understanding into improved early-warning products [12]. Closing this gap will likely require a combination of improved model physics, bias-corrected statistical-dynamical hybrid forecasting, and continued refinement of region-specific predictor combinations informed by the mechanistic blocking-onset pathway [8], [9].

The relative contributions of the various predictors vary with lead time and region. At shorter sub-seasonal lead times (1-2 weeks), the atmosphere's initial condition memory and MJO forcing both contribute; at longer lead times (3-6 weeks), boundary forcing (SST, soil moisture) becomes increasingly important. Seasonal background states (ENSO, IOD, and other low-frequency modes) modulate the system, but their influence on individual heatwave events is modest at sub-seasonal lead times.

V. CHALLENGES IN SUB-SEASONAL HEATWAVE PREDICTION

Several challenges constrain further progress in sub-seasonal heatwave prediction and should be acknowledged explicitly.

5.1 Model Bias in Teleconnection Representation

Model bias in teleconnection representation remains the most significant obstacle, as most coupled S2S models underestimate MJO amplitude and mislocate its extratropical response, directly limiting dynamically based heatwave-onset skill [12]. This bias arises from several sources: poor simulation of the MJO itself (errors in propagation, amplitude, and spatial structure), the mean state (bias in the position and strength of the jet streams), and the interaction between tropical forcing and extratropical dynamics. Systematic bias correction techniques, including the calibration of teleconnection amplitude and pattern, may offer a partial solution, but fundamental improvements in model physics are needed for long-term progress.

5.2 Regional Non-Stationarity

Regional non-stationarity complicates the design of universal predictor frameworks, since the dominant teleconnection pathway differs substantially between North America, Europe, and the Asia-Pacific region [6], [7], [14]. A predictor that works well in one region may have no skill in another. Even within a given region, the dominant teleconnection may shift over time due to climate variability and change. This non-stationarity means that predictor frameworks must be continually evaluated and, if necessary, recalibrated.

5.3 Land-Atmosphere Feedback Representation

Land-atmosphere feedback representation is another persistent source of error, since soil-moisture-temperature coupling strongly modulates the amplitude and persistence of blocking-driven heat extremes but remains poorly constrained in many reanalysis and model products [8]. Soil moisture observations are sparse, and model representations of land surface processes are simplified, leading to uncertainty in the representation of soil moisture memory and its influence on surface fluxes and boundary-layer development. Improved soil moisture initialization and land surface model development are needed.

5.4 Short Observational Records

Short observational records limit the training data available for machine-learning approaches, particularly LSTM-based architectures that benefit from long, homogeneous time series [16]. High-quality reanalysis products are available only from approximately 1979 onward, providing only 45 years of training data—marginal for deep learning applications that often

require much longer records. This data limitation restricts the complexity of ML models and increases the risk of overfitting. Transfer learning approaches and the use of climate model output for pre-training may offer partial solutions.

5.5 Communication and Operational Implementation

Communication of probabilistic sub-seasonal forecasts to public health and emergency-management stakeholders remains underdeveloped relative to the technical skill already demonstrated in the research literature, limiting the practical impact of scientific advances in this domain. Probabilistic forecasts are inherently more difficult to communicate and act upon than deterministic forecasts. Developing effective visualization, communication, and decision-support products requires collaboration between atmospheric scientists and end-users, which has historically been limited.

5.6 Event Frequency and Sample Size

The relative rarity of extreme heatwave events poses a statistical challenge: with limited event samples, robustly estimating skill and validating models is difficult. This is particularly challenging for machine learning approaches that require ample examples of both event and non-event conditions. Ensemble forecasting and multiple reforecast datasets can help address this limitation.

5.7 Stratospheric Influences

The influence of the stratospheric polar vortex and stratosphere-troposphere coupling on sub-seasonal heatwave predictability remains relatively underexplored compared to tropospheric teleconnections [20]. Stratospheric sudden warmings and the quasi-biennial oscillation (QBO) can modulate tropospheric circulation on sub-seasonal timescales, potentially affecting heatwave risk. This pathway represents an important frontier for future research.

VI. CONCLUSION

This study has reviewed the physical mechanisms and empirical evidence underlying the sub-seasonal predictability of heatwave onset through coupled ocean-atmosphere teleconnections. The Madden-Julian Oscillation, ENSO, and atmospheric blocking together form a two-step causal pathway—tropical and interannual forcing modulating blocking persistence, which in turn drives regional heatwave onset—that provides a physically coherent basis for extended-range prediction beyond the deterministic weather forecast horizon [5], [7], [8]. Reported skill metrics indicate that combined multi-teleconnection statistical and machine-learning frameworks consistently outperform single-predictor approaches and, in several documented cases, outperform current dynamical S2S model reforecasts, primarily due to persistent model bias in MJO teleconnection representation [10], [12], [15].

While meaningful predictability exists at the three-to-four week lead time most relevant for public health and infrastructure preparedness, this skill remains regionally heterogeneous and sensitive to the specific teleconnection pathway operating in a given basin, underscoring the need for regionally tailored, physically informed prediction frameworks rather than a single universal model. The gap between observed teleconnection-based predictability and operational dynamical model skill represents the primary barrier to translating scientific understanding into improved early-warning systems.

For operational forecasters, the findings suggest that integrating teleconnection-based statistical guidance alongside dynamical model output could improve heatwave forecast skill. For public health and emergency management stakeholders, the finding that meaningful predictability exists at 3-4 week lead times suggests that heat action plans can be activated with some confidence in advance of events, though forecast uncertainty must be clearly communicated. For researchers, priority areas include improving MJO teleconnection representation in dynamical models, developing hybrid statistical-dynamical frameworks, extending analysis to underexplored regions, and improving communication of probabilistic forecasts to decision-makers.

VII. FUTURE WORK

Future research should prioritize the following areas:

7.1 Hybrid Statistical-Dynamical Frameworks

The development of hybrid statistical-dynamical frameworks that correct for known MJO teleconnection biases in operational S2S models should be a priority, rather than relying on either pure dynamical output or pure statistical regression in isolation. These hybrid systems could combine dynamical model output with observation-based statistical corrections, potentially

improving skill while maintaining physical consistency. Machine learning approaches that learn the relationship between model-simulated and observed teleconnections offer a promising pathway for bias correction.

7.2 Extension to Underexplored Regions

Further work is needed to extend combined-predictor frameworks, incorporating MJO phase, ENSO state, and soil moisture, to underexplored regions such as South Asia and the Sahel, where heatwave risk is high but teleconnection-based predictability evidence remains limited. These regions have high population density, limited adaptive capacity, and increasing heatwave risk, making improved early warning a high priority. The influence of monsoon dynamics and regional circulation patterns must be understood.

7.3 Deep Learning and AI Refinement

Continued refinement of deep learning architectures, including attention-based sequence models (e.g., transformers, BERT-like architectures for climate), should be pursued as longer, higher-quality reanalysis records become available, enabling more robust characterization of nonlinear lagged teleconnection dependencies. Transfer learning approaches that leverage climate model output for pre-training could address the limited training data available. Interpretability of ML models should be emphasized to maintain physical understanding.

7.4 Operational Translation

Research should address the translation of probabilistic sub-seasonal heatwave forecasts into actionable early-warning products for public health and energy-sector stakeholders, closing the gap between demonstrated scientific predictability and realized societal benefit. This requires collaboration between atmospheric scientists, social scientists, and end-users to develop effective communication, visualization, and decision-support products that account for the inherent probabilistic nature of S2S forecasts.

7.5 Process Understanding

Further process-level studies are needed to understand the interactions between MJO, blocking, and soil moisture feedbacks, particularly how these interactions evolve under different background states (ENSO, QBO, climate change). Process understanding is essential for improving both statistical and dynamical prediction frameworks.

7.6 Multi-Model Intercomparison

Systematic multi-model intercomparison studies should be conducted to evaluate the skill of different S2S prediction systems for heatwave prediction, identifying which models (and which model physics) best capture teleconnection-heatwave relationships. This would guide model development and operational system selection.

7.7 Climate Change Interactions

Future work should investigate how climate change—warming background temperatures, changing jet stream position, modifying Rossby wave propagation, and altering soil moisture—will affect sub-seasonal heatwave predictability. Will the MJO teleconnection be strengthened or weakened? How will the frequency and persistence of blocking change? These questions are critical for long-term planning of early warning systems.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Developing Basic Agribusiness Skills in Marketing toward Sustainable Development Goals in Nigeria

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Abstract— Agribusiness plays a crucial role in Nigeria's economy, contributing significantly to employment, revenue, and food security. However, the sector faces challenges such as limited market accessibility, inadequate infrastructure, and lack of basic marketing skills. This study emphasizes the importance of developing basic agribusiness skills in marketing to increase competitiveness, improve market accessibility, and achieve sustainable development goals. The study identifies essential skills required for agribusiness marketing, including market research, product development, pricing, promotion, distribution, digital marketing, and sustainability marketing. It also provides recommendations for agribusiness owners, research institutes, and the government to support the development of these skills. The study's findings highlight the potential of agribusiness to contribute to Nigeria's sustainable development, particularly in achieving the Sustainable Development Goals (SDGs) 1, 2, 8, and 12. By acquiring basic agribusiness skills in marketing, agribusiness owners can increase their competitiveness, improve market accessibility, and contribute to Nigeria's economic development. This study provides valuable insights for stakeholders in the agribusiness sector, policymakers, and researchers.

Keywords— Agribusiness, Skill, Marketing, Sustainable Development Goals, Nigeria, Small and Medium Enterprises, Agricultural marketing, Capacity building, Rural development.

I. INTRODUCTION

Agribusiness is the commercial activities involved in the production, processing, and distribution of agricultural products. It comprises different firms and farm activities, such as food processing, manufacturing, marketing, farming, ranching, fishing, forestry, etc. It plays a crucial role in contributing to Nigeria's economy. It has the potential to promote employment opportunities and contribute to the Gross Domestic Product (GDP). In other words, it has the potential to promote economic growth, reduce poverty through job creation and increase revenue, and improve food and environmental security.

Despite its importance to Nigeria's economy, it confronts a series of setbacks, including limited market accessibility, inadequate infrastructure, and inadequate or limited basic marketing skills. The majority of agribusinesses lack the skills and knowledge to identify target market segments, develop and brand products that meet consumer needs, and promote their products effectively. These challenges reduced the ability of entrepreneurs or Small and Medium Enterprises (SMEs) in agribusiness to compete effectively in the market, limited market accessibility, reduced profitability, and their contribution to sustainable development. Adamu (2020) stated that any agribusiness aiming to thrive in a competitive market must employ strategic marketing tactics.

Skill is a learned ability that allows an individual to perform specific tasks, which can be acquired through education, training, and experience. So, agribusiness skills refer to the ability acquired by an individual to perform their duties or business activities towards meeting market competitiveness in a profitable manner.

Marketing involves understanding consumer needs, creating value for the products produced by entrepreneurs, and communicating the usage benefits to the consumer with effective and positive results.

Sustainable development is a social-ecological process characterized by the fulfillment of human needs while maintaining the quality of the natural environment.

II. CONCEPT OF AGRIBUSINESS, SKILLS, MARKETING, AND SUSTAINABLE DEVELOPMENT

Agribusiness includes all farms and firms involved in producing, harvesting, packaging, processing, preserving, distributing, marketing, and disposing of food and non-food agricultural products (Mghenyi et al., 2022). Davies and Goldberg (2021) stated that agribusiness is the total of all the operations (economic activities) involved in the manufacture and distribution of farm commodity items made from them. Oseme and Susan (2023) also explained agribusiness as the sum totality of all operations involved in the production and distribution of farm products in raw or processed forms or both. Agribusiness is the application of theories and practices of business management towards engaging in agriculture and agricultural-related products and services (Van Fleet, 2015). Agribusiness includes several key components that work together to create a food supply (Todd, 2024). Agribusiness involves harnessing agricultural science theories, practice, and application of business management principles towards creating valuable products, creating quality, and a conducive environment. It is a process of managing agricultural enterprises through the application of relevant business management principles towards sustaining quality and a conducive environment.

Skill is an individual's ability to perform specific tasks or solve a problem at a high level of proficiency (Rick, 2024). Merriam-Webster (2025) explained skills as the ability to use one's knowledge effectively and readily in execution. Skill is the ability to apply knowledge and use it to complete tasks and solve useful problems.

Agribusiness skills are the ability to apply knowledge acquired in agricultural science and business management in managing Small and Medium Enterprises. It is an application of the learned ability to operate Small and Medium Enterprises related to agricultural products and services efficiently and effectively toward contributing to a peaceful and stable society.

Marketing is the set of activities engaged by Small and Medium Enterprises towards processing and creating valuable products for consumers profitably. It involves understanding customer needs, creating valuable products that meet consumer needs, communicating the usefulness of the product in a way that yields good results, and creating a healthy society. Burgess (2019) stated that marketing is the process by which a firm's profitability translates customer needs into revenue. It is a process used by companies to communicate with consumers and make them knowledgeable about the various features of the products and services (Oladunjoye and Alli, 2023). AMA (2018), as cited in Akinyiola and Dosunmu (2024), explained marketing as a set of activities, institutions, and processes for creating, communicating, delivering, and exchanging offerings that have value for customers. Julie (2019) opined that marketing skills are traditionally how an organization communicates to connect with and engage its target audience to convey value and ultimately sell products and services. Bloomberg (2018) also stated that marketing skills meet the needs of the customer at a profit.

Sustainable development is concerned with the general improvement of living conditions for human beings, without undermining the biosphere's ability to regulate and evolve (Makhrout and Aithbib, 2023). The International Institute for Sustainable Development (2022) explained sustainable development as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Sustainable development is expected to bring lasting socio-economic benefits to all people and the environment (Szymanska, 2021).

III. SUSTAINABLE DEVELOPMENT GOALS

Sustainable Development Goals were designed and adopted by the United Nations in 2015 and are to be achieved by 2030. The goals are seventeen (17) in number, which are:

- 1) No Poverty
- 2) Zero Hunger
- 3) Good Health and Well-being
- 4) Quality Education
- 5) Gender Equality

- 6) Clean Water and Sanitation
- 7) Affordable and Clean Energy
- 8) Decent Work and Economic Growth
- 9) Industry, Innovation, and Infrastructure
- 10) Reduced Inequality
- 11) Sustainable Cities and Communities
- 12) Responsible Consumption and Production
- 13) Climate Action
- 14) Life Below Water
- 15) Life on Land
- 16) Peace, Justice, and Strong Institutions
- 17) Partnerships for the Goals

IV. BASIC AGRIBUSINESS SKILLS IN MARKETING

Basic agribusiness skills in marketing are required to achieve Sustainable Development Goals. There are some skills essential for agribusiness in marketing that can promote sustainability and contribute to Nigeria's economic development. These are some of the essential skills for agribusiness.

4.1 Market Research/Analysis Skills

Marketing research/analysis is the process of evaluating the viability of a new service or product through research conducted directly with potential customers. It comprises:

- Ability to analyze market, consumer behavior, and competitors (market analysis skills)
- Ability to position products or services with market (market positioning skills)
- Ability to identify target and specific markets (market segmentation skills)

4.2 Product Development Skills

Product development is the creation and launch of products to meet customer needs. It is used for new products or to improve existing products or to rebrand the products. Product development skills include:

- Ability to design products that meet customer needs (product design skills)
- Ability to test products and ensure they meet quality and safety standards (product testing skills)
- Ability to develop brands that are recognized and attractive to consumers (product branding skills)

4.3 Pricing Skills

Pricing is the amount of money charged for a product or the sum of value the customers exchange for the benefits of having or using the product. It involves:

- Ability to develop pricing strategies in order to maintain balance between profitability and competitiveness (pricing strategies skills)
- Ability to analyze costs and develop pricing strategies that allow for profit (cost analysis skills)
- Ability to develop pricing strategies based on the value of products and services offered to consumers (value-based pricing skills)

4.4 Promotion Skills

Promotion is a way of creating awareness of a particular brand of products, creating interest, and generating sales. It consists of the following skills:

- Ability to develop and execute advertising campaigns that reach the target market (advertising skills)
- Ability to develop and execute sales promotion campaigns that increase sales (sales promotion skills)
- Ability to develop and maintain relationships with stakeholders (consumers, suppliers, and government agencies) (public relations skills)

4.5 Distribution Skills

Distribution is the process of making products or services available to the consumer. It embraces the following skills:

- Ability to manage supply chains to allow efficient and effective distribution of goods and services (supply chain management skills)
- Ability to manage logistics to guarantee timely and cost-effective delivery of goods and services (logistics management skills)
- Ability to manage inventory to ensure adequate stock levels and reduce waste (inventory management skills)

4.6 Digital or Online Marketing Skills

Digital marketing is a way of using digital channels to connect with customers, such as websites, social media, and mobile. It contains the following skills:

- Ability to develop and execute social media marketing campaigns that reach the target market (social media marketing skills)
- Ability to develop and execute email marketing campaigns that increase sales (email marketing skills)
- Ability to optimize websites to improve search engine rankings (search engine optimization skills)

4.7 Sustainability Marketing Skills

Sustainability marketing involves the promotion of environmentally and socially responsible products, practices, and brand values. It entails the following skills:

- Ability to develop marketing strategies that promote sustainability and reduce environmental impact (sustainable marketing skills)
- Ability to analyze environmental impact and develop strategies to reduce them (environmental analysis skills)
- Ability to develop marketing strategies that promote social responsibility and ethical business practices (social responsibility marketing skills)

V. TYPES OF AGRIBUSINESSES IN NIGERIA

Farm-based Agribusiness: This involves farming and ranching operations that produce agricultural products for sale.

Non-farm Agribusiness: This involves businesses that transform raw agricultural products for farmers, such as input suppliers, equipment manufacturers, and agricultural consultants.

Food Processing Agribusiness: This involves businesses that transform raw agricultural products into consumable goods, such as food manufacturers and processors.

Agricultural Service Agribusiness: This involves businesses that provide services to farmers, such as crop protection, irrigation, and veterinary services.

VI. IMPORTANCE OF DEVELOPING BASIC AGRIBUSINESS SKILLS IN MARKETING TOWARD SUSTAINABLE DEVELOPMENT GOALS

Developing basic agribusiness skills in marketing is very crucial to achieving Sustainable Development Goals in Nigeria. Some of the importance of it are:

- 1) It is important to reduce poverty among rural dwellers through job creation and increased revenue. This is crucial in achieving Sustainable Development Goal number 1, which states that there should be no poverty among the populace.
- 2) It is important to guarantee food security through the production and distribution of food products to consumers. This works towards achieving Sustainable Development Goals number 2 and 12, which stated that there should be zero hunger and responsible consumption and production.
- 3) It promotes economic growth through job creation, income generation, and foreign exchange earnings. This leads to achieving Sustainable Development Goal number 8, which is decent work and economic growth.
- 4) It promotes environmental sustainability by adopting sustainable agricultural practices and reducing waste. This is related to Sustainable Development Goal number 11, which is sustainable cities and communities.

VII. RECOMMENDATIONS

To develop basic agribusiness skills in marketing towards achieving Sustainable Development Goals in Nigeria, the following recommendations are made:

- 1) Agribusiness owners and the government should invest in training and capacity building to develop marketing skills.
- 2) Agribusiness owners should adopt digital or online marketing technologies, such as social media and online advertising, to reach new markets and other customers.
- 3) Agribusiness owners should partner with other stakeholders, such as government agencies, NGOs, and private sector companies, to access markets and customers.
- 4) Research institutes related to agribusiness need to embark on sensitization programs through different channels for the masses to know their duties and responsibilities, such as the Agricultural and Rural Management Training Institute (ARMTI) and the Nigeria Stored Products Research Institute (NSPRI).
- 5) The government needs to provide more funds to the research institutes related to agribusiness in Nigeria to perform their duties and responsibilities.
- 6) The bureaucratic process that serves as the bottleneck to accessing financial aid through the Bank of Industry and other financial institutions by agribusiness owners should be removed or minimized. This would allow agribusiness owners to secure the financial aid required to invest in new technologies and expand their business.
- 7) Agricultural institutions should integrate marketing skills training into their curricula to prepare future agribusiness professionals.
- 8) Mentorship programs should be established to connect experienced agribusiness owners with new entrepreneurs to share knowledge and best practices.

VIII. CONCLUSION

Developing basic agribusiness skills in marketing is essential for increasing the competitiveness of agribusiness, improving market accessibility, and contributing to achieving Sustainable Development Goals in Nigeria.

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CONFLICT OF INTEREST

The authors declare no conflict of interest regarding the publication of this manuscript.

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Motivating Adult Learners toward Agribusiness Vocational Training in Taraba State, Nigeria

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Abstract— Agribusiness vocational training holds transformative potential for rural adult populations in Taraba State, Nigeria, yet participation rates remain critically low. This study investigated the motivational factors influencing adult learners' engagement with agribusiness vocational training programs in Taraba State, drawing on Self-Determination Theory (SDT) and andragogy as theoretical frameworks. Employing a mixed-methods research design, data were collected from 347 adult learners, 28 vocational instructors, and 14 extension officers across six Local Government Areas (LGAs) in the state. Quantitative data were gathered using a validated 42-item Likert-scale questionnaire, while qualitative insights were obtained through semi-structured interviews and focus group discussions. Findings revealed that economic incentives, perceived social relevance, access to market linkages, and peer support networks were the dominant intrinsic and extrinsic motivators. In contrast, low literacy levels, cultural barriers, family obligations, inadequate training infrastructure, and the absence of government-backed credit facilities emerged as the principal demotivating factors. The study recommends the integration of flexible, context-sensitive curriculum designs that align with the agricultural calendar, the strengthening of farmer cooperative learning clusters, and enhanced policy commitment to agribusiness training funding in Taraba State. These findings contribute to a growing body of knowledge on adult vocational education in Nigeria's Middle Belt region.

Keywords— Adult learning motivation, Agribusiness vocational training, Taraba State, Self-Determination Theory, Andragogy, Rural education, Nigeria, Adult education, Agricultural extension, Rural development, Vocational education.

I. INTRODUCTION

Agriculture remains the cornerstone of Nigeria's economy, accounting for approximately 24% of the nation's Gross Domestic Product (GDP) and providing livelihoods for an estimated 70% of the rural population (National Bureau of Statistics [NBS], 2023). Despite this significance, Nigeria's agricultural sector continues to grapple with structural inefficiencies, particularly in human capital development and value chain management. Taraba State, located in the North-East geopolitical zone and endowed with vast arable land, diverse ecological zones, and abundant water resources, represents one of the country's most agriculturally promising states. Yet, the full potential of this endowment remains largely unrealized.

Agribusiness—the composite of farm and off-farm activities that connect primary agricultural production with final consumers through processing, marketing, and trade—offers a compelling pathway for rural economic transformation. Vocational training in agribusiness encompasses practical instruction in areas such as crop production technologies, post-harvest handling, agro-processing, farm business management, supply chain logistics, and agricultural entrepreneurship. When effectively delivered to adult learners, such training can stimulate income diversification, reduce post-harvest losses, and foster rural enterprise development.

However, the uptake of agribusiness vocational training programs in Taraba State has remained disappointingly low. Reports from the Taraba State Agricultural Development Programme (TADP) indicate that fewer than 18% of eligible rural adults in

the state participated in any formal or semi-formal agribusiness training between 2018 and 2023. This figure is even more troubling given the state government's repeated policy commitments to agricultural transformation. The persistent gap between available training opportunities and actual participation raises a fundamental question: what motivates or demotivates adult learners in Taraba State from engaging with agribusiness vocational training?

This question is not merely academic. Understanding the motivational architecture of adult learners is a prerequisite for designing programs that are genuinely responsive to their needs, aspirations, and lived realities. Traditional deficit narratives that frame low participation as evidence of learner apathy or cultural resistance obscure the systemic, institutional, and personal barriers that shape adult learning decisions. A more nuanced examination—one that centers the perspectives of adult learners themselves—is both overdue and necessary.

This study therefore set out to examine the motivational factors driving and hindering adult learners' participation in agribusiness vocational training in Taraba State, Nigeria. Specifically, the study sought to: (i) identify the primary intrinsic and extrinsic motivational factors influencing adult learners' engagement with agribusiness vocational training; (ii) determine the principal barriers to participation; (iii) assess the role of socio-demographic variables such as gender, age, and educational attainment in shaping motivation; and (iv) propose evidence-based strategies for improving adult learner motivation and training uptake.

II. THEORETICAL FRAMEWORK

This study is grounded in two complementary theoretical traditions: Self-Determination Theory (SDT) and Malcolm Knowles' theory of andragogy. Together, these frameworks provide a robust conceptual lens through which to examine the motivational dynamics of adult learners in vocational education contexts.

2.1 Self-Determination Theory (SDT)

Developed by Deci and Ryan (1985, 2000), Self-Determination Theory posits that human motivation is best understood along a continuum from amotivation through extrinsic motivation to intrinsic motivation. At the core of SDT are three fundamental psychological needs: autonomy (the experience of volition and self-endorsement in one's actions), competence (the sense of effectiveness and mastery in valued activities), and relatedness (the sense of connection and belonging within a community). When these three needs are met within a learning environment, individuals are more likely to develop autonomous motivation—a form of engagement characterized by genuine interest, personal endorsement, and volitional commitment.

In the context of adult agribusiness vocational training, SDT suggests that programs which respect learners' agency, build on their existing competencies, and foster a sense of community are more likely to attract and retain adult participants. Conversely, training environments that are coercive, shame-inducing, or disconnected from learners' communities of practice will undermine intrinsic motivation and reinforce dropout tendencies. SDT has been applied productively in adult education research in sub-Saharan Africa (Adekunle & Olowu, 2021; Nwachukwu, 2022), though its application to agribusiness training in the Middle Belt region of Nigeria remains limited.

2.2 Andragogy

Malcolm Knowles' andragogical model (Knowles, 1984) provides a complementary framework by articulating the distinctive learning characteristics of adults. According to Knowles, adult learners differ from children in several critical respects: they possess a self-concept oriented toward self-direction; they bring a rich reservoir of life experience that constitutes a resource for learning; their readiness to learn is tied to developmental tasks and social roles; they are problem-centered rather than subject-centered in their orientation; and they are internally rather than externally motivated. A sixth principle, later added by Knowles and colleagues, recognizes adults' need to understand why they should learn something before committing to the learning process.

Applied to agribusiness vocational training, andragogy suggests that programs must actively negotiate with adult learners rather than imposing predetermined curricula. Training content must be immediately applicable to learners' agricultural livelihoods, must honor their existing knowledge of farming practices, and must position them as active co-constructors of knowledge

rather than passive recipients of technical information. This theoretical orientation informed both the research design and the interpretive analysis of this study.

III. LITERATURE REVIEW

3.1 Adult Vocational Education in Nigeria: Context and Challenges

Vocational and Technical Education (VTE) in Nigeria operates within a complex policy landscape shaped by the National Policy on Education (NPE), the Technical and Vocational Education and Training (TVET) Policy of 2019, and various state-level frameworks. The National Board for Technical Education (NBTE) and the National Commission for Colleges of Education (NCCE) coordinate vocational training provision, though significant gaps persist in quality, relevance, and reach, particularly in rural areas. The National Directorate of Employment (NDE) has historically delivered agribusiness-related vocational training, though evaluations of program effectiveness have been mixed (Ogundele, 2020; Eze & Ikwuakam, 2021).

Research consistently identifies multiple barriers to adult participation in vocational education in Nigeria, including direct and opportunity costs, geographic inaccessibility, inadequate childcare provisions, scheduling inflexibility, cultural norms that devalue formal training for adults, and the perceived irrelevance of curricula to local production contexts (Adeleke, 2019; Babangida & Umar, 2022). Gender constitutes a particularly significant axis of exclusion: women in rural northern Nigeria face compounded constraints related to mobility, spousal permission, domestic responsibilities, and cultural proscriptions on female participation in mixed-gender learning environments.

3.2 Motivation and Adult Learning in Agricultural Contexts

The literature on motivation for agricultural training among rural adults in sub-Saharan Africa reveals a nuanced picture. Economic motivation—specifically, the prospect of increased income, improved yields, and access to market opportunities—consistently emerges as a dominant driver of training participation (Asante et al., 2020; Birner et al., 2021). However, purely instrumentalist accounts of agricultural training motivation are increasingly challenged by research demonstrating the importance of social identity, community recognition, and self-efficacy as motivational drivers (Nwachukwu, 2022; Osei-Bonsu et al., 2021).

A study by Okeke and Adeyemi (2020) in Kogi State found that adult farmers who perceived agribusiness training as consistent with their occupational identity as "progressive farmers" were significantly more likely to complete training programs than those who experienced training as an implicit criticism of traditional practices. Similarly, research in Tanzania and Kenya has demonstrated that peer mentorship and social learning networks substantially increase motivation and retention among adult agricultural learners (Waweru et al., 2022; Mwangi & Kariuki, 2023). These findings underscore the importance of social and relational dimensions of motivation that go beyond individual incentive structures.

3.3 Taraba State Agricultural Context

Taraba State spans approximately 54,473 square kilometers and hosts a population of approximately 3.7 million people across sixteen Local Government Areas. The state's diverse agroecological zones—ranging from the Guinea Savannah in the north to the Montane forests of the Mambilla Plateau—support a wide range of agricultural commodities, including yam, cassava, maize, sorghum, groundnuts, rice, cocoa, tea, and livestock. Despite this diversity, agricultural productivity in the state remains significantly below potential, constrained by poor rural infrastructure, limited access to improved inputs, inadequate extension services, and fragmented value chains.

The Taraba State Government's Agricultural Transformation Agenda (2021-2025) explicitly identifies human capital development and agribusiness training as priority intervention areas. The program commits to establishing fifty agribusiness training hubs across the state's sixteen LGAs by 2025. Yet baseline assessments conducted for this study revealed that only eleven such hubs were operational as of December 2023, with significant variations in quality, equipment, and instructor capacity. This implementation gap provides the immediate policy context for the motivational challenges explored in this study.

IV. METHODOLOGY

4.1 Research Design

This study adopted a sequential explanatory mixed-methods design, in which quantitative data collection and analysis preceded and informed the subsequent qualitative phase. The mixed-methods approach was chosen to leverage the complementary strengths of both paradigms: quantitative analysis provided breadth and generalizability in identifying motivational patterns across the study population, while qualitative methods provided depth and contextual richness in understanding the lived experiences of adult learners and training facilitators.

4.2 Study Area and Population

The study was conducted across six Local Government Areas (LGAs) in Taraba State: Jalingo, Wukari, Bali, Gashaka, Karim-Lamido, and Zing. These LGAs were purposively selected to represent the state's ecological and socioeconomic diversity. The target population comprised adult learners (defined as individuals aged 18 years and above) who had either participated in, were currently enrolled in, or had been invited to participate in agribusiness vocational training programs within the preceding three years.

4.3 Sampling Procedure and Sample Size

A multi-stage sampling procedure was employed. In the first stage, six LGAs were purposively selected. In the second stage, three agribusiness training hubs or extension centers were randomly selected per LGA, yielding eighteen study sites. In the third stage, adult learners at each site were selected using systematic random sampling from available registers. Using Yamane's (1967) formula for determining sample size at a 95% confidence level and 5% margin of error from an estimated population of 4,200 registered participants across the eighteen sites, a minimum sample of 354 was determined. After accounting for non-response, 347 usable questionnaires were returned, representing a 98.0% response rate. Additionally, 28 vocational instructors and 14 agricultural extension officers were purposively selected for qualitative data collection.

4.4 Data Collection Instruments

The primary quantitative instrument was a researcher-developed and validated 42-item Likert-scale questionnaire, the Agribusiness Training Motivation Scale (ATMS), organized into six subscales: economic motivation (8 items), social-relational motivation (7 items), intrinsic/personal development motivation (8 items), institutional factors (7 items), structural barriers (7 items), and socio-cultural barriers (5 items). The instrument was piloted on 40 adult learners outside the main sample, yielding a Cronbach alpha reliability coefficient of 0.87, indicating strong internal consistency. The instrument was translated into Hausa and Jukun to accommodate participants with limited English proficiency, with back-translation checks performed to ensure conceptual equivalence. Qualitative data were collected through 28 semi-structured individual interviews (averaging 45 minutes each) with vocational instructors and extension officers, and 6 focus group discussions (FGDs) with adult learners (5-8 participants per FGD).

4.5 Data Analysis

Quantitative data were entered into SPSS version 27.0 and analyzed using descriptive statistics (means, standard deviations, and percentages), one-way Analysis of Variance (ANOVA) to assess differences in motivational profiles by demographic variables, and Pearson's Product-Moment Correlation to examine associations between motivational constructs and training participation frequency. Qualitative data were audio-recorded with participants' consent, transcribed verbatim, and analyzed using Braun and Clarke's (2006) six-phase thematic analysis. NVivo 12 software supported qualitative data management and coding. Triangulation of quantitative and qualitative findings was conducted in the interpretation phase to develop a comprehensive account of motivational dynamics.

V. RESULTS AND FINDINGS

5.1 Sociodemographic Profile of Respondents

Of the 347 adult learner respondents, 54.5% were male and 45.5% female. The majority (61.4%) fell within the 25-44 age bracket, with 22.8% aged 18-24 and 15.8% aged 45 and above. In terms of educational attainment, 31.1% had no formal education, 28.8% had primary education, 29.1% had secondary education, and 11.0% held tertiary qualifications. The occupational profile of respondents was predominantly farming (73.8%), with small-scale trading (15.6%) and artisanal work (10.6%) also represented. A summary of motivational factor mean scores is presented in Table 1 below.

TABLE 1
MEAN SCORES OF MOTIVATIONAL FACTORS FOR AGRIBUSINESS TRAINING PARTICIPATION (N=347; SCALE: 1=STRONGLY DISAGREE TO 5=STRONGLY AGREE)

Motivational Factor / Subscale	Mean Score	Std. Dev.	Ranking
Economic incentives and livelihood improvement	4.31	0.61	1st
Access to market linkages and buyers	4.18	0.73	2nd
Peer and community encouragement	4.06	0.79	3rd
Desire for personal/skills development	3.94	0.82	4th
Social recognition as a 'modern farmer'	3.87	0.88	5th
Government/NGO facilitation and support	3.72	0.91	6th
Access to credit/inputs after training	3.65	0.97	7th

5.2 Key Motivating Factors

Economic motivation emerged as the most powerful driver of agribusiness training participation, with a mean score of 4.31. In FGDs, participants consistently articulated the desire to "earn more from the same land" as a primary rationale for seeking training. As one female participant in the Wukari FGD stated, the aspiration to learn how to add value to cassava and sell processed products rather than raw tubers had motivated her attendance despite significant travel costs. This finding is consistent with SDT's conceptualization of identified regulation, wherein adults engage in activities because they recognize their personal importance, even when they are not intrinsically enjoyable per se.

Access to market linkages ranked second (mean = 4.18), reflecting a sophisticated understanding among adult learners that technical skills alone are insufficient without reliable market outlets. Respondents who had been exposed to previously organized farmer-buyer linkage events through the Taraba Agribusiness Development Programme (TADP) reported significantly higher motivation scores than those without such exposure ($F(2, 344) = 14.37, p < .001$). This finding underscores the importance of embedding market development support within vocational training programs rather than treating technical skills training as an end in itself.

Peer and community encouragement (mean = 4.06) emerged as the third most significant motivator, a finding that resonated strongly with SDT's emphasis on relatedness. Qualitative data revealed that in communities where local opinion leaders—including traditional rulers, community development association chairpersons, and church or mosque leaders—visibly endorsed agribusiness training, participation rates were significantly higher. An agricultural extension officer in Bali LGA described how the endorsement of the Ardo'en (community head) for a poultry management training program in 2022 resulted in a threefold increase in enrollment compared to the previous cohort.

5.3 Principal Barriers to Participation

Five primary barriers to agribusiness training participation were identified from the data. First, low literacy levels constrained both the comprehension of training materials and the confidence of potential participants to enroll in programs perceived as academically oriented (cited by 67.4% of respondents). Second, cultural and gender barriers—particularly restrictions on women's mobility and the expectation that adult men should generate income rather than "return to school"—significantly inhibited participation, especially in the Karim-Lamido and Zing LGAs, where conservative social norms are more pronounced. Third, scheduling conflicts with the agricultural calendar meant that training sessions offered during peak planting or harvesting seasons were poorly attended regardless of content quality. Fourth, the absence of government-backed microcredit schemes to help trainees invest in new agribusiness practices post-training reduced the perceived utility of training. Fifth, inadequate training infrastructure—including lack of functional demonstration farms, processing equipment, and reliable electricity—undermined the credibility and attractiveness of available programs.

5.4 Gender and Age Differences in Motivation

One-way ANOVA revealed significant gender differences in motivational profiles. Female respondents scored significantly higher on intrinsic motivation subscales (personal development and community contribution) compared to male respondents

($F(1, 345) = 8.21, p = .004$), but significantly lower on institutional motivation subscales related to government facilitation ($F(1, 345) = 6.43, p = .011$), reflecting women's greater reliance on informal networks and lower confidence in government-delivered programs. Younger adult learners (18-24 years) demonstrated higher levels of aspiration-related motivation—particularly the desire to transition out of subsistence farming—while older learners (45+) were more strongly motivated by the desire to pass on improved techniques to their children and preserve their social standing within farming communities.

VI. DISCUSSION

The findings of this study illuminate a complex, multi-layered motivational landscape that challenges both deficit narratives of rural adult learners in Nigeria and purely instrumentalist accounts of vocational training participation. Several important implications emerge from the data.

The primacy of economic motivation, while unsurprising given the poverty context of rural Taraba State, should not be interpreted as evidence that adult learners are solely transactional in their educational orientations. The qualitative data revealed that economic aspirations were frequently interwoven with narratives of dignity, family responsibility, and community development. This resonates with Nwachukwu's (2022) contention that economic and social motivations in African adult education contexts are not easily disentangled, as livelihood improvement carries deep social meaning within communal value systems.

The significance of peer and community encouragement as a motivational factor has critical programmatic implications. Current agribusiness training designs in Taraba State tend to be structured around individual skill acquisition rather than collective learning and community mobilization. A shift toward cooperative learning models—in which groups of community members are recruited, trained, and supported together—could harness the relational motivation identified in this study. This approach aligns with Vygotsky's (1978) zone of proximal development and with recent evidence from farmer learning group interventions in Ghana and Ethiopia (Asante et al., 2020; Abebe et al., 2021).

The finding that scheduling conflicts with the agricultural calendar constitute a major barrier reflects a fundamental misalignment between training program design and the temporal rhythms of rural life. This is not a new observation in Nigerian adult education research (Adeleke, 2019; Babangida & Umar, 2022), yet it persists in practice, suggesting institutional inertia rather than lack of awareness. The integration of agricultural calendar mapping into training program planning—ensuring that intensive training sessions are offered during the dry season when farmers have more time—should be a non-negotiable design requirement.

Gender disparities in motivation and participation represent perhaps the most urgent finding of this study. Women's higher intrinsic motivation scores, combined with their significantly lower rates of actual participation, suggest that the barriers they face are primarily structural and social rather than attitudinal. This has important implications for program design: rather than focusing on changing women's attitudes toward training, interventions should focus on removing structural barriers through community sensitization campaigns, female-only training cohorts, childcare provision during training sessions, and the deliberate recruitment of female instructors and community champions.

The absence of post-training credit and market linkage support as a demotivating factor speaks to a critical gap in the current agribusiness training ecosystem in Taraba State. Training programs that equip adults with new skills but fail to provide the capital and market connections needed to apply those skills create frustration and erode trust in future training invitations. Vocational education researchers have increasingly called for the integration of training programs within broader agricultural support ecosystems that include input access, credit facilitation, and market development (Birner et al., 2021; Waweru et al., 2022). The findings of this study provide further empirical support for this systemic approach.

VII. RECOMMENDATIONS

Based on the findings and discussion above, the following evidence-based recommendations are made to policymakers, program designers, and implementing agencies involved in agribusiness vocational training in Taraba State:

- 1) **Adopt Agri-Calendar-Aligned Training Schedules:** Agribusiness training programs should be systematically scheduled during the dry season (November to February) when farmers' time demands are lowest. A state-wide agricultural calendar mapping exercise should be conducted and shared with all training providers to prevent scheduling conflicts.

- 2) **Establish Community-Based Learning Clusters:** Rather than recruiting individual learners, training programs should recruit cohorts of 15-20 community members from the same village or ward, building on existing social networks and community trust. These learning clusters should continue as peer support and enterprise development groups after formal training ends.
- 3) **Integrate Market Linkage and Credit Facilitation into Training Packages:** No vocational training program in agribusiness should be considered complete without connecting graduates to market buyers and microfinance facilities. The Taraba State Government should mandate the establishment of training-to-finance corridors in all TADP-funded programs.
- 4) **Design Gender-Responsive Training Structures:** Women-only training cohorts should be established in LGAs with pronounced gender barriers. Female community mobilizers should be recruited and trained to serve as recruitment agents. Training venues should be within walking distance of participants' homes, and crèche facilities should be provided for mothers of young children.
- 5) **Strengthen Instructor Capacity in Adult Learning Pedagogy:** Vocational instructors in agribusiness training centers should receive mandatory training in adult learning facilitation techniques, including andragogical principles, participatory training methods, and culturally responsive communication. The current over-reliance on lecture-based, textbook-oriented instruction is misaligned with adult learners' experiential learning orientations.
- 6) **Leverage Traditional and Religious Leaders as Motivation Champions:** State and LGA extension services should systematically engage traditional rulers, religious leaders, and community development associations as advocates for agribusiness training participation. Community endorsement was identified as a powerful motivator, yet this resource remains largely untapped in current program designs.
- 7) **Invest in Demonstration Infrastructure:** Functional demonstration plots, processing equipment, and solar-powered training facilities should be established at all TADP training hubs. The credibility and attractiveness of training programs is significantly undermined when learners cannot see and practice with the technologies being promoted.
- 8) **Establish Monitoring and Evaluation Frameworks:** Regular monitoring and evaluation of training programs should be conducted to assess effectiveness, identify challenges, and inform continuous improvement.

VIII. CONCLUSION

This study has provided a comprehensive empirical examination of the motivational factors shaping adult learners' engagement with agribusiness vocational training in Taraba State, Nigeria. The findings demonstrate that adult learners in this context are not passive or apathetic actors in relation to vocational education, but rather purposive decision-makers who weigh the perceived benefits, social implications, and practical feasibility of training participation against the very real constraints of poverty, family obligation, and structural exclusion.

The study's contribution is twofold. Theoretically, it extends the application of Self-Determination Theory and andragogy to the specific context of agribusiness vocational training in Nigeria's Middle Belt region, demonstrating the explanatory power of these frameworks while also highlighting dimensions—particularly the communal and relational aspects of motivation—that require greater theoretical elaboration. Empirically, it provides a rich, multi-method evidence base on which program designers and policymakers in Taraba State can draw.

Ultimately, the transformation of Taraba State's agricultural economy depends not only on technical interventions and market infrastructure but on the meaningful engagement of adult rural populations as skilled, entrepreneurial agribusiness actors. Motivating adult learners toward agribusiness vocational training is therefore not merely a pedagogical challenge but a development imperative. The evidence presented in this study suggests that with the right institutional commitments, community engagement strategies, and gender-responsive program designs, this challenge is eminently surmountable.

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CONFLICT OF INTEREST

The author declares no conflict of interest regarding the publication of this manuscript.

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Addressing the Challenges of Herders-Farmers Crisis in Nigeria through Intercultural Leadership in Adamawa State, Nigeria

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Abstract— Agricultural products for both crops and animals are essential commodities worldwide, and the issue of food security is one of the major global challenges that demands serious concern and attention. This paper focuses on ways of addressing the farmers-herders crisis through the use, support, and cooperation of all village heads and community leaders in the farming communities of Adamawa State. This is because the village head knows all the caliber of farmers within their territories, and the majority of farmers listen to and give maximum respect to their community leaders. The paper reveals that Nigeria has experienced the highest number of farmer-herder fatalities in West or Central Africa over the past decade. The crisis has resulted in a large number of deaths among farmers, low agricultural productivity, and high prices of food items across West African countries. The paper recommends that village heads should organize regular meetings with farmers to enlighten them on the consequences of crisis on social, cultural, and economic aspects. The government should encourage, motivate, and support community leaders and engage them in decision-making. Additionally, the provision of infrastructural facilities is of paramount importance to support all cultural and community leaders to do the needful, in order to address the challenges of the farmers-herders crisis in Nigeria and ensure economic sustainability.

Keywords— Farmer-herder conflict, Nigeria, Adamawa State, Intercultural leadership, Conflict resolution, Community leadership, Pastoralism, Food security.

I. INTRODUCTION

The herders-farmers conflict has emerged as one of the most pressing security challenges facing most West African countries, including Nigeria, with far-reaching implications for peace, social and economic stability, and food supply in all affected regions (Okoli, 2019). Resulting in continuous competition for scarce resources such as farmland, water, and other social and infrastructural facilities, this conflict has been worsened by other factors including environmental degradation, climate change, and socio-economic pressures (Adeoye, 2017). The clashes between pastoralists and farmers have resulted in massive loss of life, displacement of several productive farming communities, and destruction of millions of valued assets and properties, further expanding the humanitarian crisis in all affected areas (Internal Displacement Monitoring Centre, 2020). These undesirable activities happening in the farming communities seriously threaten Nigeria's agricultural productivity, food security, rural development, and social cohesion, making it imperative to address the primary causes and find permanent resolutions for sustainable growth and development (Food and Agriculture Organization, 2018).

Furthermore, no society or nation can develop without peace and security; ensuring security is of paramount importance for any nation to attain sustainable development in both human and material resources. Addressing the security challenges can be done through collaborative efforts between government, non-governmental organizations, community leaders, and religious groups. There is a need for continued dialogue and creating more awareness among youth and other members of society.

II. IMPACT OF THE CONFLICT ON THE NIGERIAN ECONOMY

Due to the nature of multi-ethnicity, the impact of herder-farmer conflict on the Nigerian economy cannot be overemphasized. The incidents are recurring, and the effects on human lives and livelihoods, as well as the resulting negative economic consequences, are worrisome. Studies show that since 2016, more than 3,600 lives and millions of naira have been lost as a result of the farmer-herder conflicts in Nigeria. Also, no fewer than 62,000 people have been displaced in the Middle Belt region where the conflict is mostly concentrated. Many farmers and herders, including women and children, have lost their homes and lives as well (Nweze, 2005), while experiencing serious declines in crop production and herd productivity. The crisis has reportedly cost the country over \$2.3 million (47 percent) of its internally generated revenue, which could have been used for improving the economic and social well-being of the citizens (Assessment Capacities Project Thematic Report – ACAPS, 2017).

III. EFFORTS OF THE NIGERIAN GOVERNMENT IN TACKLING THE FARMERS-HERDERS CRISIS

There have been several efforts by past and present government administrators in handling and tackling the menace of the farmer-herder conflict. Before the collapse of the First Republic, the government introduced the Grazing Reserve Act of 1964, which provided adequate grazing areas and paths for the passage of livestock. However, after 1966, the paths became moribund and were overtaken by other anthropogenic activities (Relief Web, 2018). More recently, bills have been presented by lawmakers such as the National Grazing Routes and Reserve Bill 2012 and the National Grazing Reserve Bill 2016, which sought to establish new grazing reserves and routes in each State of the Federation. However, these bills have been unsuccessful. This is largely due to criticisms and distrust of the outcomes by different regions. For instance, southern leaders and groups fear that the bill is an attempt to seize power and colonize the region. Similarly, in mid-2019, Nigeria's executive branch proposed to establish Rural Grazing Area (RUGA) settlements all over the country in a bid to check the conflicts and improve agricultural productivity. The RUGA program sought to settle migrant pastoral families and other animal farmers in an organized place with provision of necessary and adequate social amenities (Daily Trust, 2019). This too met a dead end and was eventually shelved as different ethnic groups accused the process of being a plan to "Fulanize" the country.

Other government initiatives to tackle the crisis include:

- 1) **Ranching System:** The Federal Government has proposed establishing ranches to reduce conflicts between farmers and herders. This approach aims to provide a more organized and sustainable way of managing livestock, reducing competition for land and resources.
- 2) **Conflict Resolution Mechanisms:** The government has recommended conflict resolution mechanisms, such as mass orientation and dialogue, to promote peaceful coexistence between farmers and herders.
- 3) **Piloting Ranching Initiatives:** It has been suggested that the government pilot ranching initiatives in affected states to assess their potential and effectiveness.
- 4) **State and Local Government Involvement:** The government has involved state and local governments in addressing the crisis, recognizing that a multi-level approach is necessary to resolve the complex issues involved.

Despite these efforts, the crisis persists, and there are concerns about the government's response, including:

- **Inadequate Response:** Critics argue that the government's response has been inadequate, failing to effectively address the root causes of the conflict.
- **Lack of Consensus:** There is a lack of consensus between the Federal Government and affected state governments on the best approach to resolving the crisis.
- **Need for Community-Led Solutions:** Some argue that community-led solutions, rather than top-down approaches, may be more effective in addressing the crisis.

Overall, the government's efforts to address the farmers-herders crisis are ongoing, but the complexity of the issue requires a multifaceted and inclusive approach.

IV. THEORETICAL FRAMEWORK: INTERCULTURAL LEADERSHIP

This study is grounded in the concept of intercultural leadership, which refers to the ability to influence, motivate, and enable others to contribute toward the effectiveness and success of organizations or communities across cultural boundaries. In the

context of conflict resolution, intercultural leadership involves the capacity to bridge cultural divides, facilitate dialogue between different ethnic and occupational groups, and build trust and understanding across communities (House et al., 2004; Northouse, 2018).

Intercultural leadership is particularly relevant to the herders-farmers crisis because the conflict involves two distinct groups with different cultural practices, livelihood strategies, and historical grievances. Effective intercultural leaders—such as village heads, traditional rulers, and community elders—possess the cultural competence, local knowledge, and social capital needed to mediate between these groups and foster peaceful coexistence (Okoli, 2019). By leveraging their influence and respect within their communities, these leaders can facilitate dialogue, build trust, and promote sustainable solutions to the crisis.

The application of intercultural leadership to conflict resolution is supported by the work of scholars such as Goleman (1998) on emotional intelligence, Heifetz (1994) on adaptive leadership, and Hofstede (2001) on cultural dimensions. These frameworks highlight the importance of empathy, cultural awareness, and adaptive capacity in leading diverse groups through conflict and change.

V. THE ADAMAWA STATE CONTEXT

Adamawa State, located in the North-East geopolitical zone of Nigeria, is one of the states most affected by the herders-farmers crisis. The state shares borders with Borno, Gombe, and Taraba States, as well as the Republic of Cameroon. Its diverse ethnic composition includes Fulani, Hausa, Gude, Bata, Bachama, and numerous other groups, creating a complex social and cultural landscape (Adamawa State Government, 2021).

The state's agricultural economy is characterized by both crop farming and livestock herding, making it a microcosm of the national conflict. Farmers in Adamawa State cultivate crops such as maize, sorghum, millet, groundnuts, and rice, while pastoralists move their cattle across the state in search of water and pasture. Competition for land and water resources has intensified due to population growth, climate change, and environmental degradation, leading to increased conflict (Blench, 2010).

The crisis in Adamawa State has been particularly severe in areas such as Girei, Yola South, Demsa, and Numan Local Government Areas, where incidents of violence have displaced thousands of people and disrupted agricultural activities (Internal Displacement Monitoring Centre, 2020). The state government has implemented various initiatives to address the crisis, including the establishment of peace committees and the promotion of dialogue between farmers and herders. However, these efforts have been hampered by limited resources, weak institutional capacity, and the complexity of the conflict dynamics.

VI. MEASURES TO ADDRESS THE HERDERS-FARMERS CRISIS IN NIGERIA

- 1) **Dialogue and Mediation:** Facilitate dialogue between herders and farmers to resolve conflicts peacefully (Okoli & Atelhe, 2014). Use mediation and negotiation to address grievances and find mutually beneficial solutions.
- 2) **Sustainable Land Use:** Promote sustainable land use practices, such as agro-pastoralism, to reduce conflicts over land (Blench, 2010). Implement land reform policies to ensure equitable access to land for both herders and farmers.
- 3) **Ranching and Livestock Management:** Establish ranches to provide a more organized and sustainable way of managing livestock (Audu, 2013). Promote modern livestock management practices, such as vaccination and breeding programs.
- 4) **Conflict Resolution Mechanisms:** Establish conflict resolution mechanisms, such as community-based dispute resolution committees (Okoli, 2019). Provide training and support for conflict resolution initiatives.
- 5) **Economic Empowerment:** Provide economic empowerment programs for herders and farmers, such as access to credit and markets (United Nations Development Programme, 2020). Promote economic diversification to reduce dependence on agriculture and livestock.
- 6) **Community Engagement:** Engage communities in peacebuilding initiatives, promoting social cohesion and cooperation (International Crisis Group, 2018). Foster partnerships between herders, farmers, and government agencies to address the crisis.
- 7) **Policy and Legislative Frameworks:** Develop and implement policy and legislative frameworks that address the root causes of the conflict (Food and Agriculture Organization, 2018). Ensure policies are inclusive and responsive to the needs of both herders and farmers.

By leveraging cultural leadership, Nigeria can develop context-specific solutions to the herders-farmers crisis, promoting peaceful coexistence and sustainable development.

VII. THE ROLE OF CULTURAL LEADERSHIP IN ADDRESSING THE HERDER-FARMER CRISIS

Cultural leadership can be utilized to address the herder-farmer crisis through:

- 1) **Promoting Dialogue and Understanding:** Cultural leaders need to be involved to facilitate community dialogues to foster understanding and cooperation between herders and farmers (Okoli & Atelhe, 2014). Leaders can organize peacebuilding initiatives, such as workshops and conferences, to promote peaceful coexistence in the farming communities.
- 2) **Mediation and Conflict Resolution:** Cultural leaders are in a position to mediate conflicts between herders and farmers, leveraging their influence and knowledge of local customs (Audu, 2013). Traditional justice systems can be utilized to resolve disputes and promote reconciliation.
- 3) **Encouraging Sustainable Practices:** Cultural leaders can promote sustainable land use practices, such as agro-pastoralism, to provide adequate grazing areas in order to reduce conflicts over land (Blench, 2010). Leaders can encourage environmental conservation practices, such as tree planting and soil conservation.

7.1 Benefits of Using Cultural Leadership in Tackling Herder-Farmer Crisis:

- **Local Ownership:** Cultural leaders understand local dynamics, ensuring solutions are context-specific.
- **Trust Building:** Leaders can build trust between herders and farmers, tackling the existing tensions between the two groups.
- **Community Buy-in:** Cultural leaders can gather community support for peace initiatives.

7.2 Examples of Cultural Leadership:

- Traditional rulers, such as emirs and obas, can play key roles in mediating conflicts and promoting peace (Okoli, 2019).
- Community leaders can facilitate dialogue and promote peaceful coexistence.

VIII. RECOMMENDATIONS

- 1) **Empower Cultural Leaders:** Government should provide continuous and effective training and support for cultural leaders to effectively address the crisis.
- 2) **Collaborate with Government:** Cultural leaders should collaborate with government agencies to develop comprehensive and permanent solutions.
- 3) **Community Engagement:** Engage communities in peacebuilding initiatives, leveraging cultural leaders' influence.
- 4) **Provide Adequate Grazing Areas:** Government should provide adequate grazing areas as well as cattle routes in all the farming communities.
- 5) **Collaborate with Community Leaders:** Government should collaborate with community leaders, village heads, and prominent farmers in decision-making.
- 6) **Provide Adequate Water Supply:** Government or relevant agencies should help in providing adequate water supply for farmers and their animals. This would help in reducing farm destruction as well as crisis with the farmers.
- 7) **Develop Inclusive Policies:** Develop inclusive policies that address the root causes of the conflict and promote peaceful coexistence.
- 8) **Provide Support for Conflict-Affected Individuals/Communities:** Provide support for conflict-affected individuals and communities, including rehabilitation and reconstruction efforts.
- 9) **Strengthen Institutions:** Strengthen institutions responsible for conflict resolution and management.

IX. CONCLUSION

The conflicts that emanate from pastoralist and farmer interactions in Nigeria have assumed unprecedented violent dimensions and have far-reaching impacts on the people and the country as a whole. While the policies, interventions, and negligence of colonial and post-colonial administrators, among other factors, have been blamed for instigating and escalating the conflicts, lessons can nonetheless be drawn from the past for transformative solutions. It is imperative that workable measures be put in place by the government to check the conflicts. This can be in the form of a framework for peaceful coexistence between local farming communities and pastoralist groups supported by legislation, such as the traditional Ruga (rural grazing area) administrative system once practiced in the pre-colonial era. However, the lack of efficient social amenities like water supply, good marketing systems, schools, and roads also contributes to community unrest.

The engagement of community leaders and traditional rulers in conflict resolution offers a promising pathway for addressing the herders-farmers crisis in Adamawa State and beyond. By leveraging their influence, cultural knowledge, and trust within their communities, these leaders can facilitate dialogue, build bridges between conflicting groups, and promote sustainable solutions. With the right support from government and other stakeholders, intercultural leadership can play a transformative role in resolving one of Nigeria's most intractable conflicts and ensuring peace, security, and economic sustainability.

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CONFLICT OF INTEREST

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Youth Agripreneurship: A Driver for Sustainable Economic Development in Nigeria

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Abstract— This review examines the role of governmental agricultural policies and programs, and targeted interventions in fostering youth agripreneurship as a driver for sustainable economic development in Nigeria. Accordingly, the paper analyzes the effectiveness of existing programs, policies, and institutional frameworks designed to support young people's engagement in the agricultural sector. Therefore, having identified and reviewed the best practices, gaps, and areas for improvement in policy design and implementation, it was however noticed that some key areas such as access to finance, land access, skills development, market access, and technology transfer need to be refocused. Hence, it concludes by offering specific policy recommendations to strengthen the enabling environment for youth agripreneurship and maximize its contribution to Nigeria's sustainable economic development, among others.

Keywords— Youth Agripreneurship, Driver, Sustainable, Economic Development, Nigeria, Agricultural entrepreneurship, Youth empowerment, Food security, Policy, Unemployment, Rural development.

I. INTRODUCTION

The current global economic crisis has forced many nations, including Nigeria, to consider unconventional approaches to economic diversification. Population growth, climate change, the COVID-19 pandemic, and violent conflicts are some of the main causes of this economic crisis (Iwuagwu, 2021). Because the world is committed to achieving the Sustainable Development Goals (SDGs) of the United Nations by 2030, especially goals 1 and 2 (reducing poverty and hunger) and the eighth goal, which points to sustainable economic development, the trend of economic diversification has therefore been a major source of concern among these countries. Nigeria, one of the most troubled economies in the world, has been rocked by its over-reliance on oil as a monoculture; therefore, a strong economic diversification plan is essential, according to Donatus et al. (2019). According to Isukul et al. (2019), human capital development is crucial for substantial economic diversification in a country like Nigeria.

Before gaining independence, Nigeria's economy was based on agriculture and had a strong GDP and foreign exchange, being the most populous black country in the world and the most densely populated country in Africa. When oil was discovered in the early 1970s, however, the nation ignored its thriving agricultural industry because of some political machinations (Onuka, 2017). Given that it is an agrarian country with about 85 million hectares of arable land, only less than 10% of which is under cultivation (NBS, 2015), Nigeria has the capacity to feed itself and export the excess for foreign exchange, but it still imports a lot of food (Ajekwe & Ibiamke, 2020). Nevertheless, despite the ongoing neglect, the sector is especially well-known for providing jobs, foreign exchange, and raw materials for industries, as well as meeting the nation's growing population needs without needlessly relying on the importation of necessities (Jamal et al., 2018).

According to Adeyanju (2017), the sector has also been reported by various researchers to hold high employment potentials (70%) for the populace, provided that it is supported by adequate investments and a conducive legal environment with

appropriate policy framework. Therefore, it is imperative to equip young people with entrepreneurial orientation in order to help themselves and become employers of labor in the future.

Undoubtedly, Nigeria has the capacity to actively contribute to its agricultural growth in order to achieve sustained food security and wealth creation, having a sizable youth population. However, these resources have not been harnessed and as such they experience a high unemployment rate as a result of limited options in their immediate doorsteps, which mostly leads to poverty (Kabiru et al., 2021). As a result, many of them turn to criminal activities such as kidnapping, banditry, armed robbery, political thuggery, and cybercrime in response to these immense problems, while others become depressed or hopeless (Surajo & Karim, 2016). Given this, the Nigerian National Bureau of Statistics (NBS, 2021) reported that the country's youth unemployment rate is 42.5%, which frequently leads to a variety of social ills in society as they become vulnerable to its detrimental effects, such as low self-esteem, a lack of skills, and poverty, which can result in the waste of vast human resources. Nonetheless, it is clear from the aforementioned submissions that encouraging young people to work together is crucial, especially in agriculture, which has historically had a low level of accommodation, so they can contribute their fair share to the long-term economic growth of our beloved country.

One promising way to solve the issues of unemployment, poverty, and food security in emerging nations including Nigeria is through youth agripreneurship. Young people benefit economically, socially, and psychologically from it, and it promotes sustainable development by fostering innovation and employment creation (Subhiksha & Vennila, 2024). In line with the foregoing, Ouko et al. (2022) believed that young people's involvement in agribusiness may boost food production and address unemployment, especially in rural areas where a large population is always assumed. However, a large number of educated young people thought that agriculture was an unappealing job choice because they associated it with antiquated methods and an unfavorable way of life (Ajekwe & Ibiamke, 2020). A multi-stakeholder approach is required to dispel these misconceptions and encourage youth involvement in agripreneurship, as will the provision of entrepreneurial education, training, start-up capital, and the establishment of agricultural incubation centers (Ouko et al., 2022). The development of human capital and the resolution of problems such as corruption and poor planning are essential to the nation's capacity to reap the benefits of its population (Pontianus & O.E.D, 2021).

Sustainable economic development, according to Kruja (2013), refers to a key idea for the twenty-first century which seeks to satisfy current needs without endangering the capacity of future generations to satisfy theirs. Additionally, the concept integrates economic, social, and environmental performance with an emphasis on human welfare and fair economic growth distribution. Thus, this can play a major role in achieving sustainable economic development in Nigeria, especially by engaging the youth in agribusinesses who are the nation's engine room. Therefore, this paper aimed at reviewing the role of youth agripreneurship in driving sustainable economic development in Nigeria, putting into consideration the challenges and opportunities.

II. CONCEPTUAL FRAMEWORK

2.1 Entrepreneurship

Entrepreneurship has several associative concepts such as: having an "entrepreneurial mind," an "entrepreneurial spirit," "being passionate about one's undertaking," "taking financial risks in the hope of making profit," "bringing about beneficial innovations and creative transformations," "increasing productivity"; "creating employment for self and others," "making improvements to one's standard of living in an economy," "eradicating poverty through legal and socially acceptable means," among others. Therefore, agricultural entrepreneurship/agripreneurship results from the associative concepts and ideas of entrepreneurship that are applied to agriculture. Hence, the concept of agripreneurship, according to Nwibo et al. (2016), is perceived to be the combination of agriculture and business in a profitable way. It is however, considered a process of determining the farmers' creativeness, imaginative capacity, preparing them to take calculated risks, and constantly looking for methods to enhance and extend their farm business to make money/profit. In the same vein, SIANI (2017) viewed agripreneurship as an effective way of getting rid of poverty or its reduction as it enables farmers to produce surpluses for sale and can involve the whole value chain, hence, sustaining food production.

Therefore, those who undertake business activities within the agricultural value chain with an entrepreneurial spirit are agricultural entrepreneurs/agripreneurs. In that regard, agripreneurs are those set of people who will initiate and accelerate transformative agricultural changes that raise productivity to a level of reducing real food prices, yet boosting rural incomes and creating jobs, and making financial profit from performing the activity or activities in any stage(s) of the agricultural value chain.

III. OVERVIEW OF THE AGRICULTURAL SUPPORT PROGRAMMES IN NIGERIA

In an effort by the government of the Federal Republic of Nigeria to reduce youth redundancy by boosting their productive capacities and to make them self-reliant, several agricultural empowerment programs have been put in place. These programs include; Farm Settlement Scheme (FSS) of 1967, National Accelerated Food Production Programme (NAFPP), 1972, Nigeria Agricultural and Cooperative Bank (NACB), 1973 to date (now Bank of Agriculture), Agricultural Development Programme (ADP), 1975 to date, Operation Feed the Nation (OFN), 1976 to 1979, River Basin Development Authority (RBDA), 1977 to date, Green Revolution (GR), 1979 to 1983, Directorate of Food, Roads and Rural Infrastructure (DFFRI), 1988 to 1993, National Agriculture, Land Development Authority (NALDA), 1986 to date, National Agricultural Insurance Corporation (NAIC), 1987 to date, National Fadama Development Projects (NFDP), 1990 to date, Agricultural Transformation Agenda (ATA), 2011 and Anchor Borrowers' Program of the Central Bank of Nigeria 2015 to 2021 (Cokes et al., 2017). Growth Enhancement Support Scheme (GESS) provides subsidized inputs to small-scale farmers, enhancing farm output despite challenges like politicization and delayed input delivery (Michael et al., 2018). The Nigeria Incentive-Based Risk-Sharing System for Agricultural Lending (NIRSAL) aims to de-risk agricultural lending, while the Agricultural Transformation Agenda Support Program focuses on infrastructure improvement and job creation (Ntukidiem Inimfon Imaenyin, 2015).

In addition to that, non-governmental organizations and other philanthropic sets of individuals also keyed into these empowerment programs by empowering the youth with different sets of agricultural skills with the aim of making them important personalities in the society. Similarly, a replica of such a program was carried out by the TETFund Center of Excellence for Teaching Agribusiness Skills at FCE, Yola, for a period of one month. Where participants were trained in different agricultural skills such as poultry, feed formulation, crop production, fish farming, etc. and were all given a stipend as a start-up and equally certificated.

However, given the above overview of the bold steps taken by several governments in power, individuals and government affiliates to see to the youth capacity development toward increased food production in the country and, by extension, economic development sustainability of the country. Still, the rate of youth unemployment is on the increase in the country, with its attendant massive food insecurity and poverty among the populace. Therefore, this advocates urgent need for more effective policies and programs that can engage young people in meaningful agricultural practices. By fostering innovation and providing access to resources, governments can empower the youth to become active contributors to both food security and economic stability.

IV. ROLES OF YOUTH AGRIPRENEURSHIP ON SUSTAINABLE ECONOMIC DEVELOPMENT

A promising approach to fostering sustainable economic growth and national development is empowering young people in agribusiness, which blends entrepreneurship and agriculture (Arumugam & Manida, 2023; Subhiksha & Vennila, 2024). Arumugam and Manida added that by encouraging eco-friendly behaviors and boosting regional economies, agriprenurship aligns with sustainable development objectives. Furthermore, it encourages creativity and the development of societal value by empowering young people to create their own employment possibilities (Subhiksha & Vennila, 2024). To ensure the successful implementation of the aforementioned programs, they also suggest a multi-stakeholder approach that incorporates government assistance, entrepreneurial education, and start-up capital. These, however, are in line with the conclusions of Ouko et al. (2022), who pointed out that young people's involvement in agribusiness has the potential to boost food production and lower poverty in the Kenyan Republic. They went on to say that by encouraging youth agriprenurship, nations have a better chance of advancing towards achieving sustainable development goals and converting smallholder agriculture into a contemporary, economically focused industry.

Based on the foregoing, recent research emphasizes the value of young people's orientation in agriprenurship, showing that youth intentions to pursue agriprenurship are positively influenced by favorable economic perspectives of agriculture, secondary school agricultural instruction, and financial support (Magagula & Tsvakirai, 2020). Agribusiness, according to Radha & Renjini (2019), includes, among other things, horticulture, dairying, apiculture, poultry, food processing, feed formulation, snailry, and nursery farming which particularly are highly profitable. Additionally, it has been demonstrated that agricultural training initiatives, like Nigeria's Fadama Graduate Unemployed Youth and Women Support (GUYS) greatly enhance young agripreneurs' success as indicated by their average revenue from agribusiness ventures (Adeyanju et al., 2021).

Unemployment causes a lot of societal issues, and young people are particularly susceptible to its negative impacts, which include poverty, marginalization, low self-esteem, a lack of skills, and the waste of vast human resources (Obayelu, 2019). Therefore, these unemployment issues can be handled by empowering and training youth through agricultural development

programs. Through agricultural entrepreneurship, they will be able to work as independent contractors or employers in the agricultural industry and earn money on their own (Agu, 2013). Nwibo et al. (2016) stated that the problem of underemployment, unemployment, and disguised employment has created a gap between the "haves" and "have nots" in the population, which must be closed and as such agribusiness can play a vital role. Agripreneurship is the outcome of a shift in agriculture's perception as an enterprise that combines entrepreneurship with agriculture (Uche, 2018). The agriculture sector's reform will contribute to eradicating the negative perception of poverty that industrialization has produced. The majority of countries have been burdened by the issue of unemployment, which this will help to resolve (Ripoll et al., 2017).

However, given the foregoing, a similar program may help our young people become more productive, which would contribute to the nation's long-term economic growth. This method encourages creativity and entrepreneurship in addition to equipping youth with the required abilities and information. We can build a more robust economy that benefits all by investing in their potential. Additionally, cooperation among the public and private sectors will be essential in supplying the tools and assistance required to develop this talent. By working together, we can create a strong foundation that supports lifelong learning and adjusts to the constantly shifting needs of the labor market.

V. CHALLENGES OF YOUTH PARTICIPATION IN NIGERIA'S AGRICULTURAL SUPPORT PROGRAMMES

Although several opportunities exist in youth agripreneurship, internal and external barriers hinder its success among the youth. As such, they often find it difficult to effectively participate in the programs designed and implemented by both the government and non-governmental organizations with the sole aim of making them productive, hence, accelerating the country's food production capacities for sustainable economic development. According to Ouko et al. (2022), these challenges include; negative perception of agricultural activities, lack or inadequate skills, limited access to infrastructure, lack of access to land, finance, and information, networking and mentoring, insufficient market information, negative effects of climate change, low levels of value-addition, inadequate policies supporting youth agripreneurship, and poor markets.

According to Afande et al. (2015), most farmers have trouble getting loans from financial institutions because they don't have the collateral that the lenders require. As a result, young people, especially those from rural areas, are never able to get the money they need, which limits their ability to invest in agriculture (FAO, 2014). Because of this, young people are always dependent on traditional finance sources like friends, family, clubs, support groups, etc. for saving and lending, or on contractor loans for insurance or agricultural inputs (Demirguc-Kunt et al., 2015).

Another challenge is the negative perception of agricultural activities among the said youth. This is seen as one of the most difficult challenges in Nigeria, where the youth, particularly those in urban areas, perceived agriculture as a venture for the less privileged individuals (Ajekwe & Ibiamke, 2020). Rural residents, who make up a greater portion of the nation's youth, frequently migrate to cities in search of better opportunities, if applicable. According to Okello (2014), in the majority of Sub-Saharan African nations, schools penalize students with agricultural tasks, which exacerbates their unfavorable opinion. In their contribution, Mugisha & Nkwasiabwe (2014) provided a very good example of Uganda, where youth still find agricultural-related activities unappealing in part because schools employ them as a form of discipline and reprimand for misbehavior. By implication, this influences how young people view agribusiness and may lessen their excitement for it.

Youth engagement in agripreneurship is hampered by inadequate policies. According to a 2018 United Nations report, young rural women's and men's opinions are frequently ignored by the appropriate authorities, which mostly leads to subpar execution of the agricultural policy-making process in the SSA. Youths also often miss out on involvement in policy forums due to a lack of negotiation strength and experience. Laxity and a failure to engage young people have been seen as a deterrent to promoting agriculture (World Bank, 2016). Geza et al. (2022) also discovered that youth participation in agricultural and rural development projects is restricted by a lack of inclusivity in the creation and application of policies.

The land tenure system is another factor contributing to the youth's distaste for agriculture, and it still plagues the majority of African youth. While some young people are interested in engaging in agricultural ventures, their hopes are frequently dashed by the country's rigid tenure system. To support the aforementioned, Njeru & Gichimu (2014) believed that land is a valuable resource in agriculture, and that having access to it encourages one to work in the field. According to Justine et al. (2012), while parents typically hold the title to land for agricultural production, youths may also have access to small parcels of land that are unsuitable for commercial and large-scale agriculture. As a result, policymakers must immediately devise strategies to support and facilitate youths' access to land.

Another problem identified with encouraging youth agripreneurship is a lack of expertise. According to Gitau, as mentioned in Ouko et al. (2022), most young people are receptive to new ideas and are able to try out new methods, therefore they can overcome the majority of the obstacles that agricultural production faces. They can utilize their thoughts to guide the adoption of new technologies, pest management, and genetic enhancement in order to increase agricultural productivity. Upon discovering that the young people engaged in agriculture are rural and less educated, Addo (2018) argues that youth involvement in the agro-food system should be more inclusive.

VI. CONCLUSION

The paper concludes that, considering the position occupied by the youth in our immediate societies and the role they can play for the economic development of the nation if empowered, youth agripreneurship will not just be looked at as a mere solution to youth unemployment; but a strategic pathway to building a resilient and diversified economy in Nigeria. Therefore, empowering young people to become innovators and leaders in the agricultural sector can help the nation to address her critical challenges such as food insecurity, poverty, and climate change, among others.

However, sustainable economic development hinges on the ability to create an ecosystem that supports youth agripreneurs, fostering innovation, promoting sustainable practices, and ensuring equitable access to resources. Moving forward, a collaborative approach involving government, private sector, academia, and civil society is essential to cultivate a thriving youth-driven agricultural sector that contributes to Nigeria's long-term prosperity and sustainable development goals—a quest for all the members of the United Nations.

VII. RECOMMENDATIONS

The paper puts forward the following recommendations:

- 1) **Youth Reorientation:** Youth should be reoriented on the embedded benefits of agricultural profession to them and to the society at large.
- 2) **Youth Inclusion in Policy:** Efforts should always be made in integrating views of the youth in drafting, implementing, monitoring, and evaluating the policies and programs related to agriculture.
- 3) **Dedicated Youth Agripreneurship Fund:** The need to create a specialized dedicated fund for youth agribusinesses with accessible financing.
- 4) **Constant Training and Mentorship:** The need for implementing constant practical trainings and mentorship programs for skill development among the youth as well as follow-up by the officials.
- 5) **Secure Land Access:** Simplify the bureaucracy for land access and tenure for young farmers.
- 6) **Digital Agriculture Promotion:** Expand technology adoption particularly among the rural populace where agricultural activities are given more priorities.
- 7) **Strengthen Market Linkages:** Improve market access and value chain development within which the young aspiring agripreneurs can showcase their entrepreneurial skills.
- 8) **Supportive Policy Framework:** There is also the need to create enabling policies and regulations for youth agripreneurship to thrive.
- 9) **Monitoring and Evaluation:** Establish robust monitoring and evaluation frameworks to track the effectiveness of youth agripreneurship programs.
- 10) **Public-Private Partnerships:** Foster partnerships between government, private sector, and civil society to support youth agripreneurship initiatives.

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CONFLICT OF INTEREST

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Effects of Storage Methods on Lesser Grain Borer (*Rhyzopertha dominica*) during Rice (*Oryza sativa*) Storage in Yola, Adamawa State-Nigeria

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Abstract— This study aimed to assess the effectiveness of some storage methods in controlling the effect of Lesser Grain Borer (LGB) on rice quality during storage. The experiment consisted of four treatment storage methods and laid in a Completely Randomized Design (CRD). Ten unsexed adults LGB were then introduced into a jar containing 200 g of rice grains and kept for 7 days under ambient conditions. Data were collected on the percentage mortality, weight loss, and 100 seeds weight loss and were analyzed using Analysis of Variance (ANOVA) and SAS (Statistical software version 9.0) and means were separated using Least Significant Difference (LSD) at a five percent level of significance ($P \leq 0.05$). Percentage weight loss was impacted by the storage method in a highly significant ($P \leq 0.01$) and floor storage gave the highest percentage weight loss of 9.12% whereas metallic and plastic containers had the lowest percentage weight loss (5.57% and 4% respectively). Similarly, it affected adult mortality of the lesser grain borer in a highly significant ($P \leq 0.01$) with highest number of dead insects at 21 days (5.33 from jute bag and 4.67 from metallic jar). However, at 21 days, mortality was also highly significant ($P \leq 0.01$) and polythene bag gave the highest value of 2.67 while lowest value was recorded of 0.00 floor storage. Plastic containers is the best for reducing percentage weight loss during storage of rice while polyethylene, plastic and metallic containers are the best for controlling Lesser Grain Borer during rice storage..

Keywords— Lesser Grain Borer, *Rhyzopertha dominica*, *Oryza sativa*.

I. INTRODUCTION

Rice (*Oryza sativa*) is an essential component of the diet of many people (Divyasree and Yadav, 2023) and it was estimated that half of the world's population subsists partly or wholly on rice (Karunakaran et al., 2004; Chougourou et al., 2013; Nehemiah et al., 2020; Pungavil et al., 2023). The byproducts are also used as animal feed, oil extraction, and manufacture of glass, solar panels, construction materials, biofuel, paper products, and flour (Nehemiah et al., 2020; Wastex, 2022). Broken rice grains are used for the distillation of alcohol and in the production of laundry starch. Traditionally, rice grains are stored in granaries, either in the threshed or uncherished forms. These traditional methods exposed stored grains to pest infestation.

Pest infestation in the field and during storage has greatly reduced the production of rice. In Nigeria, pest infestation plays a key role in keeping cereal production below the quality and quantities demanded by an increasing population and rapidly expanding livestock industry (Jia et al., 2008). The Lesser Grain Borer (LGB) (*Rhyzopertha dominica*) is a major cosmopolitan pest affecting stored rice the world over (Chougourou et al., 2013). A survey on the incidence of major pests of rice in different agro-ecological zones of Nigeria showed in general, that the amount of damage caused by LGB was high (Soto et al., 1976; Chougourou et al., 2013; Suleiman et al., 2020). It also shows that both the larvae and adult stages of this insect devour the kernel, causing weight loss (Johnson, undated; Ahmad et al., 2021).

Different methods such as safe handling practices to avoid mechanical damage, cold and modified storage atmosphere, application of chemical pesticides, biocontrol agents botanicals and UV-C treatment have been used to control postharvest losses of produces as reported by Al-Hdhrani et al. (2023) but due to lack of knowledge or cost had made them unavailable. Planting of resistant varieties has been reported to be effective in the control of insect pest as reported by Kumar and Kalita (2017); and Chougourou et al. (2013) that resistant rice varieties IIA306 and American Lamonant inhibited LGB infestation. The most important and commonly used control measure is chemical control (Ahmad et al., 2021). This involves the use of synthetic chemicals such as primoplosmethy (Acetelic), permitri (Copera), etc. which are effective in controlling lesser grain borer (Agunbiade et al., 2009; Ahmad et al., 2021).

Although the use of synthetic chemical insecticides is a powerful tool against insect pests, the indiscriminate use of different conventional insecticides by farmers and marketers has led to the development of resistance and a resurgence in some insect pests (Ahmed et al., 2024). For example, it was documented that LGB showed resistance to deltamethrin (Ceruti and Lazzari, 2003; Ahmad et al., 2021). Insecticide resistance and the consequent losses of food arising from the failure of chemicals to control pests have caused economic losses of several billion dollars worldwide each year (Elzen and Hardee, 2003; Nehemiah et al., 2020) in addition to its harmful effects on both the environment and human beings.

The control of pests using synthetic insecticides has its attendant problems which include high cost of procurement, unavailability at critical periods, and may pose health hazards to men and livestock (Pungavil et al., 2023). The use of these synthetic chemicals in the control of stored products is of global concern concerning environmental hazards, chemical residues in foods, side effects on non-target organisms, resistance development, etc (Pungavil et al., 2023).

The present policy of the Federal Government of Nigeria encourages the attainment of self-sufficiency may not be achieved due to postharvest loss which constitutes one of the main obstacles to ensuring food security (Al-Dairi et al., 2021). Sustainable rice production can only be realized if affordable and effective means of storage are achieved (Otitodun et al., 2017; Pungavil et al., 2023). One of the most important problems facing rice farmers in the country is that of lesser grain borer due to a lack of enough research to find a safer and cheaper method. This is poised to address this problem, by seeking a cheap, safe, and effective method for reducing postharvest losses caused by LGB. This study, therefore, was carried out purposely to determine the effectiveness of the various storage methods in reducing the effect of LGB on rice quality.

II. MATERIALS AND METHODS

The experiment was conducted at the Postharvest Technology Laboratory of the Department of Crop Production and Horticulture, Modibbo Adama University of Technology, Yola located between Latitude 9°11'N, 9°19'N and Longitude 12°20'E and 12°31'E (Adebayo and Tukur, 1999). The paddy rice Faro 44 variety used for the study was obtained from Adamawa State Agricultural Development Programme (AADP) Yola, Adamawa State.

The experiment consisted of four treatments (storage methods), namely; [floor (control), jute bag, polythene bag, plastic jar, and metallic jar] and was replicated three times in a Completely Randomized Design (CRD) in the Laboratory. Adult LGB was obtained from infested grains in the Yola grain market. This was reared on a susceptible rice variety (Faro 44) and later introduced into a transparent jar. Disinfection was achieved by drying for an hour at 60°C. Ten unsexed adults were then introduced into a jar containing 200 g of rice grains. The jar was covered with 10 mm mesh muslin cloth to allow for ventilation and also to prevent insects from escaping while the weevil was safely kept at room temperature (35±2 °C) and relative humidity (65–85%).

The jar was kept for 7 days after which the required quantity of the LGB was obtained and kept under laboratory conditions until all F1 progeny emerged and was harvested for the experiment as reported by Abebe et al. (2009).

2.1 Data Collection

Data were collected on the following parameters.

2.1.1 Percentage Mortality

This was done by emptying each container on a piece of white cloth separating both dead and live weevils in each container physically counting the dead insects then expressed in percentage using equation 1.

$$\text{Percentage mortality} = (Ti - Li)/Ti \times 100 \quad (1)$$

Where Ti = Total number of insects both live and dead; Li = number of live insects.

2.1.2 Percentage Weight Loss of Seeds

One hundred seeds were randomly taken at the end of the storage period (21 days) and the number of damaged seeds was then assessed. This was done by expressing the seeds damaged as a percentage of the total number of seeds sampled. Weight loss was then determined using Equation 2.

$$\text{Percentage weight loss} = [(Wu \times Nd) - (Wd \times Nu) \div Wu(Nd + Nu)]100 \quad (2)$$

Where: Wu = weight of undamaged seed; Wd = weight of damaged seed; Nu = Number of undamaged seed; Nd = Number of damaged seed.

2.2 Data Analysis

Data collected was subjected to Analysis of Variance (ANOVA) using SAS Software (Version 9.0) and means were separated using Least Significant Difference (LSD) at a five percent level of significance ($P \leq 0.05$).

III. RESULTS AND DISCUSSION

3.1 Effect of Storage Methods on Percentage Weight Loss of Rice Grain Caused by Lesser Grain Borer

The storage method had a significant ($P \leq 0.05$) influence on 100 seed weight of rice grain caused by lesser grain borer as depicted in Table 1. The various methods of storage used revealed that floor storage gave the highest percentage weight loss of 9.12% then followed by polythene bags which recorded 6.49% weight loss. Whereas metallic and plastic containers had the lowest percentage weight loss (5.57% and 4% respectively) are statistically the same.

TABLE 1
PERCENTAGE WEIGHT LOSS OF RICE AFTER INFESTATION WITH LESSER GRAIN BORER

Storage method	Weight loss (%)	Weight of 100 seeds (g) (before)	Weight of 100 seeds (g) (after)
Floor	9.12	2.333	2.567
Jute bag	6.93	2.367	2.6
Polythene bag	6.49	2.2	2.6
Plastic container	5.57	2.433	2.537
Metallic container	4	2.267	2.767
P of F	0.001	0.067	0.027
LSD	1.867	0.367	0.23

Both plastic and metallic containers had the best percentage of weight loss during the study because they provided hermetic storage conditions by cutting off the supply of oxygen to both the produce and weevils inside the containers thereby asphyxiating the pests. This finding is in line with that of Kumar and Kalita (2017); Suleiman et al. (2020) and Abdulazeez et al. (2023) who reported that scientific storage methods such as air-tight containers can reduce postharvest grain losses to as low as 1%–2%.

3.2 Effect of Storage Methods on Mortality of Lesser Grain Borer

From the result obtained, the storage method affected adult mortality of the lesser grain borer on rice in a highly significant ($P \leq 0.01$) way as illustrated in Table 2. Number of dead insects at 7 and 14 days were highly significant ($P \leq 0.01$). The maximum mean recorded for insects dead at 7 days was 6.00 for polyethylene bag and 5.67 for plastic container while the minimum value of 0.00 occurred in floor storage. However, at 14 days, mortality was highly significant ($P \leq 0.01$) on insect mortality with the polythene bag giving the highest value of 2.67 for most of the containers (metallic, plastic and jute) whereas floor storage recorded zero mortality. At 21 days, the highest adult mortality value was recorded against jute bag (2.33) whilst floor storage had the lowest value (0.00).

TABLE 2
MORTALITY OF LESSER GRAIN BORER

Storage method	Storage Period (Days)		
	7	14	21
Floor	0	0	0
Jute Bag	4.67	2.67	2.33
Poly. Bag	6	2.33	1.67
Plastic	5.67	2.67	1.67
Metallic	5.33	2.67	1.67
P of F	0.001	0.021	0.021
LSD	1.993	1.485	1.485

These findings could be due to the hermetic effect of the storage methods in question which asphyxiate the insects inside the container while the floor storage allow the insect to escape to safer hiding places as reported by Kumar and Kalita (2017); Ahmad et al. (2021).

IV. CONCLUSION

It can be concluded from the results obtained in this study, that plastic containers is the best for reducing percentage weight loss during storage of rice while polyethylene, plastic and metallic containers are the best for controlling Lesser Grain Borer during rice storage. Farmers in the study area can therefore adopt it as an eco-friendly and low rice storage method.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Space Horticulture as a Green Shield: Life Force Foods and the Vedic Nexus for Deep-Space Astronaut Sustenance

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Abstract— Sustaining human crews through multi-year interplanetary missions demands a food and life-support paradigm that extends far beyond calorie provisioning. This review synthesizes the emerging discipline of Space Horticulture — defined as the sovereign confluence of plant science, survival engineering, and human sustenance dedicated to nourishing, healing, and psychologically anchoring astronauts across long-duration deep-space journeys — and situates it within contemporary aerospace bioregenerative research, plant stress physiology, and ancient Vedic nutritional philosophy. Drawing on internationally established programmes, including the National Aeronautics and Space Administration (NASA) Veggie and Advanced Plant Habitat platforms, the NASA Deep Space Food Challenge, the European Space Agency (ESA) Micro-Ecological Life Support System Alternative (MELiSSA), and the Indian Space Research Organisation (ISRO) Compact Research Module for Orbital Plant Studies (CROPS), the paper traces the transition from mechanical life-support hardware toward closed-loop, bioregenerative ecosystems. It further reviews recent empirical evidence on plant physiological responses to microgravity, altered gravity, and ionising radiation; the emergence of duckweed (*Wolffia* spp.) as a rapid-cycle protein crop; comparative water-use efficiency of aeroponic and hydroponic cultivation; lunar and Martian regolith bio-conditioning strategies; the documented psychological benefits of crew horticultural activity; and the radioprotective role of dietary phytochemicals. The review then presents, in detail, the author's own three-dimensional (3D) printed nutrient-delivery research reported in the Dr. Jadala Shankaraswamy's book, *Space Horticulture* (Narendra Publishing House, 2026, ISBN 978-93-7763116-1) — believed to be the first global attempt at fabricating plant-based, fast-dissolving oral dispersible films (ODF) from shelf-stable powders of underutilised ethnic vegetables, namely Spine Gourd (*Momordica dioica*), Chekurmanis (*Sauropus androgynus*), and Alternanthera (*Alternanthera sessilis*), bound with Moringa gum and stimulated by Roselle (*Hibiscus sabdariffa*) calyx powder. The films demonstrated a saliva dissolution time of 115.55 ± 2.00 seconds, tensile strength of 1.394 ± 0.06 kg/mm², swelling index of $43.68 \pm 2.55\%$, and were characterised by High-Resolution Liquid Chromatography-Mass Spectrometry (HR-LCMS) to contain 136 bioactive phytochemicals, Inductively Coupled Plasma Mass Spectrometry (ICP-MS) confirming 11 essential minerals, and Mass Spectrometry Quadrupole Time-of-Flight (MS-QTOF) profiling identifying 17 amino acids. These findings are interpreted as a mucosal, crumb-free nutrient delivery route uniquely suited to countering microgravity-induced gastrointestinal ('space-gut') malabsorption while simultaneously supplying radioprotective phytochemical load. The review concludes with a forward look toward lunar and Martian horticultural infrastructure including regolith bio-conditioning, aeroponic and hydroponic cultivation, robotic 3D-printed habitat construction, and India's Bharatiya Antariksha Station and Vision 2047 roadmap — arguing that the fusion of Vedic Prana-centred nutritional philosophy with cutting-edge additive food-manufacturing technology and validated plant-stress science constitutes a credible and culturally-rooted pathway toward Earth-independent, psychologically resilient deep-space food systems.

Keywords— *Space Horticulture; Bioregenerative Life Support System (BLSS); 3D-Printed Oral Dispersible Films; Life Force Foods (Prāṇa); MELiSSA; Deep Space Food Challenge; Lunar Regolith; Radioprotective Phytochemicals.*

I. INTRODUCTION

As crewed exploration extends from low-Earth orbit toward the Moon and Mars, mission durations expand from months to years, rendering the pre-packaged, freeze-dried food paradigm of the twentieth century increasingly untenable [1], [2]. Stored space food undergoes progressive degradation of heat-sensitive vitamins, palatability, and psychological acceptability over multi-year transit, a limitation now widely recognised across the astronaut nutrition literature [1]–[3]. In response, space agencies have shifted strategic emphasis from carrying finite food inventories to cultivating living, self-renewing biological systems — a transition this review terms the movement from 'picnic basket' logistics to 'cosmic farming'.

Space Horticulture, as proposed and defined in the Dr. Jadala Shankaraswamy's book *Space Horticulture: A Future Green Shield with Life Force Foods* (Narendra Publishing House, 2026, ISBN 978-93-7763116-1), is "the emerging, sovereign, and irreplaceable discipline at the confluence of plant science, survival engineering, and human sustenance ... with the singular and non-negotiable purpose of sustaining, nourishing, healing, and psychologically anchoring the human crew across the entirety of long-duration interplanetary missions" [4]. This definition deliberately positions horticulture not as a supplementary comfort but as a life-critical subsystem furnishing oxygen regeneration, water purification, medicinal compounds, and — through the Vedic lens explored later in this review — a tether of psychological and spiritual continuity with Earth [4].

This review has three integrated objectives. First, it consolidates the current state of bioregenerative life-support and space-crop cultivation research, spanning NASA's Veggie and Advanced Plant Habitat (APH) systems, the NASA Deep Space Food Challenge, ESA's MELiSSA closed-loop ecosystem, and ISRO's CROPS experiments [5]–[11]. Second, it expands the evidentiary base by reviewing recent peer-reviewed findings on plant physiological responses to microgravity and radiation [12]–[15], candidate rapid-cycle protein crops such as duckweed [20]–[22], comparative soilless cultivation efficiency [32], [33], lunar/Martian regolith bio-conditioning [29]–[31], the documented psychological benefits of crew horticultural engagement [23]–[25], and the radioprotective function of dietary phytochemicals [26]–[28]. Third, and centrally, it extracts and critically discusses the author's original three-dimensional (3D) food-printing research on plant-based oral dispersible nutrient films, together with the accompanying Vedic 'Life Force Foods' framework, projecting both toward future lunar and Martian applications in line with India's Vision 2047 space exploration roadmap [4].

While the integration of Vedic philosophy with space horticulture is a distinctive cultural contribution, it should be noted that this framework is presented as a conceptual and philosophical scaffold requiring empirical validation. The review distinguishes between the established peer-reviewed literature (Sections 3-5) and the author's original research (Section 6), which is currently documented in the author's monograph and presented here as a proof-of-concept requiring independent validation.

II. REVIEW METHODOLOGY

This is a narrative-integrative review. Primary source material was drawn from the author's book *Space Horticulture: A Future Green Shield with Life Force Foods — A Narrative Vedic Nexus to Sustain Astronauts on Deep Space Journeys* (Narendra Publishing House, New Delhi, India, 2026, ISBN 978-93-7763116-1) [4], which compiles the author's original 3D-printed nutrient film research alongside a synthesis of international bioregenerative life-support literature and Vedic physiological philosophy. The book was subjected to editorial review by the publisher but has not yet been independently peer-reviewed in a scientific journal.

This material was cross-verified and substantially extended through a supplementary literature search of peer-reviewed journals (2020–2026) and institutional space-agency sources covering: (i) NASA plant-growth hardware and challenge programmes [5]–[7]; (ii) ESA's MELiSSA programme [8], [9]; (iii) ISRO's CROPS module [10], [11]; (iv) plant physiological and molecular responses to microgravity, altered gravity, and ionising radiation [12]–[15]; (v) the 3D/4D oral-film drug and nutrient delivery literature [16]–[19]; (vi) duckweed (*Wolffia* spp.) as an emerging space protein crop [20]–[22]; (vii) empirical studies of astronaut psychological response to horticultural activity [23]–[25]; (viii) the radioprotective role of dietary phytochemicals and antioxidants [26]–[28]; and (ix) lunar/Martian regolith bio-conditioning and comparative soilless cultivation efficiency [29]–[33].

Literature Search Strategy: The supplementary literature search was conducted using Web of Science, Scopus, and Google Scholar with search terms including "space horticulture," "bioregenerative life support," "MELiSSA," "Veggie," "Advanced Plant Habitat," "microgravity plant physiology," "duckweed space protein," "regolith bio-conditioning," and "space nutrition." The search was restricted to peer-reviewed English-language publications from 2020 to 2026. Grey literature and conference abstracts were included only if they had been subsequently published as peer-reviewed articles.

Inclusion and Exclusion Criteria: Studies were included if they: (1) addressed plant growth, life support, or nutrition in spaceflight or space-analogue contexts; (2) presented original empirical data, systematic reviews, or validated models; (3) were published in peer-reviewed journals or official space agency technical reports. Studies were excluded if they addressed terrestrial agriculture without spaceflight relevance or were not available in English.

Numerical and analytical results reported for the author's ODF research (dissolution kinetics, tensile strength, swelling index, HR-LCMS, ICP-MS, and MS-QTOF profiling) are reproduced as documented in the author's book [4] and presented here as preliminary findings requiring independent validation.

III. FROM MECHANICAL LIFE SUPPORT TO BIOREGENERATIVE ECOSYSTEMS

3.1 NASA Veggie and the Advanced Plant Habitat (APH)

NASA's Vegetable Production System ('Veggie') is a compact, low-resource space garden employing clay-based 'plant pillows' pre-loaded with slow-release fertiliser to manage root-zone water and nutrient delivery under microgravity [5], [6]. Veggie has demonstrated successful on-orbit cultivation of 'Outredgeous' red romaine lettuce, 'Tokyo Bekana' Chinese cabbage, Mizuna mustard, and Red Russian kale aboard the International Space Station (ISS) [4], [6]. The Advanced Plant Habitat represents a substantially more automated successor: an enclosed, environmentally-controlled chamber instrumented with over 180 sensors and cameras and illuminated by tunable LED arrays (red 660 nm, blue 450 nm, far-red 730 nm, and infrared wavelengths) to optimise photosynthetic efficiency and enable detailed study of plant gene expression under spaceflight stress [4], [5]. Collectively, these platforms mark NASA's incremental transition from demonstrating that plant growth is possible in orbit to engineering production-scale, crew-interactive space gardens [4].

3.2 The NASA Deep Space Food Challenge

The NASA Deep Space Food Challenge, conducted in partnership with the Canadian Space Agency, is an international, multi-phase competition inviting innovators to design, build, and demonstrate food production technologies that are minimally resource-intensive yet maximally safe, nutritious, and palatable for missions of up to five years' duration, including transit to Mars [7]. The Challenge's 'Mars to Table' extension broadens participation to chefs and culinary innovators tasked with designing complete, Earth-independent food systems for the lunar and Martian surface [7]. This review situates the author's ODF research as directly responsive to the Challenge's core mandate: shelf-stable, nutrient-dense, minimal-waste food technology suited to multi-year autonomy [4].

3.3 ESA's MELiSSA Programme

The European Space Agency's Micro-Ecological Life Support System Alternative (MELiSSA), initiated in 1989, is architected as a closed-loop, bio-industrial ecosystem that mimics terrestrial biospheric function through five interconnected compartments comprising microbial bioreactors, wet-oxidation units, filtration stages, and higher-plant chambers [8], [9]. The system is designed to recycle carbon dioxide, urine, and organic waste into breathable air, potable water, and edible biomass, forming what this review characterises as a 'mutually sustaining biological dyad' between human crew and cultivated plant/algal systems [4], [8]. MELiSSA remains the most systems-integrated closed-loop life-support demonstration to date and provides the conceptual scaffold for the 'Green Shield' framework discussed in Section 5 [4].

3.4 ISRO's CROPS Module

India's Compact Research Module for Orbital Plant Studies (CROPS), flown by ISRO, represents the nation's first orbital plant-growth experiment. Its initial mission (CROPS-1) successfully demonstrated germination and early two-leaf-stage growth of cowpea (*Vigna unguiculata*) seeds within four days aboard a PSLV orbital platform, validating baseline seed viability under spaceflight conditions [10], [11]. Future CROPS phases are intended to extend cultivation cycles to 30–45 days under active atmospheric control, positioning the programme as India's incremental pathway toward indigenous bioregenerative life-support capability in support of the planned Bharatiya Antariksha Station (BAS) [4], [10].

3.5 Plant Physiological Responses to Microgravity, Altered Gravity, and Ionising Radiation

A growing body of peer-reviewed evidence complements the platform-level findings above by clarifying the cellular and molecular mechanisms through which spaceflight stressors affect plant growth. Nie et al. review how altered gravity vectors perturb auxin distribution, cytoskeletal organisation, and gene expression across cellular, subcellular, and genetic levels, while confirming that plants remain capable of completing vegetative and reproductive cycles under sustained microgravity [12]. De

Micco et al. similarly conclude, from a decade of ISS and ground-analogue experimentation, that microgravity does not categorically prevent plant growth and reproduction but does induce measurable stress responses requiring targeted physiological countermeasures [13]. Maffei further demonstrates that partial-gravity environments such as lunar gravity can, counter-intuitively, exert more severe effects on cell proliferation than full microgravity, a finding with direct implications for lunar-surface cultivation design [14]. Arantes et al. extend this picture by systematically reviewing the combined effects of microgravity and ionising radiation on plant development, concluding that radiation exposure compounds microgravity-induced developmental stress through oxidative and genomic damage pathways [15]. Collectively, this literature substantiates the rationale, articulated in the author's book, for selecting and engineering crops with heightened antioxidant and phytochemical density as a biological countermeasure to the combined stressors of deep-space transit [4], [12]–[15].

IV. CROP SELECTION CRITERIA FOR DEEP-SPACE CULTIVATION

Across the reviewed platforms, candidate space crops are selected against four convergent criteria: nutritional density, rapid growth cycle, radiation and oxidative-stress resilience, and psychological value (texture, colour, and aroma diversity to offset the sensory monotony of long-duration missions) [4], [5], [12]–[15]. Leafy greens such as 'Outredgeous' lettuce, Red Russian kale, and spinach are prioritised for antioxidant density; dwarf cultivars including 'Red Robin' tomato and strawberries are valued for psychological morale and textural relief; and duckweed (*Wolffia* spp.) is highlighted as a high-priority protein source owing to its 2–5 day growth cycle and complete amino-acid profile [4]. This assessment is strongly corroborated by recent independent research: Romano et al. report that *Wolffia globosa* retains rapid growth and adaptive physiological responses under simulated altered-gravity conditions, confirming its viability as a space-agriculture candidate [20]. Venkatachalam et al. further characterise *Wolffia globosa* as an emerging plant-based protein source with an amino-acid profile competitive with conventional protein staples and a biomass doubling time of approximately 48 hours [21], while Ofoedu et al., in a broader food-security review, confirm duckweed's exceptional area-efficiency and protein yield relative to terrestrial crops, reinforcing its suitability for volume-constrained space-habitat cultivation [22]. The source monograph further nominates a set of nutritionally dense 'Life Force' crops — Moringa (*Moringa oleifera*), Amla (*Phyllanthus emblica*), turmeric (*Curcuma longa*), Spirulina, Holy Basil (*Ocimum sanctum*), and Roselle (*Hibiscus sabdariffa*) — selected specifically for their phytochemical vitality rather than caloric contribution alone [4]. This nutritional philosophy is elaborated in the Vedic framework discussed next.

V. THE VEDIC NEXUS: PRĀṆA, PANCHA MAHABHUTAS, AND THE 'GREEN SHIELD'

A distinguishing contribution of the author's book is its narrative synthesis of Vedic physiological philosophy with modern bioregenerative science. The Pancha Mahabhutas — the five classical elements of Earth (Pṛthvī), Water (Jala), Fire (Agni), Air (Vāyu), and Space (Ākāśa) — are invoked as a framework for understanding cellular and systemic health under the extreme physiological stressors of spaceflight [4]. Central to this framework is the concept of Prāṇa, or life force, which the book links to biophotonic vitality in fresh plant tissue — drawing on biophotonics research associated with Fritz-Albert Popp — and contrasts with the comparatively inert nutritional profile of long-stored, freeze-dried rations [4]. The book proposes that fresh harvests from bioregenerative systems such as MELiSSA, Veggie, or the APH constitute genuine 'Life Force Foods,' supplying a vitality that processed substitutes cannot replicate [4].

This philosophy is operationalised through the 'Green Shield' concept: a biological interface intended to extend beyond mechanical air and water recycling to actively supply phytochemical protection against cosmic radiation and microgravity-induced physiological decline, while simultaneously anchoring astronaut psychological wellbeing through cultivation ritual and sensory engagement with living plants [4]. The book additionally references a symbolic Sarvatobhadra Chakra (a traditional 9×9 Vedic astrological grid) and a seven-day Dhātu nutritional cycle mapping specific foods to the nourishment of plasma, blood, muscle, fat, bone, marrow, and vital essence (Ojas), proposed as a scheduling and psychological-support template for long-duration crews [4].

Scientific Basis and Validation of the Vedic Framework: It is important to acknowledge that the Vedic framework presented here is primarily a conceptual and cultural contribution rather than a validated clinical model. While the biophotonics literature provides some scientific grounding for the concept of biological vitality (Popp, 1980s), the direct translation of Prāṇa to biophotonic emission in fresh plant tissue remains an active area of investigation rather than established fact. Similarly, the Pancha Mahabhutas and Dhātu cycle represent philosophical constructs that may inform system design and crew psychological support, but they have not been empirically validated as nutritional or physiological interventions in the spaceflight context. The value of this framework lies primarily in providing a culturally-rooted, psychologically meaningful approach to astronaut

nutrition and wellbeing, and in generating testable hypotheses about the comparative benefits of fresh versus stored foods, the role of phytochemical diversity, and the psychological impact of structured nutritional rituals. These hypotheses warrant empirical investigation in future spaceflight and analogue studies.

5.1 Empirical Support for the Psychological Value of Space Horticulture

Independent of the Vedic framework, an emerging empirical literature now substantiates the psychological premise underlying the 'Green Shield' concept. Landon et al., analysing crew interaction with the ISS 'Pick-and-Eat' salad crop programme, report measurable behavioural-health benefits associated with both the act of caring for growing plants and the consumption of freshly harvested produce, including improved mood and a subjective sense of connection to Earth [23]. Earlier survey-based reporting on ISS crew experience similarly found that gardening activity was associated with reduced reported stress during long-duration increments [24]. Pagnini et al., reviewing psychological countermeasure tools for long-duration spaceflight more broadly, identify structured self-regulation and environmental-engagement practices — of which horticultural activity is a prominent example — as effective strategies for sustaining crew emotional resilience and focus during isolation and confinement [25]. These findings collectively provide independent empirical corroboration for the book's central thesis that space-grown food functions simultaneously as a nutritional and psychological life-support modality [4].

VI. ORIGINAL 3D-PRINTED NUTRIENT FILM RESEARCH

The centrepiece experimental contribution of the reviewed work, documented in the author's book *Space Horticulture* (Narendra Publishing House, 2026, ISBN 978-93-7763116-1) [4], is a first-of-its-kind fabrication of three-dimensional (3D) printed, plant-based, fast-dissolving oral dispersible films (ODF) intended as a space-adapted nutrient-delivery format. This section consolidates the reported methodology, formulation, characterisation results, and their rationale for spaceflight application. As noted in the methodology, these results are presented as preliminary findings documented in the author's monograph; independent peer-reviewed validation is currently being pursued.

6.1 Rationale: Addressing 'Space-Gut' and Microgravity Constraints

Long-duration microgravity exposure is associated with altered gastrointestinal motility and absorption efficiency, colloquially termed 'space-gut' in the author's book, as well as fluid-shift effects that dull taste perception [4]. Conventional solid or powdered supplements are further disfavoured in microgravity because loose crumbs pose inhalation and electronics-contamination hazards [4]. An oro-mucosal film that dissolves rapidly in the mouth, bypassing conventional digestive transit and partial first-pass metabolism, was therefore proposed as a targeted engineering response to both constraints [4], consistent with the broader pharmaceutical literature establishing ODFs as an efficient mucosal delivery route for active compounds [16]–[19].

6.2 Formulation and Fabrication

The films were formulated from shelf-stable powders of three underutilised ethnic vegetable species: Spine Gourd (*Momordica dioica*, locally 'Boda Kakarakaya'), Chekurmanis (*Sauropus androgynus*), and Alternanthera (*Alternanthera sessilis*, water amaranth) [4]. Moringa gum and Ghatti gum served as natural binders to preserve structural integrity during extrusion, while Roselle (*Hibiscus sabdariffa*) calyx powder was incorporated as a saliva stimulant to accelerate mucosal contact and dissolution [4]. Additional excipients reported include pharmaceutical-grade HPMC (hydroxypropyl methylcellulose), pullulan, glycerol as a plasticiser, and monk-fruit syrup as a natural sweetener [4]. Fabrication employed extrusion-based 3D printing, with the author's book additionally proposing a space-adapted printer specification using syringe-based cold extrusion (to preserve heat-labile vitamins C and B), nozzle diameters of 0.2–0.8 mm for ultra-thin film production, and stepper-motor-driven piston feed mechanisms as a microgravity-compatible substitute for gravity-fed ink delivery [4]. This fabrication approach is consistent with, and extends, established extrusion- and fused-deposition-based 3D printing methods documented in the pharmaceutical oral-film literature [16]–[19].

6.3 Characterisation Results

Reported physicochemical characterisation of the fabricated films is summarised in Table 1. The films exhibited a saliva dissolution time of 115.55 ± 2.00 seconds — reported as the fastest dissolution among comparator formulations in the underlying study — a tensile strength of 1.394 ± 0.06 kg/mm², a swelling index of $43.68 \pm 2.55\%$ indicative of favourable mucoadhesive behaviour, and a surface pH of 6.78 ± 0.28 , close to oral physiological pH [4]. Scanning Electron Microscopy (SEM) at 15,000 $\times$ magnification revealed a smooth, continuous film surface with a porous internal structure consistent with

efficient rehydration and disintegration [4]. Fourier-Transform Infrared (FTIR) spectroscopy identified characteristic absorption peaks at 3307.92 cm^{-1} (O–H stretching, attributable to polymeric and plant-phenolic hydroxyl groups), 2910.58 cm^{-1} (C–H stretching), 1028.06 cm^{-1} (C–O–C linkage, indicative of polysaccharide backbone), and a cluster at 1639.49 , 1624.06 , and 1492.90 cm^{-1} attributed to C=C vibrations consistent with flavonoid and anthocyanin presence [4].

Phytochemical profiling via High-Resolution Liquid Chromatography–Mass Spectrometry (HR-LCMS) identified 136 distinct bioactive compounds, comprising 18 alkaloids, 15 terpenoids, 14 phenolic compounds, 14 amino derivatives, 8 nitrogenous compounds, 3 flavonoids, and 2 saponins [4]. Mineral analysis by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) confirmed 11 essential minerals, with calcium, zinc, copper, iron, potassium, and magnesium present at the highest relative concentrations, alongside trace-level selenium, manganese, chromium, and cobalt [4]. Amino-acid profiling via Mass Spectrometry Quadrupole Time-of-Flight (MS-QTOF) analysis identified a total of 17 amino acids [4]. The films were packaged in aluminium-laminate blister packaging and are reported to retain potency for 3–5 years without refrigeration, remaining stable across a temperature range of $-20\text{ }^{\circ}\text{C}$ to $+40\text{ }^{\circ}\text{C}$ — a stability profile consistent with multi-year Mars-transit logistics requirements [4].

TABLE 1

SUMMARY OF PHYSICOCHEMICAL AND PHYTOCHEMICAL CHARACTERISATION OF THE 3D-PRINTED, PLANT-BASED ORAL DISPERSIBLE FILM (ODF) REPORTED IN THE AUTHOR'S BOOK [4]

Parameter	Reported Value
Saliva dissolution time	$115.55 \pm 2.00\text{ s}$
Tensile strength	$1.394 \pm 0.06\text{ kg/mm}^2$
Swelling index	$43.68 \pm 2.55\%$
Surface pH	6.78 ± 0.28
SEM magnification examined	15,000×
Total bioactive phytochemicals (HR-LCMS)	136 (18 alkaloids, 15 terpenoids, 14 phenolics, 14 amino derivatives, 8 nitrogenous compounds, 3 flavonoids, 2 saponins)
Essential minerals (ICP-MS)	11 (highest: Ca, Zn, Cu, Fe, K, Mg; trace: Se, Mn, Cr, Co)
Amino acids identified (MS-QTOF)	17
Shelf life (unrefrigerated)	3–5 years
Thermal stability range	$-20\text{ }^{\circ}\text{C}$ to $+40\text{ }^{\circ}\text{C}$

6.4 Significance for Deep-Space Nutrition and Radioprotection

Interpreted collectively, these results position the 3D-printed ODF as a compact, zero-crumb, long-shelf-life nutrient carrier capable of delivering a broad phytochemical, mineral, and amino-acid payload through a rapid mucosal route unaffected by microgravity-altered digestive transit [4]. This significance is reinforced by an established radiobiological literature: Weiss and Landauer's foundational review documents the radioprotective and antimutagenic properties of dietary antioxidant nutrients and phytochemicals against ionising-radiation injury [26], while Chavhan et al. detail the specific mechanism by which polyphenolic compounds up-regulate antioxidant-enzyme gene expression under radiation exposure [28]. Mortazavi et al., focusing specifically on the spaceflight context, identify vitamin-C-rich vegetables as a promising dietary radiation mitigator for exploration crews [27]. Given that HR-LCMS profiling of the author's ODF confirmed 14 phenolic compounds and 3 flavonoids among its 136 bioactive constituents [4], this radioprotective literature provides an independent mechanistic rationale, beyond the film's nutrient-delivery function alone, for its proposed inclusion in deep-space dietary protocols. The book further proposes a zero-waste circular design wherein inedible plant residues (stems, husks) from onboard Veggie- or APH-style cultivation could be dehydrated and reprocessed into the very powders used for film printing, closing the loop between fresh cultivation and engineered nutrient delivery within a single habitat module [4]. This integration exemplifies the broader thesis of the review: that space horticulture and advanced food manufacturing are not parallel tracks but a single, converging bioregenerative-and-engineered nutrition system.

Validation Gaps and Future Research Needs: It is important to acknowledge that the ODF research, while characterized extensively at the physicochemical and phytochemical level, requires substantial further validation before spaceflight qualification. Critical gaps include: (i) in-vitro and in-vivo bioavailability studies to confirm nutrient absorption from the mucosal route; (ii) stability testing under spaceflight-specific conditions (microgravity, vibration, cosmic radiation); (iii) organoleptic testing (taste, texture, acceptability) with astronaut panels; (iv) comparative efficacy studies against existing space nutrition delivery systems; and (v) production scalability and resource requirement assessments. The author is currently pursuing these validation studies through planned collaborations with space-agency research programmes.

VII. FUTURE PROSPECTS FOR SPACE HORTICULTURE RESEARCH

7.1 Lunar and Martian Regolith Bio-Conditioning

Future cultivation infrastructure is expected to progress from purely hydroponic and aeroponic systems toward hybrid regolith-based substrates. The author's book describes 'biological weathering' using microbial consortia (e.g., *Bacillus mucilaginosus*) and mycorrhizal associations to convert sterile lunar regolith into a fertile, 'living' growing medium, potentially supplemented by earthworm-mediated soil conditioning [4]. This proposal is well aligned with recent independent regolith-cultivation research: Atkin et al. demonstrate that targeted bioremediation amendments of lunar regolith simulant measurably improve its viability as a plant-growth medium by increasing bioavailable nutrient content [29]. Duri et al., in a comprehensive review of commercially available lunar and Martian regolith simulants, catalogue the physicochemical and mineralogical constraints — including elevated heavy-metal content and poor water retention — that any bio-conditioning strategy must overcome [30]. Ding et al. further review microorganism-mediated approaches to rendering lunar soil simulants suitable for cultivation, confirming that microbial inoculation is among the most promising near-term pathways to fertile regolith-based substrates [31]. These converging findings substantiate the book's regolith bio-conditioning proposal as an active and rapidly maturing research frontier rather than a purely speculative concept [4], [29]–[31].

Aeroponic systems, reported in the book to reduce water consumption by up to 95% relative to conventional irrigation, and Deep Water Culture hydroponics are identified as the preferred near-term cultivation modes for microgravity and partial-gravity root-zone management [4]. This is corroborated by Regmi et al.'s comparative review of resource-use efficiency, which reports that aeroponic and hydroponic systems can reduce water usage by more than 90% and fertiliser usage by up to 60% relative to conventional soil-based cultivation, depending on crop and system configuration [32]. Hasenstein's white paper on hydroponic cultivation for spaceflight further confirms that hydroponic water management remains effective under both weightless and partial-gravity conditions, while noting that hydrogel-based substrate modification can further improve water-use efficiency and root-zone stability for crops such as corn under simulated space conditions [33].

7.2 3D-Printed Habitat Infrastructure and the 'Modular Space Kitchen'

Beyond food, 3D-printing technology is projected to extend into habitat construction, with robotic printers using high-powered lasers or microwave sintering to melt lunar regolith into landing pads, roads, and protective habitat shells [4]. Within living quarters, the book envisions a 'modular space kitchen' in which a dedicated space-grade nutrient printer is integrated adjacent to the crop harvest station, enabling on-demand, health-monitor-linked personalised nutrition — for instance, algorithmically adjusting iron or calcium content of a printed film in response to real-time physiological telemetry — while further research extends toward four-dimensional (4D) printing for stimulus-responsive nutrient formulations [4].

7.3 India's Bharatiya Antariksha Station and Vision 2047

India's long-range space exploration roadmap anticipates the Bharatiya Antariksha Station (BAS) becoming operational by 2035, with a crewed lunar mission targeted by 2040 [4]. The book frames a three-phase roadmap toward a permanent Indian lunar base under the 'Amrit Kaal' Vision 2047 framework, with the final phase (2040–2047) envisioning full base activation supported by industrial-grade robotic regolith processing and AI-driven bioreactors [4]. Continued development of ISRO's CROPS programme, extending cultivation cycles from the current few-day germination demonstration toward full 30–45 day growth cycles, is identified as the critical near-term technical bridge toward this goal [4], [10].

7.4 Large-Scale Habitats and Governance

At a longer horizon, the book discusses theoretical large-scale habitats such as O'Neill cylinders — rotating structures generating centrifugal artificial gravity sufficient to support Earth-like, large-scale agricultural production — alongside the colonisation of lunar lava tubes, whose 10–40 metre basalt overburden offers natural radiation shielding and thermal stability

suitable for protected cultivation [4]. These ambitions are situated within an evolving legal and economic framework, including the Artemis Accords and India's Space Policy 2023, which begin to formalise commercial ownership of in-situ resources and interoperable lunar navigation infrastructure such as LunaNet [4].

VIII. DISCUSSION

The reviewed evidence indicates convergence, rather than competition, between mechanical/biological life-support engineering (Veggie, APH, MELiSSA, CROPS), plant-stress physiology research [12]–[15], advanced food-manufacturing technology (3D-printed ODFs) [16]–[19], and human-factors science [23]–[25]. Bioregenerative systems address the volumetric bulk of crew caloric and atmospheric needs, while targeted nutrient-delivery technologies such as the reviewed ODF address precision micronutrient, radioprotective phytochemical, and psychological gaps that fresh cultivation alone may not reliably meet across a multi-year mission — particularly during early transit phases before on-board crops reach harvest maturity [4]. The independent corroboration found across five distinct literatures — plant gravitropic/radiation biology [12]–[15], duckweed protein research [20]–[22], astronaut psychological response studies [23]–[25], dietary radioprotection science [26]–[28], and regolith/soilless cultivation engineering [29]–[33] — substantially strengthens confidence in the book's integrated 'Green Shield' thesis, since each of its core claims now finds support in literature the author's original monograph did not itself cite.

The explicit incorporation of Vedic nutritional philosophy — Prāṇa, the Pancha Mahabhutas, and the Dhātu cycle — represents a distinctive, culturally-grounded contribution rarely seen in the predominantly Western aerospace nutrition literature [1]–[3], [5]–[9], and merits further empirical validation, particularly regarding any measurable psychological or physiological benefit attributable to structured nutritional-cultural scheduling during isolation. A limitation of the present review is that the book's ODF characterisation, while methodologically detailed, has not yet been independently replicated in the space-nutrition literature; future work should pursue microgravity-analogue (parabolic flight or ISS-based) validation of dissolution kinetics and nutrient bioavailability under altered gastrointestinal conditions, and should quantify the in-vivo radioprotective efficacy of the film's phenolic and flavonoid load under simulated cosmic-radiation exposure.

Critical Assessment of Implementation Challenges: Several challenges must be acknowledged in translating the proposed vision to operational reality. First, the integration of ODF production with on-board crop cultivation requires solving significant engineering challenges, including dehydration of fresh biomass, powder processing, and 3D printing under microgravity — each of which has unique technical constraints. Second, the mass, power, volume, and crew-time requirements of the proposed systems (cultivation modules, processing equipment, printers) must be quantified against mission resource budgets. Third, crew acceptance of the ODF format, particularly over multi-year missions, requires human factors validation. Fourth, the Vedic-based nutritional scheduling framework, while conceptually appealing, may not be readily accepted by culturally diverse crews and requires adaptation. Fifth, the regulatory pathway for spaceflight food certification is complex and requires significant safety and efficacy data. These challenges are substantial but not insurmountable, and they define the research priorities outlined below.

IX. CONCLUSION

Space Horticulture is maturing from a demonstration science — proving that seeds germinate and leaves unfurl in microgravity — into an integrated engineering discipline encompassing bioregenerative life-support, validated plant-stress physiology, precision nutrient manufacturing, and culturally-informed crew psychological support. The reviewed 3D-printed oral dispersible film research, documented in the Dr. Jadala Shankaraswamy's book *Space Horticulture* (Narendra Publishing House, 2026, ISBN 978-93-7763116-1), offers a concrete, characterised, and potentially scalable technology addressing microgravity-specific nutrient-delivery and radioprotective constraints, while the accompanying Vedic 'Green Shield' and 'Life Force Foods' framework contributes a novel philosophical scaffold for understanding astronaut nutrition beyond caloric sufficiency — a framework now independently corroborated by empirical literature on plant stress biology, duckweed protein crops, astronaut psychological response, dietary radioprotection, and regolith cultivation engineering.

As India progresses toward the Bharatiya Antariksha Station and a crewed lunar presence under its Vision 2047 roadmap, continued interdisciplinary research combining horticultural science, additive food manufacturing, and indigenous nutritional

philosophy will be essential to achieving genuinely Earth-independent, psychologically sustainable deep-space human exploration.

Summary of Key Contributions:

- 1) **Conceptual Integration:** The 'Green Shield' and 'Life Force Foods' framework provides a unified conceptual scaffold connecting bioregenerative life support, nutritional science, and crew psychological wellbeing.
- 2) **Technological Innovation:** The 3D-printed ODF technology offers a novel crumb-free, mucosal nutrient delivery route with documented physicochemical and phytochemical properties.
- 3) **Cultural Grounding:** The Vedic philosophical framework enriches the predominantly Western aerospace nutrition literature with a culturally-rooted perspective.
- 4) **Forward-Looking Roadmap:** The connection to India's Vision 2047 provides a concrete path toward implementation.

Limitations:

- 1) The ODF research has been characterized at the physicochemical and phytochemical level but requires independent validation, bioavailability studies, and spaceflight-specific stability testing.
- 2) The Vedic framework is primarily conceptual and cultural; empirical validation of its nutritional and psychological benefits is needed.
- 3) The practical implementation of the proposed systems (integration, mass, power, volume, crew-time) requires detailed engineering assessment.
- 4) The review is based on the author's monograph supplemented by literature; comprehensive systematic review methodology was not employed.

Research Priorities:

- 1) Independent validation of ODF characterization and bioavailability studies.
- 2) Spaceflight-analogue testing of ODF dissolution kinetics and nutrient stability.
- 3) Organoleptic testing and crew acceptance studies.
- 4) Integration engineering for closed-loop crop-to-ODF processing.
- 5) Empirical testing of the Vedic framework's psychological and physiological benefits.
- 6) Comparative analysis of ODFs against existing space nutrition technologies.
- 7) Scale-up and resource requirement assessments.

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CONFLICT OF INTEREST

The author declare no conflict of interest.

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Application of N-ZEO-SR Plus Fertilizer on the Dynamics of Lead (Pb) Heavy Metal in Soybean Plants (*Glycine max* L.)

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Abstract— Lead (Pb) contamination in agricultural soil poses serious risks to crop productivity and food safety. This study investigated the effects of N-ZEO-SR Plus fertilizer dosage and Pb concentration on the growth and yield of soybean (*Glycine max* L.), as well as on Pb content in soil and seeds, and their interactions. A randomized block design (RBD) with two factors was employed: N-ZEO-SR Plus fertilizer dose (0, 50, 100, and 150 kg ha⁻¹) and Pb concentration (0, 50, and 100 ppm), with three replications. N-ZEO-SR Plus fertilizer significantly increased the number of leaves at 6 weeks after planting (WAP) ($R^2 = 0.937$, linear), chlorophyll content (optimum at 111.33 kg ha⁻¹, quadratic), and seed weight per plant, while significantly reducing soil Pb content ($R^2 = 0.906$, linear). Pb concentration significantly increased soil Pb content ($R^2 = 0.957$) and the percentage of Pb reduction ($R^2 = 0.891$), but did not affect growth or yield variables. Significant interactions between N-ZEO-SR Plus and Pb were observed for the number of filled pods, chlorophyll content, soil Pb content, and Pb reduction percentage. The interaction revealed competitive ion exchange at the highest combination (150 kg ha⁻¹ N-ZEO-SR Plus + 100 ppm Pb), where NH_4^+ displaced adsorbed Pb^{2+} from zeolite exchange sites. All soybean seed samples exceeded the 0.5 ppm maximum permissible Pb limit (Permentan No. 53/2018), indicating that N-ZEO-SR Plus alone is insufficient to reduce seed Pb to safe levels. Moderate N-ZEO-SR Plus application (100 kg ha⁻¹) provided the best balance between growth enhancement and Pb immobilization.

Keywords— Heavy metals, Lead, N-ZEO-SR Plus, Zeolite, Soybean, Ion exchange, Soil remediation, Glycine max, Slow-release fertilizer, Heavy metal immobilization, Phytoremediation.

I. INTRODUCTION

Soybean (*Glycine max* L.) is one of the most important leguminous crops in Indonesia, serving as a primary source of plant-based protein processed into tofu, tempeh, soy sauce, and soy milk [25]. However, soybean cultivation in Pb-contaminated soil raises concerns about food safety, as Pb can accumulate in plant tissues and enter the food chain [1, 16].

Lead (Pb) is a non-biodegradable toxic heavy metal that accumulates in soil and is readily absorbed by plant roots. Sources of Pb contamination include fertilizers, pesticides, industrial wastewater, mining waste, and vehicular emissions [4]. Pb inhibits plant growth by disrupting physiological processes such as photosynthesis, respiration, and nutrient absorption, ultimately leading to chlorosis, necrosis, reduced seed germination, and plant death [4]. Plants absorb Pb through roots and translocate it to stems, leaves, and seeds through three principal mechanisms: (1) root absorption, (2) translocation from roots to aerial parts, and (3) cellular localization [5].

Remediation of Pb-contaminated agricultural soil is essential for food security. Among various approaches, the use of zeolite-based slow-release fertilizers has shown promise. N-ZEO-SR Plus is a nitrogen fertilizer combining urea with nano-zeolite, nano-montmorillonite, nano-silicate, and humic substances [7]. Zeolite, a microporous aluminosilicate mineral with high cation exchange capacity (CEC) and large specific surface area, can adsorb Pb^{2+} ions through ion exchange and surface complexation [6]. In a slow-release fertilizer formulation, zeolite serves a dual function: regulating N release to improve nitrogen use efficiency, and immobilizing heavy metals through adsorption [2, 22].

Recent studies have demonstrated the effectiveness of zeolite amendments in reducing heavy metal bioavailability in contaminated soils. Wang et al. [24] reported that zeolite application significantly reduced Cd and Pb uptake in wheat, while Lati et al. [8] found that nano-zeolite decreased Pb availability in acid sulfate soil by 46–62%. Furthermore, Shen et al. [19] showed that biochar-zeolite composites immobilized Pb in soil through cation exchange and precipitation mechanisms, reducing Pb bioavailability by up to 71%. These findings support the potential of zeolite-based fertilizers for simultaneous nutrient supply and heavy metal remediation.

This study aimed to: (1) evaluate the effects of N-ZEO-SR Plus fertilizer dosage on soybean growth and yield under Pb stress, (2) determine the effects of Pb concentration on soil Pb dynamics and plant responses, (3) assess the interaction between N-ZEO-SR Plus and Pb on observed variables, and (4) determine whether N-ZEO-SR Plus can reduce seed Pb content below the 0.5 ppm safety threshold.

II. MATERIALS AND METHODS

2.1 Study Site and Period

The research was conducted from December 2023 to June 2024 in a screen house at the Faculty of Agriculture, Jenderal Soedirman University, Purwokerto, Indonesia (110 m a.s.l., average temperature 30.9°C, relative humidity 73%, light intensity 12,664 lux). Soil and plant analyses were performed at the Soil Science and Land Resources Laboratory, Faculty of Agriculture, Jenderal Soedirman University.

2.2 Soil Characteristics

Inceptisol soil was collected from an ex-farm area of Jenderal Soedirman University and sieved to 2 mm. The initial soil analysis (Table 1) revealed low organic C, low CEC, and a background Pb content of 17.26 ppm.

TABLE 1
INITIAL SOIL ANALYSIS OF THE INCEPTISOL USED IN THE EXPERIMENT

Parameter (unit)	Value	Category*
Pb (ppm)	17.26	Normal
pH H ₂ O	6.48	Slightly acidic
pH KCl	5.12	Neutral
EC (dS/cm)	1.599	Low
Organic C (%)	0.152	Very low
Total N (%)	0.465	Medium
Available N (ppm)	59.93	Very low
Available P (%)	47.6	High
Available K (mg/100 g)	19.55	Low
CEC (mg/100 g)	8.8	Low

Categories according to Balai Pengujian Standar Instrumen Tanah dan Pupuk (2023).

2.3 Experimental Design

A randomized block design (RBD) with two factors was used. Factor 1 was N-ZEO-SR Plus fertilizer dose (D): D0 = 0 kg ha⁻¹ (control), D1 = 50 kg ha⁻¹, D2 = 100 kg ha⁻¹, D3 = 150 kg ha⁻¹. Factor 2 was Pb concentration (K): K0 = 0 ppm (control), K1 = 50 ppm, K2 = 100 ppm. The total of 12 treatment combinations was replicated three times (36 experimental units, 108 plants). Pb was applied as Pb(NO₃)₂ solution to the soil one week before planting. N-ZEO-SR Plus fertilizer was applied at planting according to treatment doses. SP-36 and KCl fertilizers were applied as basal fertilizers.

2.4 Observed Variables

Growth variables: plant height (cm), number of leaves, leaf area (cm²), chlorophyll content (mg L⁻¹), and proline content (μmol g⁻¹). Yield variables: plant dry weight (g), number of filled pods per plant, 100-seed weight (g), and seed weight per plant (g). Soil Pb variables: Pb content in soil (ppm), percentage of Pb reduction in soil (%), and Pb content in soybean seeds (ppm).

2.5 Statistical Analysis

Data were analyzed using analysis of variance (ANOVA) with an F-test at the 5% significance level. Significant effects were further examined using Duncan's Multiple Range Test (DMRT) at 5%. Regression analysis was performed to model dose-response relationships.

III. RESULTS AND DISCUSSION

3.1 Analysis of Variance

The ANOVA results (Table 2) showed that N-ZEO-SR Plus fertilizer had a highly significant effect ($p < 0.01$) on the number of leaves at 6 WAP and chlorophyll content, a significant effect ($p < 0.05$) on seed weight per plant, soil Pb content, and the percentage of Pb reduction, but no significant effect on plant height, leaf area, proline content, 100-seed weight, plant dry weight, or the number of filled pods. Pb concentration had a highly significant effect ($p < 0.01$) on soil Pb content and the percentage of Pb reduction, but did not affect any growth or yield variable. A significant interaction between N-ZEO-SR Plus and Pb was observed for the number of filled pods ($p < 0.05$), chlorophyll content ($p < 0.01$), soil Pb content ($p < 0.01$), and the percentage of Pb reduction ($p < 0.01$).

TABLE 2
SUMMARY OF ANOVA F-TEST RESULTS FOR OBSERVED VARIABLES

No.	Variable	D (Fertilizer)	K (Pb)	D×K
1	Plant height	ns	ns	ns
2	Number of leaves (6 WAP)	**	ns	ns
3	Leaf area	ns	ns	ns
4	Chlorophyll content	**	ns	**
5	Proline content	ns	ns	ns
6	100-seed weight	ns	ns	ns
7	Seed weight per plant	*	ns	ns
8	Plant dry weight	ns	ns	ns
9	Number of filled pods	ns	ns	*
10	Soil Pb content	*	**	**
11	Pb reduction (%)	*	**	**

*ns = not significant; * = significant at 5%; ** = significant at 1%; WAP = Weeks After Planting*

3.2 Effect of N-ZEO-SR Plus Fertilizer

The mean values across all treatment combinations are presented in Table 3. The following subsections discuss the significant effects in detail.

TABLE 3
MEAN VALUES OF OBSERVED VARIABLES ACROSS TREATMENT COMBINATIONS

Treatment	TT (cm)	JD (leaves)	LD (cm ²)	KK (mg/L)	KP (μmol/g)	B100 (g)	BBPT (g)	BKT (g)	JPI (pods)	KPbT (ppm)	PPb (%)
N-ZEO-SR Plus fertilizer dose (D)											
D0	64.61 a	25.00 c	36.53 a	24.05 b	5.89 a	10.67 a	16.45 b	21.08 a	49.33 a	27.62 a	43.00 ab
D1	64.82 a	25.55 bc	37.91 a	34.14 a	6.74 a	10.94 a	20.08 a	24.95 a	50.44 a	27.57 a	41.33 b
D2	66.64 a	27.66 b	34.88 a	34.24 a	6.58 a	10.73 a	16.62 b	23.00 a	49.66 a	26.04 ab	44.44 a
D3	65.46 a	30.22 a	37.30 a	35.62 a	7.07 a	11.30 a	21.46 a	30.13 a	52.77 a	24.71 b	45.67 a
Pb concentration (K)											
K0	66.31 a	27.16 a	37.50 a	32.04 a	6.59 a	10.83 a	18.72 a	25.28 a	49.58 a	18.28 c	0 c
K1	64.27 a	27.08 a	37.32 a	32.94 a	6.82 a	10.96 a	17.82 a	23.64 a	49.50 a	28.06 b	58.25 b
K2	65.57 a	27.08 a	37.15 a	31.06 a	6.29 a	10.94 a	19.42 a	25.44 a	52.58 a	32.11 a	72.58 a

TT = Plant height; JD = Number of leaves; LD = Leaf area; KK = Chlorophyll content; KP = Proline content; B100 = 100-seed weight; BBPT = Seed weight per plant; BKT = Plant dry weight; JPI = Number of filled pods; KPbT = Soil Pb content; PPb = Pb reduction percentage. Different letters within the same column and treatment group indicate significant differences (DMRT, 5%).

3.2.1 Number of Leaves at 6 WAP

N-ZEO-SR Plus fertilizer significantly increased the number of leaves from 25.00 (D0) to 30.22 (D3), a 20.9% improvement (Table 3). The regression equation $Y = 0.0356x + 24.444$ ($R^2 = 0.937$) indicated a strong linear relationship, suggesting that each increment of N-ZEO-SR Plus directly contributed to additional leaf production. Nitrogen is a structural component of amino acids, nucleic acids, and chlorophyll, all essential for leaf initiation and expansion [26]. The sustained N release from the zeolite matrix in N-ZEO-SR Plus likely maintained N availability throughout the vegetative phase, supporting progressive leaf formation. This finding is consistent with Lati et al. [8], who reported that nano-zeolite-based fertilizers increased leaf area index in rice by 18–32% compared to conventional urea. The strong linear response ($R^2 = 0.937$) suggests that higher doses could further increase leaf number, although agronomic returns must be weighed against input costs.

3.2.2 Chlorophyll Content

Chlorophyll content responded quadratically to N-ZEO-SR Plus dosage: $Y = -0.0009x^2 + 0.2004x + 24.615$ ($R^2 = 0.926$), with a calculated optimum at 111.33 kg ha⁻¹ (predicted chlorophyll: 35.77 mg L⁻¹). Chlorophyll increased from 24.05 mg L⁻¹ (D0) to 35.62 mg L⁻¹ (D3), a 48.1% improvement. The quadratic pattern reflects diminishing marginal returns: at low doses, additional N directly supports chlorophyll biosynthesis, as nitrogen constitutes four atoms per porphyrin ring. Beyond the optimum, saturation of the biosynthetic pathway and dilution effects from increased leaf area limit further gains [12]. The optimum dose of 111.33 kg ha⁻¹ approximates the D2 level (100 kg ha⁻¹), confirming that moderate N-ZEO-SR Plus application is sufficient to maximize photosynthetic pigment production. Wang et al. [24] similarly reported that zeolite-amended fertilizers improved chlorophyll content in wheat under heavy metal stress by reducing metal phytotoxicity and enhancing N uptake.

3.2.3 Seed Weight per Plant

Seed weight per plant increased from 16.45 g (D0) to 21.46 g (D3), a 30.4% improvement (Table 3). The quadratic response ($Y = 0.0001x^2 + 0.005x + 17.221$, $R^2 = 0.374$) had a low R^2 value, reflecting the inherent variability in yield measurements that integrate multiple biological processes including pod formation, seed filling, and carbon partitioning [15]. The significant effect of N-ZEO-SR Plus on seed weight, despite the low R^2 , is agronomically important. Adequate N supply supports seed filling by sustaining photosynthetic activity during the reproductive phase and facilitating carbohydrate translocation from source

leaves to developing seeds [21]. Shen et al. [19] noted that slow-release nitrogen fertilizers based on zeolite matrices improved grain yield in cereals by 15–28% compared to conventional urea, which is consistent with our findings.

3.2.4 Soil Pb Content

N-ZEO-SR Plus fertilizer significantly reduced soil Pb content from 27.62 ppm (D0) to 24.71 ppm (D3), a 10.5% reduction (Table 3). The linear regression $Y = -0.0205x + 28.03$ ($R^2 = 0.906$) demonstrated a dose-dependent decrease. The primary mechanism is ion exchange on the zeolite surface: zeolite's three-dimensional SiO_4/AlO_4 framework generates a net negative charge balanced by exchangeable cations (Na^+ , K^+ , Ca^{2+}), which are replaced by Pb^{2+} through cation exchange reactions [6]. The high selectivity of zeolite for Pb^{2+} arises from its charge density and hydrated ionic radius, which favor the displacement of monovalent and divalent nutrient cations from exchange sites [3]. The linear response ($R^2 = 0.906$) indicates that Pb adsorption by zeolite was not saturated within the tested dose range, suggesting potential for further Pb immobilization at higher application rates. This finding aligns with Lati et al. [8], who reported that nano-zeolite amendments reduced Pb availability in acid sulfate soil by 46–62%, and Shen et al. [19], who found that biochar-zeolite composites reduced Pb bioavailability by up to 71%.

3.2.5 Percentage of Pb Reduction

The percentage of Pb reduction in the soil ranged from 41.33% (D1) to 45.67% (D3), with the control (D0) at 43.00% (Table 3). The quadratic response $Y = 0.0003x^2 - 0.0211x + 42.667$ ($R^2 = 0.788$) indicated an initial decrease at low doses followed by a progressive increase at higher doses. At very low application rates, zeolite may be insufficient to create a measurable impact relative to background soil adsorption. At higher doses, additional exchange sites and surface area lead to progressively greater Pb^{2+} immobilization. Pratama and Destiarti [13] reported that zeolite addition reduced Pb concentrations by up to 97.49%, although the magnitude depends on soil properties, zeolite type, and initial Pb concentration. Shen et al. [19] found that combined biochar-zeolite amendments achieved 65–71% Pb immobilization in contaminated soil, consistent with the range observed in this study.

3.3 Effect of Pb Concentration

Pb concentration did not significantly affect any growth or yield variable (Table 2), suggesting that the tested concentrations (0–100 ppm) were within the tolerance range of the Deja-1 soybean variety. Soybean employs several defense mechanisms against heavy metal stress, including chelation by phytochelatins, cell wall immobilization, and vacuolar compartmentalization [10, 17]. However, Pb concentration significantly affected soil Pb dynamics:

3.3.1 Soil Pb Content

Soil Pb content increased linearly from 18.28 ppm (K0) to 32.11 ppm (K2), a 75.7% increase ($Y = 0.1283x + 20.077$, $R^2 = 0.957$). Each 1 ppm increase in exogenous Pb application resulted in approximately 0.128 ppm increase in extractable soil Pb, reflecting both direct Pb addition and the fraction remaining in the soil solution or loosely bound to soil colloids. The near-unity R^2 confirms a strong and predictable relationship between Pb application rate and soil Pb accumulation. Elevated soil Pb levels pose risks of long-term accumulation and food chain entry [10].

3.3.2 Percentage of Pb Reduction

The percentage of Pb reduction increased from 0% (K0) to 72.58% (K2) ($Y = 0.7258x + 7.3194$, $R^2 = 0.891$). This counterintuitive result—higher Pb leading to higher percentage reduction—is explained by adsorption equilibrium: higher adsorbate concentrations drive more ions onto available adsorption sites until saturation is approached [13]. Additionally, higher soil Pb concentrations may increase plant Pb uptake, effectively removing Pb from the soil solution [9].

3.4 Interaction Effects

3.4.1 Number of Filled Pods

A significant D×K interaction was found for the number of filled pods (Table 4).

TABLE 4
INTERACTION OF N-ZEO-SR PLUS FERTILIZER DOSE AND Pb CONCENTRATION ON THE NUMBER OF FILLED PODS

Dose	K0 (0 ppm)	K1 (50 ppm)	K2 (100 ppm)	Mean
D0	46.33 bB	47.00 bB	54.67 aA	49.33
D1	45.00 bB	55.33 aA	51.00 aAB	50.44
D2	49.33 aA	50.33 aA	49.33 aA	49.67
D3	57.67 aA	45.33 bB	55.33 aA	52.78
Mean	49.58	49.5	52.58	

Different uppercase letters (columns) or lowercase letters (rows) indicate significant differences (DMRT, 5%).

The highest number of filled pods (57.67) was observed at D3K0, indicating that maximum N supply without Pb stress produced optimal pod yield. The D2 treatment maintained consistent pod numbers across all Pb concentrations (49.33–50.33), suggesting that moderate N-ZEO-SR Plus doses buffer Pb effects on reproductive development. At D3K1, pod number dropped to 45.33, possibly because the high N-ZEO-SR Plus dose released NH_4^+ ions that competed with Pb^{2+} for zeolite exchange sites, increasing Pb bioavailability and reducing pollen viability or fertilization efficiency. The dual function of N-ZEO-SR Plus is evident: at low to moderate Pb levels, the zeolite component adsorbs Pb, reducing bioavailability and allowing N to support pod formation; at higher Pb levels, the adsorption capacity may be partially overwhelmed.

3.4.2 Chlorophyll Content

The D×K interaction was highly significant for chlorophyll content (Table 5).

TABLE 5
INTERACTION OF N-ZEO-SR PLUS FERTILIZER DOSE AND Pb CONCENTRATION ON CHLOROPHYLL CONTENT (MG L^{-1})

Dose	K0 (0 ppm)	K1 (50 ppm)	K2 (100 ppm)	Mean
D0	23.17 cA	24.43 cA	24.56 cA	24.05 B
D1	30.86 bB	38.26 aA	33.31 bB	34.15 A
D2	32.70 bB	31.71 bB	38.33 aA	34.25 A
D3	41.44 aA	37.36 aB	28.07 cC	35.62 A
Mean	32.04	32.94	31.07	

Different uppercase letters (columns) or lowercase letters (rows) indicate significant differences (DMRT, 5%).

The highest chlorophyll content (41.44 mg L^{-1}) was recorded at D3K0. At D1K1 (38.26 mg L^{-1}) and D2K2 (38.33 mg L^{-1}), chlorophyll values were comparable, suggesting that moderate fertilizer doses can compensate for moderate Pb stress by supplying additional N for chlorophyll biosynthesis [11]. However, at D3K2, chlorophyll dropped sharply to 28.07 mg L^{-1} . This decline indicates that competitive ion exchange between NH_4^+ and Pb^{2+} on zeolite sites may release adsorbed Pb into the soil solution, increasing phytotoxicity and inhibiting chlorophyll biosynthesis. This finding is consistent with Wang et al. [24], who reported that high NH_4^+ fertilizer rates can desorb heavy metals from soil colloids, increasing their bioavailability and phytotoxicity.

3.4.3 Soil Pb Content

The D×K interaction was highly significant for soil Pb content (Table 6).

TABLE 6

INTERACTION OF N-ZEO-SR PLUS FERTILIZER DOSE AND Pb CONCENTRATION ON SOIL Pb CONTENT (PPM)

Dose	K0 (0 ppm)	K1 (50 ppm)	K2 (100 ppm)	Mean
D0	21.68 aB	29.62 abA	31.59 abA	27.63 A
D1	17.98 abB	32.12 aA	32.62 abA	27.57 A
D2	20.53 abB	28.03 bA	29.56 bA	26.04 AB
D3	16.96 bC	22.50 cB	34.69 aA	24.72 B
Mean	19.29 C	28.07 B	32.11 A	

Different uppercase letters (columns) or lowercase letters (rows) indicate significant differences (DMRT, 5%).

The lowest soil Pb (16.96 ppm) occurred at D3K0, confirming that zeolite effectively adsorbs even background Pb (initial soil Pb was 17.26 ppm). At K1, increasing fertilizer doses reduced soil Pb from 29.62 (D0) to 22.50 ppm (D3), demonstrating dose-dependent adsorption. However, at K2, the D3 treatment yielded the highest soil Pb (34.69 ppm). This paradoxical result is explained by competitive adsorption: at high Pb concentrations, zeolite sites approach saturation, and additional NH_4^+ from N-ZEO-SR Plus displaces previously adsorbed Pb^{2+} back into the soil solution [3]. Shen et al. [19] reported similar findings, noting that excessive ammonium from fertilizers can remobilize adsorbed heavy metals from zeolite and biochar surfaces, increasing their bioavailability.

3.4.4 Percentage of Pb Reduction

The D×K interaction for Pb reduction percentage was highly significant (Table 7).

TABLE 7

INTERACTION OF N-ZEO-SR PLUS FERTILIZER DOSE AND Pb CONCENTRATION ON THE PERCENTAGE OF Pb REDUCTION IN SOIL (%)

Dose	K0 (0 ppm)	K1 (50 ppm)	K2 (100 ppm)	Mean
D0	0 C	56.00 bB	73.00 abA	34.44
D1	0 C	52.00 cB	72.00 abA	39.89
D2	0 C	58.33 bB	75.00 aA	38.11
D3	0 C	66.67 aB	70.33 bA	46.33
Mean	0 C	58.25 B	72.58 A	

Different uppercase letters (columns) or lowercase letters (rows) indicate significant differences (DMRT, 5%).

The highest Pb reduction (75.00%) was observed at D2K2. At K1, the D3 treatment achieved the highest reduction (66.67%), consistent with dose-dependent adsorption. At K2, D2 achieved the highest reduction (75.00%), while D3 showed a slightly lower reduction (70.33%), again suggesting competitive ion exchange effects at the highest combination. The overall pattern confirms that N-ZEO-SR Plus, through its zeolite component, can serve as both a nutrient source and a Pb adsorbent [2, 13].

3.5 Non-Significant Variables

Plant height, leaf area, proline content, 100-seed weight, and plant dry weight were not significantly affected by either factor (Table 2). The lack of significant effects on height and leaf area may reflect limited plasticity of these genetically conserved traits at the tested dose range. The non-significant effect of Pb on proline suggests that the tested concentrations did not induce severe oxidative stress sufficient to trigger proline accumulation. Pandey et al. [10] noted that proline accumulation in legumes typically occurs at Pb concentrations exceeding 150 ppm, which is above the maximum tested in this study. The non-significant effects on 100-seed weight and plant dry weight are consistent with the observation that seed weight is a genetically conserved trait in soybean [20].

3.6 Pb Content in Soybean Seeds

Pb content in soybean seeds showed a decreasing trend with increasing N-ZEO-SR Plus doses, attributable to the adsorption of soil Pb by organic compounds and zeolite in the fertilizer, which reduces Pb bioavailability for root uptake [14]. However, all seed samples exceeded the 0.5 ppm maximum permissible Pb limit established by Indonesian Ministry of Agriculture Regulation No. 53/2018. Pb enters plants through roots and is translocated to stems, leaves, and seeds [18], and contaminated seeds pose significant health risks when consumed [23]. Wang et al. [24] similarly reported that zeolite amendments alone were insufficient to reduce grain Pb below regulatory thresholds in wheat grown on moderately contaminated soil, highlighting the need for combined remediation approaches.

IV. CONCLUSIONS

- 1) N-ZEO-SR Plus fertilizer significantly increased the number of leaves at 6 WAP (linear, $R^2 = 0.937$), chlorophyll content (quadratic, optimum at $111.33 \text{ kg ha}^{-1}$), and seed weight per plant, while significantly reducing soil Pb content (linear, $R^2 = 0.906$).
- 2) Pb concentration (0–100 ppm) significantly increased soil Pb content ($R^2 = 0.957$) and Pb reduction percentage ($R^2 = 0.891$), but did not affect growth or yield, indicating that Deja-1 soybean can tolerate moderate Pb levels without visible toxicity.
- 3) Significant D×K interactions on the number of filled pods, chlorophyll content, soil Pb content, and Pb reduction percentage revealed that competitive ion exchange between NH_4^+ and Pb^{2+} on zeolite sites can reduce chlorophyll and increase soil Pb at the highest combination (D3K2).
- 4) All soybean seed samples exceeded the 0.5 ppm maximum permissible Pb limit (Permentan No. 53/2018), indicating that N-ZEO-SR Plus alone is insufficient to reduce seed Pb to safe levels. Complementary remediation strategies such as phytoremediation, biochar amendment, or soil washing should be considered.
- 5) Moderate N-ZEO-SR Plus application (100 kg ha^{-1}) provides the best balance between enhancing soybean growth and immobilizing soil Pb, while avoiding negative interactions at higher Pb concentrations.

Recommendations:

- 1) **For Farmers:** Apply N-ZEO-SR Plus at 100 kg ha^{-1} in Pb-contaminated soils to achieve optimal growth enhancement while minimizing Pb bioavailability.
- 2) **For Future Research:** Investigate complementary remediation strategies (biochar, phytoremediation with hyperaccumulator plants) combined with N-ZEO-SR Plus to reduce seed Pb content below regulatory limits.
- 3) **For Policy:** Strengthen monitoring of Pb levels in agricultural soils and develop integrated soil management guidelines for heavy metal-contaminated areas.
- 4) **For Further Studies:** Conduct long-term field validation studies to confirm the screen house findings and assess the economic viability of N-ZEO-SR Plus application in commercial soybean production systems.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

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The authors declare no conflict of interest.

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Perceptions and Attitudes of Farming Household Heads towards the Adoption of Eco-Friendly Farming Practices in Embu County, Kenya

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Abstract— *Eco-Friendly Farming Practices (EFFPs) are vital components of sustainable agriculture, particularly in regions such as Embu County, Kenya, which are vulnerable to climate change impacts, where smallholder farmers contend with soil degradation, irregular rainfall, and food insecurity. This paper explores the perceptions and attitudes of household heads regarding the adoption of EFFPs, as part of a broader thesis on the determinants of adoption. Perceptions relate to farmers' cognitive assessments of the benefits and risks associated with EFFPs, whereas attitudes reflect emotional predispositions that influence behavioural intentions. Employing a mixed-methods approach, data were collected and analyzed from 402 household heads across Embu East, North, and West sub-counties. The findings reveal favourable perceptions of the environmental advantages of EFFPs (average score 4.2 out of 5), yet show less favourable attitudes toward obstacles to adoption, such as high initial costs (average score 2.8 out of 5). Households led by women exhibited more positive attitudes (average score of 4.1 out of 5), partly attributable to agency driven by migration, in contrast to regional trends. The study, grounded in the Theory of Planned Behaviour (TPB), underscores how subjective norms and perceived behavioural control influence adoption rates. Recent literature indicates that, in Kenya, approximately 60-70% of farmers perceive Climate Smart Agriculture (similar to EFFPs) as beneficial; however, resource constraints present significant barriers to widespread adoption. The recommendations advocate targeted extension services and campaigns to shift perceptions. This research makes a substantial contribution to Sustainable Development Goals 2 and 13 by promoting perception-focused interventions that foster equitable adoption and enhance resilience within smallholder agroecosystems.*

Keywords— *Perception, Attitude, EFFPs, Adoption, Households.*

I. INTRODUCTION

Agriculture continues to be a fundamental pillar of the global economy, particularly in developing countries, where it underpins livelihoods and food security for billions of people. According to the United Nations Development Programme (UNDP, 2016), the limitations to sustainable economic growth are intricately linked to the management of environmental resources, highlighting the imperative for environmentally sustainable methodologies. In Sub-Saharan Africa, smallholder farmers, comprising over 80% of the agricultural workforce, confront biophysical challenges, including soil erosion and climate variability, which intensify environmental degradation (Mutuku et al., 2017). On a global scale, agriculture occupies 38% of terrestrial ecosystems, an increase from 37% in 1992 (World Bank, 2018), thereby expanding its ecological footprint.

Conventional farming, heavily reliant on external inputs such as synthetic fertilizers and pesticides, has increased yields but at the expense of sustainability. The Green Revolution, for instance, doubled production in Asia and Latin America in the 1960s (Kassie & Zikhali, 2009), yet it also led to nonpoint-source pollution, biodiversity loss, and soil compaction (Altieri, 2004; Lampkin, 1994). In Kenya, where agriculture accounts for 51% of GDP and employs 60% of the workforce (World Bank, 2018), these practices have contributed to declining soil fertility and heightened vulnerability to drought.

Eco-Friendly Farming Practices (EFFPs), encompassing conservation agriculture, agroforestry, and integrated pest management, represent a paradigm shift, integrating ecological principles to mitigate these challenges (Mozzato et al., 2018). EFFPs align with the Sustainable Development Goals (SDGs), particularly SDG 2 (zero hunger), SDG 5 (gender equality), and SDG 13 (climate action), by promoting resource-efficient production (UNDP, 2016). For example, EFFPs enhance soil organic matter, reducing erosion by 50-70% and improving water retention (Pretty & Hine, 2001).

The perceptions and attitudes of household heads are crucial in the adoption of EFFPs. Perceptions include farmers' beliefs regarding the characteristics of an innovation, such as its relative advantage including yield stability, and its compatibility with existing systems (Rogers, 2003). Attitudes, which are shaped by emotional responses to risks and benefits, influence behavioural intentions (Ajzen, 1991). In Africa, positive perceptions of the environmental benefits of EFFPs are widespread; however, attitudes frequently remain negative due to perceived complexities and costs (Giller et al., 2009).

Recent literature updates this narrative. A 2025 study of Kenyan smallholders found that 65% perceive climate-smart agriculture (CSA, synonymous with EFFPs) as yield-enhancing, yet attitudes toward adoption are tempered by risk aversion, with only 45% intending to adopt due to input costs (Kipng'etich et al., 2025). In Zambia, adopters reported higher perceived benefits (such as resilience to drought), while non-adopters highlighted barriers such as limited extension services. Group training narrowed adoption gaps by 40% (Assessment of the Drivers of Adoption of Climate Smart Agriculture, 2025). Mnukwa et al.'s (2025) systematic review of Sub-Saharan maize farmers found female adoption rates of 40-55% versus 55-70% for males, attributed to gendered perceptions of technology complexity. In Ethiopia, farmers' positive attitudes toward agroforestry (80% favorable) correlate with observed biodiversity gains, but negative perceptions of labor demands hinder scaling (Smallholder farmers' engagement with climate-smart agriculture, 2022).

In Kenya, perceptions are influenced by the conditions of the Arid and Semi-Arid Lands (ASAL). A 2025 study in Baringo County found that livestock farmers considered Climate-Smart Agriculture (CSA) a means to mitigate risks, with a mean perception score of 4.0 out of 5. However, these attitudes deteriorated due to limited access to credit (Livestock Farmers' Intentions to Adopt Climate-Smart Agricultural Practices, 2025). Muriuki et al. (2025) found that female-headed households in the Mount Kenya region demonstrated more favorable attitudes towards low-input Eco-Friendly Farming Practices (EFFPs), driven by food security concerns, resulting in a 20% increase in welfare impacts. Conversely, Onyango et al. (2025) observed that patriarchal norms influence perceptions, with men viewing capital-intensive practices as masculine domains. Embu County exemplifies these dynamics. With rain-fed agriculture on 1.98-acre plots, farmers encounter soil pH extremes (3.2-8.0), erosion, and 65-day dry spells (MoLAF, 2016; NAAIAP, 2014). Government initiatives through extension services have successfully increased awareness of EFFPs, although the rate of adoption remains modest at 30-40% (Amudavi et al., 2015). While perceptions of EFFPs as labor-saving are favorable among women, attitudes towards associated costs continue to be negative, primarily due to the prevailing poverty rate of 43.8% (GoK, 2014).

Recent global insights further substantiate this perspective. An article published in *Frontiers in Sustainable Food Systems* (2025) correlates farmers' risk perceptions with their willingness to adopt Climate-Smart Agriculture (CSA), noting that Kenyan adopters are 25% more inclined to recognize benefits following training. In Ghana, Owusu-Boateng and Gadogbe (2015) observed that rainwater harvesting, an example of an Eco-Friendly Farming Practice (EFFP), is perceived as sustainable; however, maintenance attitudes impede positive perception. These investigations highlight the necessity for perception-attitude frameworks to convert intention into action.

In Embu, male out-migration (Mugwe et al., 2008) has increased the proportion of female household heads to 48%, thereby shifting perceptions towards more inclusive EFFPs (Achieng', 2017). Nevertheless, land user rights restrict access to credit, resulting in negative attitudes (Barrett & Marenja, 2007). This paper draws from the thesis to examine these complexities, incorporating recent literature up to 2025 to ensure contemporary relevance.

1.1 Statement of the Problem

Despite the demonstrated benefits of EFFPs in reducing environmental degradation and strengthening resilience, their adoption in Embu County remains limited, with only 35% of households fully participating (Njeru, 2015). An essential yet insufficiently examined factor is the perceptions and attitudes of household heads, which serve as mediators between awareness and behavioral commitment. Perceptions, defined as cognitive assessments of the utility, risks, and compatibility of EFFPs, often conflict with attitudes, which are affective evaluations that influence the willingness to adopt.

In Embu, smallholders hold a positive perception of EFFPs for soil conservation, with 70% viewing agroforestry as a means to reduce erosion. However, attitudes become adverse due to the high costs and labor associated with these practices, as reflected in a mean attitude score of 3.1 out of 5 from preliminary surveys. Female heads, accounting for 48% as a result of migration, display more favorable attitudes at 4.1 out of 5, considering EFFPs as facilitators of food security. Nonetheless, patriarchal norms continue to reinforce negative perceptions regarding women's capacity for innovation, as noted by Mwaura et al. (2025). This disconnect contributes to ongoing food insecurity, which affects 20% of the population, and stunting, impacting 33%, thereby undermining Sustainable Development Goal 2.

The gaps in existing literature tend to exacerbate the issue. While Kipng'etich et al. (2025) report that 60% of individuals have positive perceptions regarding Kenyan Controlled Settlement Agriculture (CSA), attitudes remain limited due to risk aversion, with non-adopters being twice as likely to disengage. In Embu County, Chomba (2016) notes that attitude barriers are not documented, resulting in misaligned extension efforts. Recent research, such as Mnukwa et al. (2025), suggests that perception gaps related to gender have narrowed, leading to a 30% increase in adoption within arid and semi-arid lands (ASALs). Failure to address these concerns hinders the scaling of Environmentally Friendly Farming Practices (EFFPs), thereby aggravating biophysical deterioration, causing a 0.47% decline in organic matter, consequently exacerbating socioeconomic inequalities.

This study addresses a gap in research by examining the influence of perceptions, specifically the benefit-risk balance, and attitudes, such as emotional barriers, on the adoption of EFFPs among household heads in Embu County. This analysis aims to inform targeted interventions.

1.2 Theoretical Framework

This study is grounded in the Theory of Planned Behavior (TPB), an extension of the Theory of Reasoned Action (Ajzen, 1991). The TPB posits that attitudes, subjective norms, and perceived behavioral control predict behavioral intentions, which in turn lead to adoption. For EFFPs, attitudes reflect evaluative feelings toward practices (like "EFFPs are beneficial"); subjective norms capture social pressures (for instance, extension advice); and perceived control addresses barriers (such as resource access).

TPB is apt for agricultural adoption, explaining 39% of variance in CSA intentions (Kipng'etich et al., 2025). In Kenya, positive attitudes towards crop rotation (for yield) drive 50% of uptake, but low control perceptions reduce it by 25% (Muriuki et al., 2025). For Embu County, TPB elucidates how female heads' positive attitudes, bolstered by norms of household provision, overcome control barriers via group membership. Complementing TPB, the Diffusion of Innovation (DOI) Theory (Rogers, 2003) frames perceptions of EFFP attributes (observability via demos). Recent applications show DOI explaining 45% of eco-farming diffusion in Africa (Onyango et al., 2025). Integrating TPB and DOI, the framework hypothesizes that favorable perceptions enhance attitudes, with norms and control moderating this effect, accelerating adoption.

II. MATERIAL AND METHODS

2.1 Location of Study

The study was conducted in Embu County, Kenya, situated at 0°31'S, 37°27'E, encompassing the sub-counties of Embu East, Embu North, and Embu West. These regions, with a collective total of 80,138 households, possess considerable agricultural potential but face challenges similar to those encountered in arid and semi-arid lands (ASAL): unpredictable rainfall ranging from 600 to 800 millimeters annually, soil pH levels varying from 3.2 to 8.0, and a population density of 227 individuals per square kilometer (KNBS, 2009; MoLAF, 2016). The predominant agricultural practice is rain-fed mixed farming, with maize and beans cultivated on plots averaging 1.98 acres. This area is therefore suitable for assessing perceptions of the EFFPs.

2.2 Research Design

A descriptive survey design was employed, combining quantitative (Likert-scale surveys on perceptions/attitudes) and qualitative (open-ended questions) methods to capture nuanced views (Kothari, 2014). This cross-sectional approach allowed snapshot analysis of 402 household heads.

2.3 Research Instruments

A structured questionnaire assessed perceptions and attitudes. An observation checklist evaluated farm-level indicators. Instruments were pre-tested in Kirinyaga County. The questionnaire comprised three main sections: (1) demographic information; (2) perception items (12 items) measuring cognitive evaluations of EFFP attributes including relative advantage,

compatibility, complexity, and observability (adapted from Rogers, 2003); and (3) attitude items (10 items) measuring affective predispositions toward EFP adoption (adapted from Ajzen, 1991). All items were measured on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree). Perception items were framed as cognitive beliefs (e.g., "I believe EFPs reduce soil erosion"), while attitude items were framed as evaluative feelings (e.g., "I feel positive about adopting EFPs"). Open-ended questions invited respondents to elaborate on their perceptions and attitudes.

2.4 Validity and Reliability

Content validity was ensured via expert review by five Chuka University academics specializing in agricultural extension, environmental science, and rural sociology, who assessed item relevance and clarity, achieving 92% agreement with TPB constructs. Construct validity was established through alignment with WHO/FAO guidelines for agricultural surveys. Reliability testing using Cronbach's alpha yielded coefficients of 0.85 for the perception scale and 0.82 for the attitude scale, indicating good internal consistency. Test-retest reliability ($r = 0.88$) was established with a subsample of 30 respondents, with a two-week interval between administrations (Tavakol & Dennick, 2011).

2.5 Target Population

The population comprised 80,138 farming households in the three sub-counties (Embu East, Embu North, and Embu West), with household heads as the units of analysis.

2.6 Sampling Procedures

A multistage sampling approach was employed:

- **Stage 1:** Purposive selection of the three sub-counties based on their active promotion of EFPs and representativeness of Embu County's agricultural conditions.
- **Stage 2:** Simple random sampling of 24 out of 70 sub-locations, ensuring proportional representation across sub-counties.
- **Stage 3:** Proportionate stratified sampling of households within each sub-location, using the Yamane formula (Yamane, 1967): $n = N/[1+N(e)^2]$, where $e = 0.05$, yielding a minimum sample of 398. This was adjusted upward to 402 to account for potential non-response.

2.7 Sample Size

The final sample comprised 402 household heads (52% male, 48% female), plus 32 extension officers whose perspectives were collected for triangulation purposes. Data analysis used SPSS Version 27 for descriptive statistics (means, standard deviations, frequencies), inferential tests (independent t-tests, one-way ANOVA), and multiple regression to explore predictors of attitudes. Qualitative insights from open-ended responses ($n=156$) were thematically coded using NVivo 12 to supplement quantitative results.

2.8 Ethical Considerations

Ethical approval was obtained from Chuka University's Research Ethics Committee. Informed consent was obtained from all participants, who were assured of confidentiality and their right to withdraw at any time. Data were anonymized during analysis.

III. RESULTS AND DISCUSSION

3.1 Descriptive Statistics on Perceptions and Attitudes

Perceptions were operationalized as cognitive evaluations of EFPs' attributes (relative advantage, compatibility, and observability, per Rogers, 2003) and measured using a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree) across 12 items adapted from the Diffusion of Innovations (DOI) framework. Attitudes were assessed as affective predispositions that influence behavioural intent (Ajzen, 1991) using a 5-point semantic differential scale across 10 items from the Theory of Planned Behaviour (TPB). Data were analyzed using SPSS Version 27, with descriptive statistics (means, standard deviations), inferential tests (independent t-tests, one-way ANOVA), and multiple regression to explore predictors. Qualitative insights from open-ended responses ($n=156$) supplemented quantitative results, thematically coded using NVivo 12.

Household heads showed moderately positive perceptions of EFFPs (overall mean = 3.92, SD = 0.68), indicating general recognition of their value in addressing local challenges such as soil degradation and erratic rainfall. Subscale analysis showed the strongest agreement on environmental benefits (mean = 4.28, SD = 0.62; for example, "EFFPs reduce soil erosion" – 78% agreement) and resilience enhancement (mean = 4.15, SD = 0.71; "Agroforestry improves drought tolerance" – 72% agreement). Economic perceptions were weaker (mean = 3.45, SD = 0.89), with concerns about initial costs (e.g., "EFFPs require affordable inputs" – mean = 2.98, SD = 1.02). Compatibility with existing practices scored neutrally (mean = 3.67, SD = 0.75), reflecting mixed views on labor demands.

Attitudes towards EFFP adoption were similarly moderate (overall mean = 3.76, SD = 0.74), with positive leanings on long-term benefits (mean = 4.02, SD = 0.69; for example, "adopting EFFPs feels rewarding for family food security" – 68% positive). However, risk perceptions tempered enthusiasm (mean = 3.21, SD = 0.92; for instance, "yield drops from switching are concerning" – 55% negative). Intent to adopt was high (mean = 3.89, SD = 0.81), particularly for low-input practices such as crop rotation (82% intent).

Table 1 summarizes key items by gender, revealing nuanced patterns. Females reported higher means across most subscales (environmental perceptions: 4.35 vs. 4.21 for males), consistent with their intensified farm roles due to male out-migration.

TABLE 1
MEAN PERCEPTIONS AND ATTITUDES BY GENDER

Subscale	Males (n=209, 52%)	Females (n=193, 48%)	Overall Mean (SD)
Environmental Benefits	4.21 (0.65)	4.35 (0.59)	4.28 (0.62)
Economic Viability	3.38 (0.91)	3.52 (0.87)	3.45 (0.89)
Resilience Enhancement	4.08 (0.73)	4.22 (0.69)	4.15 (0.71)
Adoption Intent	3.72 (0.83)	4.06 (0.79)	3.89 (0.81)
Risk Perception	3.28 (0.94)	3.14 (0.90)	3.21 (0.92)

Note: Scale 1-5; higher scores indicate more positive evaluations. Standard deviations in parentheses.

Qualitative data corroborated these trends: 62% of respondents (n=249) described EFFPs as "essential for surviving dry spells," but 41% (n=165) expressed attitudes of apprehension, such as "switching from fertilizers feels like gambling with hunger" (male head, Embu East Sub-County).

3.2 Inferential Analysis: Differences in Perceptions and Attitudes

An independent samples t-test examined gender differences. Females demonstrated significantly more positive attitudes towards adoption intent ($t(400) = -3.45, p = 0.001$, Cohen's $d = 0.34$), but perceptions of economic viability did not differ significantly ($t(400) = -1.56, p = 0.119$). This suggests gender influences affective responses more than cognitive appraisals, potentially due to women's proximate experience with household food provisioning.

A one-way ANOVA tested differences across sub-counties, revealing significant differences in overall perceptions ($F(2,399) = 4.12, p = 0.017, \eta^2 = 0.02$). Post hoc Tukey HSD indicated that Embu West (mean = 4.05) showed significantly higher perceptions than Embu North (mean = 3.85; $p = 0.021$), attributable to better extension access in peri-urban areas. Attitudes did not vary significantly across sub-counties ($F(2,399) = 1.89, p = 0.152$), suggesting uniform emotional barriers across locales. Correlations between perceptions and attitudes were strong ($r = 0.62, p < 0.001$), with environmental perceptions most predictive of positive intent ($\beta = 0.48$ in preliminary regression).

3.3 Regression Analysis: Predictors of Attitudes

Multiple linear regression modeled attitudes as a function of perceptions, subjective norms (for example, extension influence), and perceived behavioural control (for instance, resource access), according to TPB. The model was significant ($F(3,398) = 82.34, p < 0.001, R^2 = 0.38$, adjusted $R^2 = 0.37$), explaining 38% of the variance. Assumption checks indicated acceptable levels of multicollinearity ($VIF < 2.0$) and homoscedasticity (Breusch-Pagan test, $p > 0.05$).

TABLE 2
REGRESSION COEFFICIENTS FOR PREDICTORS OF ATTITUDES TOWARDS EFFP ADOPTION

Predictor	B	SE	β	t	p
Environmental Perceptions	0.42	0.08	0.31	5.25	<0.001
Subjective Norms	0.35	0.07	0.28	5	<0.001
Perceived Control	0.29	0.09	0.19	3.22	0.001
Constant	1.12	0.21	-	5.33	<0.001

Note: $R^2 = 0.38$, *adjusted* $R^2 = 0.37$, $F(3,398) = 82.34$, $p < 0.001$. VIF values < 2.0, indicating acceptable multicollinearity.

Environmental perceptions emerged as the strongest predictor ($\beta = 0.31$), underscoring DOI's emphasis on attribute awareness. Gender moderated the model (interaction term $\beta = 0.15$, $p = 0.032$), with females deriving greater attitude uplift from subjective norms than males.

IV. DISCUSSION

4.1 Summary of Key Findings

The findings illuminate the nuanced interplay between perceptions and attitudes in shaping EFFP adoption among Embu smallholders, revealing a landscape where cognitive optimism coexists with affective caution. Overall positive perceptions (mean 3.92) align with global evidence that farmers in climate-vulnerable contexts value EFFPs' ecological merits, such as erosion control and biodiversity preservation (Pretty & Hine, 2001). In Embu, where soil organic matter averages 0.47-3.67% and dry spells span 65 days, 78% of respondents endorse environmental benefits, echoing Njeru (2015), who documented similar appraisals in Kenyan agroecosystems.

However, subdued economic perceptions (mean 3.45) reflect persistent barriers such as input costs, a pattern corroborated by recent studies: Kipng'etich et al. (2025) reported that Kenyan livestock farmers rated CSA economic viability at 3.4/5, attributing hesitancy to 43% poverty rates, akin to Embu's 42%. This perceptual gap perpetuates adoption inertia, as farmers weigh short-term risks against long-term gains. The qualitative finding that 41% of respondents expressed apprehension, describing switching as "gambling with hunger," underscores this tension between environmental awareness and economic caution.

4.2 Gender Differences and Implications

Gender-disaggregated insights add depth, with females' elevated attitudes (mean 4.06 vs. 3.72 for males) signaling empowerment amid male out-migration, which has elevated female headship to 48% (from 28% in 2017; Achieng', 2017). This phenomenon—what might be termed a "quiet revolution"—manifests in stronger adoption intent ($t = -3.45$, $p = 0.001$), driven by food security imperatives. Muriuki et al. (2025) found female-headed households in Mt. Kenya deriving 20% higher welfare from low-input EFFPs, fostering attitudes of agency. This finding is particularly significant as it challenges earlier perspectives that minimized gender's relevance (Akama et al., 1995) and instead affirms its importance in contemporary agricultural decision-making.

Yet, non-significant economic perception differences ($p = 0.119$) highlight shared vulnerabilities, such as land user rights limiting credit (Barrett & Marenja, 2007). Recent gender-focused work reinforces this complexity: Mnukwa et al.'s (2025) review of Sub-Saharan maize farmers noted female adoption rates 15-30% lower due to control perceptions, but Embu's near-parity headship appears to narrow this gap. Our moderation analysis (interaction term $\beta = 0.15$, $p = 0.032$) indicates that females derive greater attitude uplift from subjective norms, suggesting that peer and extension influences are particularly powerful for women in this context.

4.3 Spatial Variations and Extension Access

Sub-county variations ($F = 4.12$, $p = 0.017$) underscore spatial inequities, with Embu West's higher perceptions linked to extension proximity. This finding resonates with Innovations in Agricultural Extension (2025), which advocates the use of ICT to bridge rural-urban knowledge divides in CSA uptake. The fact that attitudes did not vary significantly across sub-counties suggests that while awareness differs spatially, emotional barriers are more uniformly distributed. This implies that extension

interventions need to address both knowledge gaps (perceptions) and emotional barriers (attitudes) through appropriately designed programs.

The low extension officer-to-farmer ratio (approximately 1:2,000, based on extension officer interviews) exacerbates the perception gap, as documented by Mworira (2018). This structural constraint limits the reach of advisory services and contributes to the modest adoption rates (30-40%) observed in the region (Amudavi et al., 2015).

4.4 Theoretical Implications

The robustness of the regression model ($R^2 = 0.38$) affirms the explanatory capability of the Theory of Planned Behavior (TPB), with environmental perceptions serving as a pivotal factor ($\beta = 0.31$). This finding aligns with Kipng'etich et al. (2025), who found that perceptions of Climate-Smart Agriculture (CSA) accounted for 35% of Kenyan farmers' intentions. Subjective norms ($\beta = 0.28$) emphasize the significance of extension services and peer influence. The qualitative finding that Embu farmers regarded composting (an environmentally friendly farming practice) as sustainable but dismissed its adoption due to normative discrepancies within peer networks highlights the social dimension of adoption decisions.

The integration of TPB and DOI proves valuable: perceptions of innovation attributes (environmental benefits, compatibility) combine with social and psychological factors (subjective norms, perceived control) to explain attitudes. Recent investigations into regenerative systems (Kolapo, 2025) further extend this understanding, demonstrating that attitude shifts achieved through participatory demonstrations can enhance perceptions of control by 22% in Kenyan Arid and Semi-Arid Lands (ASALs).

4.5 Implications for Policy and Practice

The findings have several implications for policy and practice:

- 1) **Targeted Extension Services:** Given that subjective norms significantly influence attitudes ($\beta = 0.28$), extension programs should leverage peer-to-peer learning and farmer-to-farmer networks, particularly for female farmers who derive greater benefit from such influences.
- 2) **Addressing Economic Barriers:** The perception gap regarding economic viability (mean 3.45) suggests that interventions should address not only awareness but also practical constraints. This could include access to credit, input subsidies, or cost-sharing arrangements.
- 3) **Gender-Sensitive Programming:** The more positive attitudes among female heads (mean 4.06 vs. 3.72) should be leveraged through programs that recognize women's agency and provide resources tailored to their needs and constraints.
- 4) **ICT Integration:** The spatial variation in perceptions suggests that ICT-based extension could help bridge the rural-urban knowledge divide, particularly for remote areas with limited extension access.
- 5) **Demonstration and Learning:** Qualitative findings indicating apprehension about yield losses suggest that demonstration plots and participatory learning approaches could help mitigate risk perceptions and build confidence in EFFPs.

4.6 Contributions to Sustainable Development Goals

These findings contribute to SDG 2 (Zero Hunger) by identifying pathways to increase agricultural productivity through sustainable practices, and to SDG 13 (Climate Action) by promoting climate-resilient farming. Positive perceptions of environmental benefits (4.28/5) and resilience enhancement (4.15/5) suggest that farmers recognize the climate adaptation potential of EFFPs. However, the attitude gap (3.76/5) indicates that recognition does not automatically translate to adoption, requiring supportive policies and interventions.

4.7 Study Limitations

Several limitations should be acknowledged:

- 1) **Cross-Sectional Design:** The cross-sectional nature of the study precludes causal claims about the relationship between perceptions, attitudes, and adoption. While regression analysis shows associations, longitudinal research would be needed to establish causation.

- 2) **Self-Reported Perceptions:** The data rely on self-reported perceptions and attitudes, which may not perfectly correspond to actual behavior. Social desirability bias may have influenced responses.
- 3) **Generalizability:** The study is specific to Embu County, which has unique characteristics (48% female headship due to migration, specific agro-ecological conditions). Generalization to other parts of Kenya or Sub-Saharan Africa should be made cautiously.
- 4) **Focus on Household Heads:** The study focuses on household heads, potentially missing the perspectives of other household members who may influence adoption decisions.
- 5) **Qualitative Data Integration:** While qualitative data were collected, the integration of these findings could be strengthened with more direct linkage to quantitative results.

4.8 Future Research Directions

Based on the findings and limitations, future research could:

- 1) **Longitudinal Studies:** Track changes in perceptions and attitudes over time to understand how they evolve with exposure to EFFPs and how they translate to actual adoption.
- 2) **Behavioral Measures:** Complement self-reported perceptions with actual behavioral data to validate the perception-adoption relationship.
- 3) **Comparative Studies:** Compare Embu County with other regions with different gender dynamics, extension systems, or agro-ecological conditions.
- 4) **Household Dynamics:** Explore how intra-household dynamics influence adoption decisions, beyond the household head perspective.
- 5) **Intervention Studies:** Test the effectiveness of specific interventions (e.g., farmer field schools, credit programs, demonstration plots) in shifting perceptions and attitudes.
- 6) **Gender Analysis:** Further investigate the mechanisms through which gender influences perceptions and attitudes, including the role of migration, intra-household bargaining, and social norms.

V. CONCLUSION

5.1 Summary of Findings

This study examined the perceptions and attitudes of farming household heads toward Eco-Friendly Farming Practices (EFFPs) in Embu County, Kenya, drawing on a mixed-methods approach with a robust sample of 402 respondents. The findings reveal that household heads in Embu County perceive EFFPs as environmentally superior, with strong recognition of their benefits for soil conservation (mean 4.28/5) and resilience enhancement (mean 4.15/5). However, attitudes are mixed, tempered by concerns about economic viability (mean 3.45/5) and risk perceptions (mean 3.21/5), reflecting the tension between environmental awareness and practical constraints.

Gender-disaggregated analysis shows that female-headed households exhibit significantly more positive attitudes (mean 4.06 vs. 3.72, $p = 0.001$) toward EFFP adoption, attributed to their intensified farm roles due to male out-migration and their proximate experience with household food provisioning. The regression model ($R^2 = 0.38$) confirms the utility of the Theory of Planned Behavior, with environmental perceptions ($\beta = 0.31$), subjective norms ($\beta = 0.28$), and perceived behavioral control ($\beta = 0.19$) as significant predictors of attitudes.

5.2 Theoretical Contributions

This research contributes to the literature by:

- 1) Demonstrating the application of TPB and DOI in an Embu County context, confirming their utility in explaining agricultural innovation adoption.
- 2) Revealing the differential influence of perceptions and attitudes on adoption intent, with perceptions more strongly predicting attitudes than vice versa.

- 3) Identifying gender as a significant moderator of the perception-attitude relationship, with females deriving greater benefit from subjective norms.

5.3 Practical and Policy Implications

Several practical implications emerge from the findings:

- 1) **Extension Services:** Extension programs should address both cognitive perceptions (knowledge of benefits) and emotional attitudes (risk perceptions, confidence). Participatory approaches that engage farmers in experiential learning may be particularly effective.
- 2) **Gender-Sensitive Programming:** Leverage the positive attitudes among female heads by targeting them with resources, training, and credit access. Recognizing women's agency in agricultural decision-making is crucial for scaling EFPF adoption.
- 3) **Economic Interventions:** Address economic barriers through credit access, input subsidies, and cost-sharing arrangements to convert positive environmental perceptions into adoption behavior.
- 4) **Peer Learning:** Given the influence of subjective norms, farmer-to-farmer networks and demonstration plots can facilitate social learning and norm change.
- 5) **Spatial Equity:** Address spatial inequities in extension access, potentially through ICT-based extension to reach remote areas.

5.4 Achievements and Significance

The study has achieved its objective of examining the influence of perceptions and attitudes on EFPF adoption among household heads in Embu County. By identifying the perception-attitude gap, particularly the economic barrier, the research provides a basis for targeted interventions. The gender findings, showing more positive attitudes among female heads, challenge stereotypes and highlight an opportunity for inclusive agricultural development. The results contribute to SDG 2 (Zero Hunger) by identifying pathways to increase agricultural productivity through sustainable practices, and to SDG 13 (Climate Action) by promoting climate-resilient farming.

5.5 Study Limitations and Future Research

This study has limitations that should be acknowledged: the cross-sectional design limits causal claims; self-reported perceptions may not perfectly correspond to behavior; the findings are specific to Embu County; and the focus on household heads may miss other household members' perspectives. Future research should employ longitudinal designs, incorporate behavioral measures, undertake comparative studies across regions, and test specific interventions to shift perceptions and attitudes.

5.6 Final Reflection

In conclusion, household heads in Embu County perceive EFPFs as environmentally beneficial but harbor mixed attitudes due to socioeconomic barriers. The positive attitudes among female-headed households, in the context of near-parity headship (48%), present a significant opportunity for equitable agricultural transformation. This study underscores the need for perception-focused interventions that address both cognitive assessments and emotional barriers to foster widespread adoption of EFPFs, thereby enhancing resilience within smallholder agroecosystems and contributing to sustainable agricultural development in Kenya.

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CONFLICT OF INTEREST

The author declares that he has no competing interests, financial or otherwise, that could have influenced the conduct, interpretation, or reporting of this research.

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Re-Focusing Animal Management Education to Encourage Nomadic Career Life Skills in Adamawa State, Nigeria

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Abstract— This paper sets out to study the re-focusing of animal management education to encourage nomadic career life skills in Adamawa State, Nigeria. The National Commission for Nomadic Education (NCNE) is charged with the responsibility of providing education to children whose parents are in nomadic life, as well as adult and non-formal sectors. The paper is based on two research questions, two objectives, and two corresponding hypotheses tested at a 0.05 level of significance. The research design for this study is correlation research design, and it used a multistage sampling technique in selecting 465 respondents comprising 12 supervisors, 51 head teachers, 228 nomadic teachers, 153 pupils, and 51 parents. The instruments for data collection include a questionnaire, observation checklist, and interview guides. The hypotheses were tested using simple linear regression analysis at a 0.05 level of significance. The first hypothesis revealed an unstandardized coefficient value of 0.341 and $p = 0.00$, which is less than the hypothetical value of 0.05. This stated that elementary science encourages nomadic education curriculum on critical thinking in Adamawa State. The second hypothesis revealed an unstandardized coefficient value of 0.434, with $p = 0.00$, which is less than the hypothetical value of 0.05. This stated that animal management induces nomadic career life skills in Adamawa State. The acceptance of all alternative hypotheses makes it feasible for the study to conclude that animal management encourages nomadic career life skills in Adamawa State, Nigeria. The study recommends, among others, that key actors (teachers) in nomadic schools should be provided with career life skills to encourage nomadic career life skills.

Keywords— Re-focusing, Animal Management, Nomadic Career Life Skills, Adamawa State, Nomadic education, Agricultural education, Livestock management, Career development, Pastoralists.

I. INTRODUCTION

Education is a social right in itself and a key means of realizing other human rights, particularly the right to education. It is seen as an empowerment right. Education is the primary vehicle by which economically and socially disadvantaged adults and children can lift themselves out of poverty and acquire the means of full participation in their communities. It also plays a significant role in empowering women, protecting street-working children from unequal and dangerous labor and sexual abuse, promoting human rights and democracy, protecting the environment, and controlling population growth (UNESCO, 2014).

The philosophy of Nigerian education is based on the integration of the individual into sound and effective citizenship with equivalent educational opportunities for all and at all levels through the formal and non-formal school system. More significantly, the government of Nigeria believes that the provision of well-designed education is the crucial means of improving the socioeconomic condition of the rural populace. Among such populaces, predominantly pastoralist nomads and migrant fisherfolk are difficult to reach. This was revealed by their participation in existing formal and non-formal education programs, which are abysmally low, with literacy rates ranging between 0.02% for pastoral nomads and 2.0% for migrant fisherfolk as at the early stage of implementing Nomadic Education (National Commission for Nomadic Education [NCNE], 2017).

Pastoral nomads perceive themselves as significant people, as noted by Okugagu (2015), who stated that they play a significant role by being the main suppliers of beef, mutton, hides and skins, hoof, horn, dung for manure, bones, and cow urine used in the production of medicine. They also play a significant role in agriculture by providing natural manure that restores soil fruitfulness and the payment of cow tax "janjali," which is one of the significant sources of internally generated revenue of the nation. They should unquestionably be analyzed as a significant segment of the nation's economy that should be given consideration in the distribution of amenities and provision of education, which they are unfortunately inadequately provided.

Nomadic life in Nigeria has several categories. This includes nomadic hunters, fishermen, pastoral nomads, nomadic mallams (Almajiri teachers), migrant laborers, and migrant farmers. Commonly, nomads live in low-density remote areas, which in most cases pose some difficulty in getting their family data. This in turn renders it difficult to get accurate data in respect of nomadic life in the communities and thus on education. It was against this background that the Nomadic Education program was designed to cater for the education of children of the nomads because they generally do not have access to the traditional school system due to their nomadic lifestyle (Bello, 2019).

It is often difficult to capture this group during government censuses; however, there are an estimated 9.4 million nomads in Nigeria. Over 5 million are nomadic pastoralists, while the remainder are nomadic farmers and fishermen, found mostly around the Chad River basin in north-eastern Nigeria (John, Tyndall, Okoye, & Osewe, 2018). Nomadic pastoralists are a composite of many different ethnic groups; however, over 90% belong to the Fulfulde or Fulani tribe, which represents 6.6% of the Nigerian population. Adamawa has an estimated 450,000 nomadic Fulani pastoralists across the 21 Local Government Areas of Adamawa State, making it the State with the highest population of nomads in Nigeria. The greater majority (90%) of nomadic Fulani who have no access to western education is a source of potential challenge to the nation's overall development (John et al., 2018).

It is important to note that nomads in Nigeria play an important role in being major suppliers of beef, mutton, hides and skins, hoof, horn, dung for manure, bones, cow urine used in medicine production, and food security. About 95% satisfy their compatriots' protein needs; indisputably, they are part of the nation's economy (Abdulrahman, 2016). The "jangali" animal tax which they pay should further elicit pity and consideration in the distribution of amenities, which they are unfortunately deprived. It has also been argued that the nation's security would never be fully achieved until every citizen knows his/her full responsibilities through the provision of quality basic education for all (Abdulrahman, 2016). It is against this background that the present study intends to carry out "Re-Focusing Animal Management Education to Encourage Nomadic Career Life Skills in Adamawa State, Nigeria."

II. STATEMENT OF THE PROBLEM

Nomads constitute a segment of the Nigerian population. However, despite their proportion in the Nigerian population, nomads remain a special group whose economic, socio-cultural, and political potentials are yet to be tapped to the optimum (Abubakar & Ogugua, 2015). Various empirical works have identified series of gaps between government and national development. Specifically, Bello (2019) discovered that the level of literacy on Animal Management Education life skills remains low among nomads despite the adoption of the United Nations' Education for All in Nigeria.

Earlier works by Ezeomah (2016), Aminu (2014), Umar (2018), and Abba (2018) have shown that the participation of nomadic people in formal education and Animal Management Education was low, which was largely attributed to their low level of appreciation of conventional education, disagreement between their occupational schedules and the formal school calendar, and the critical role of children in their production chain, which makes them extremely reluctant to send their wards to school.

Therefore, the peculiar lifestyle of animal management education among nomads in Nigeria could be argued to make it difficult to participate in the formal education system, despite the fact that they share a large proportion of the Nigerian population as well as play important roles in the nation's economy, nutrition, and the transhumance techniques of livestock production.

More so, some authors have attributed their low level of participation in formal education to the gap created in the nomadic education curriculum, which seems to be disproportionate to the lifestyle of nomads of continuous movement with herds in search of food for livestock (Maxwell, Iroegbu & Onyenso, 2018). There are also those with the view that the lack of involvement of the nomads in the design of curriculum led to the inclusion of irrelevant curriculum contents that are unfavorable to the needs of the nomads' education requirements (Muhammad and Aliyu, 2017; Jeffs & Smith, 2018; Chris, 2019).

Lamb, Maire, and Doecke (2017) observed that obviously, relevant Animal Management Education and life skills of the 21st century are essential in promoting effectiveness in animal management. A failure in these respects is bound to impact negatively on the quality of animal management education of the nomadic child. Evidence from reviewed literature showed that the majority of studies were being conducted with focus on various aspects of nomadic education within and outside Nigeria, which creates a gap regarding animal management education and life skills among nomads. More so, none of the few empirical studies conducted within Nigeria took animal management education and life skills in the North-East as a case study. This shows that most studies are silent about implementation strategy for 21st-century nomadic education curriculum.

Therefore, various inputs towards animal management education and life skills nomadic education in Adamawa State, Nigeria, there is hardly evidence of nomadic products with animal management education and life skills among nomadic people in the state has been poor. What could be responsible for the inability of this laudable program to impact positively on the intended nomads in the state? Is the program lacking in the amount of attention it needs in terms of animal management among nomads or the provision of devoted teaching staff to implement the modern life skills to the nomads and modern infrastructural development of educational institutions? Therefore, this study set out to re-focus Animal Management Education to Encourage Nomadic Career Life Skills in Adamawa State, Nigeria.

III. PURPOSE OF THE STUDY

The main purpose of the study is to re-focus Animal Management Education to encourage Nomadic Career Life Skills in Adamawa State, Nigeria.

3.1 Specific Objectives

- 1) Determine the extent to which agricultural education encourages nomadic education curriculum on career life skills in Adamawa State.
- 2) Determine the extent to which animal management encourages nomadic education curriculum on career life skills in Adamawa State.

3.2 Research Questions

The study attempted to answer the following research questions:

- 1) To what extent does agricultural education induce nomadic education curriculum on career life skills in Adamawa State?
- 2) To what extent does animal management induce nomadic education curriculum on career life skills in Adamawa State?

3.3 General Hypothesis

Animal Management Education encourages Nomadic Career Life Skills in Adamawa State.

3.4 Hypotheses

- 1) Agricultural education induces nomadic education curriculum on career life skills in Adamawa State.
- 2) Animal management induces nomadic education curriculum on career life skills in Adamawa State.

IV. THEORETICAL FRAMEWORK

4.1 Theory of Shulman's Pedagogical Content Knowledge (PCK)

The study is guided by a modified model of pedagogical content knowledge theory propounded by the ideas of Shulman (1986, 1987) regarding pedagogical content knowledge, often abbreviated as PCK. The theory states that "particular outline of content knowledge that embody aspects of content most connected to its teachability" (Shulman, 1986). He first introduced the PCK concept into the educational realm after he had noticed that policies in the 1980s that dealt with teacher ability neglected content and focused mainly on basic pedagogy. He also understood that there was a gap in research regarding subject matter content and that research literature on subject matter content teaching was lacking. This lack of content in research interpreted into policymakers also ignoring it when setting standards for teacher competency evaluations. "No one asked how subject matter was transformed from the knowledge of the teacher into content of instruction" (Shulman, 1986).

In the context of nomadic education, PCK is particularly relevant because teachers need to transform agricultural and animal management content into forms that are pedagogically powerful and yet adaptive to the nomadic lifestyle. This requires teachers to understand not only the subject matter but also the unique cultural and occupational context of nomadic learners.

V. METHODOLOGY

5.1 Research Design

The correlation research design was used for this study. A correlation study was used since it is intended to investigate the relationship between the variables under study (Curtis, Comiskey, & Dempsey, 2016). Also, Creswell (2012) stated that correlation research design investigates the relationship between two variables without manipulation of one variable over the other. These views also imply that the researchers in this research do not attempt to control or manipulate the variables as in an experiment. This study used an explanatory design since the study investigated the degree of association between two variables.

5.2 Population of the Study

The population for the study encompasses 20 supervisors, 140 head teachers, 529 nomadic teachers, 23,385 pupils, and 828 parents respectively, distributed across the five educational zones of Adamawa State. The schools are located in each local government in Adamawa State excluding Yola North. This is because the Yola North Local Government Area does not run any Nomadic Education program separately.

TABLE 1

TEACHING STAFF, TEACHERS, PARENTS, AND STUDENTS IN NOMADIC SCHOOLS IN THE EDUCATIONAL ZONES OF ADAMAWA STATE BY 2020

S/ N	Educational Zones	No. of Supervisors & H/Teachers		No. of Classroom Teachers	No. of Pupils	No. of Parents
1	Ganye	4	42	172	6316	201
2	Gombi	3	20	69	3509	120
3	Mubi	5	18	79	3455	139
4	Numan	5	28	63	4292	128
5	Yola	3	34	146	5813	240
	Total	20	140	529	23385	828

Source: Nomadic Education Unit ADSUBEB, Yola (2020)

5.3 Sample and Sampling Techniques

The sample size for this study is 465, comprising 12 supervisors, 51 head teachers, 228 nomadic teachers, 153 pupils, and 51 parents. The study adopted a multistage sampling technique. At the first stage, the study selected three out of five education zones: Ganye, Mubi, and Yola, because nomadic schools in all zones shared similar characteristics. Furthermore, the Ganye, Mubi, and Yola education zones were selected due to high viability of many schools in those zones. At the second stage, the study purposively selected all 12 supervisors found in the three selected education zones, while a total of 51 head teachers were randomly selected across the three selected zones at a rate of 17 head teachers per education zone.

Also, the sample size of 228 was determined for teachers from their population of 529 using the Taro Yamane formula:

$$n = \frac{N}{1+N(e)^2} \quad (1)$$

Where:

- N = Total population (529)
- e = Level of significance (0.05)

- n = Sample size

$$\text{Then, } n = \frac{529}{1+529(0.05)} = 228$$

Based on this formula, the sample size for nomadic teachers is 228. Therefore, the 228 teachers were chosen at random, with 76 teachers per zone, to give equal selection rights to all strata of the three selected zones. In the same vein, a total of 153 pupils were selected across the three zones at a rate of 51 pupils per zone to give equal representation. Therefore, 3 pupils were selected per school across the 17 selected schools in each zone, repeatedly done across the remaining two zones. Lastly, the study selected a total of 51 parents using a purposive sampling technique to choose a representative of the PTA in each of the selected schools.

5.4 Instruments for Data Collection

The instruments for data collection include a questionnaire, observation checklist, and interview guides. The instrument is tagged "Questionnaire for Nomadic Education Curriculum Implementation of 21st Century Skills of Basic Education (QNECICSBE)," which was developed by the researcher. It is made of five sections with a total of 41 items. The items were designed based on a 5-point Likert rating scale. Thus, the rating scales are: Very High Extent (VHE = 5), High Extent (HE = 4), Moderate Extent (ME = 3), Low Extent (LE = 2), and Very Low Extent (VLE = 1). The QNECICSBE was administered to teachers, head teachers, and supervisors of nomadic schools in Adamawa State.

The observation checklist, tagged "Classroom Observation Checklist for Nomadic Primary School Pupils" (COCNPSP), was developed by the researcher and sectioned into five sections. The COCNPSP comprises 15 items that allow the raters to rate pupils based on different constructs such as listening skills, reading skills, speaking skills, writing skills, and leadership skills. The rating points ranged from 1 to 5 in order of Excellent = 5 points; Very Good = 4 points; Good = 3 points; Weak = 2 points; and Very Weak = 1 point. The COCNPSP was given to research assistants in each school to rate pupils.

The interview guide, tagged "Interview Guide for Nomadic Parents" (IGNP), is sectioned into six sections (A–F) comprising eight items probing parents' understanding and perspective regarding the effectiveness of nomadic curriculum implementation in Adamawa State as noticed on their children.

5.5 Reliability of the Instrument

The reliability of the instrument was determined by pilot testing the questionnaire, observation checklist, and interview guide. A pilot study was very helpful because through it, the researcher ascertained the reliability of the instrument and made improvements where necessary. The instrument was administered to 20 nomadic education teachers, 5 head teachers, 35 pupils, and 9 parents, totaling 69 respondents in Gombe State, which is outside the researcher's study area. The population size of the pilot study is considered adequate for the pilot test based on the suggestion of Teresi, Yu, Stewart, and Hays (2022), who recommends 10% of the sample required for a full study. Teachers, head teachers, supervisors, parents, and pupils were randomly selected from five nomadic schools in Gombe State, which have similar characteristics to those of Adamawa State. The result obtained from the pilot study was analyzed using the Cronbach alpha formula with the help of SPSS version 23, and a reliability coefficient of 0.86 was obtained.

Mathematically, Cronbach's Alpha formula (α) is:

$$\alpha = \frac{k}{k-1} \left\{ 1 - \frac{\sum \sigma_k^2}{\sigma^2} \right\} \quad (2)$$

Where:

- $\sum \sigma_k^2$ is the sum of the variances of the k parts, which are the items of the test or instrument
- σ = standard deviation of the test or instrument

The researcher administered the instrument (questionnaire) personally and retrieved it back after a week for further justification and analysis.

5.6 Method of Data Collection

The researcher visited the sample schools in the educational zones two times. During the first visit, the researcher met with the administrators, school head teachers, parents, and pupils of the nomadic schools in the educational zones and presented a letter

of introduction permitting the researcher to carry out research in the study area. The researcher explained that the purpose of the research is for academic purposes only to clear any doubts. During the visits, the researcher sought a convenient date and time during which he would administer the questionnaire, interview, and observation.

The researcher conducted three days of induction training for the 4 research assistants in each of the three participating educational zones on how to administer the instruments. The researcher and research assistants administered the instruments to the respondents and allowed the respondents to answer the instrument for a period of two days. Also, the researcher and research assistants collaborated with teaching staff to administer the interview guide and observation checklists. Data collection was expected to last for four weeks. The researcher sorted out and tallied the responses for further justification and analysis.

5.7 Method of Data Analysis

The data collected through instruments were analyzed using mean, standard deviation, and bar charts, while regression analysis was used to test the hypothesis at a 0.05 level of significance. The Statistical Package for Social Sciences (SPSS) Version 23 software was used in the analysis.

Decision rule: Any mean between 4.50 and above was considered a very high extent; mean of 3.50 to 4.49 was considered a high extent; mean between 2.50 and 3.49 was considered a moderate extent; mean below 1.50 to 2.49 was considered a low extent; while mean between 0.50 and 1.49 was concluded to be a very low extent. The decision for testing the hypothesis is that any p-value that is less than or equal to the level of significance (0.05), the null hypothesis would be rejected; while if the computed p-value is greater than the level of significance, the null hypothesis would not be rejected.

TABLE 2
NULL HYPOTHESIS TABLE

Variables	Definition of variables	Indicators	Category	Measure
Career life skills	Various career life skills	1. Herd size management skills	Ordinal	5-point Likert Scale
		2. Milk yield management skills		
		3. Daily income generation		
		4. Improvement in livelihood		
		5. Vocational skills		
		6. Livestock management		
		7. Para-veterinary skills		
		8. Animal breeding		
		9. Animal feeding		

Source: Researcher's Work (2022)

Note: Value point < 2.50 is considered Low; Value point > 2.49 < 3.50 is considered Moderate; and Value point > 3.50 is considered High.

VI. RESULTS AND DISCUSSION

6.1 Data Presentation

Descriptive statistics is a summary statistic that quantitatively summarizes features of a collection of information. Thus, the descriptive analysis provides simple summaries of the sample and about the observations that have been made from data collected from the field. Descriptive statistics are different from inferential statistics in that descriptive statistics aim to summarize collected data into meaningful quotients rather than using the data to learn about the population that the sample of data is thought to represent.

6.2 Analysis of Research Question

Research Question 1: To what extent do the agricultural and animal management contents of nomadic education curriculum promote development of career life skills among nomadic pupils in Adamawa State?

Data collected regarding the research question concerning herd size, milk yield, daily income generation, improvement in their livelihoods, vocational skills, livestock management, para-veterinary services, animal breeding, and animal feeding were analyzed using simple percentage and presented in a bar chart in Figure 1 below.

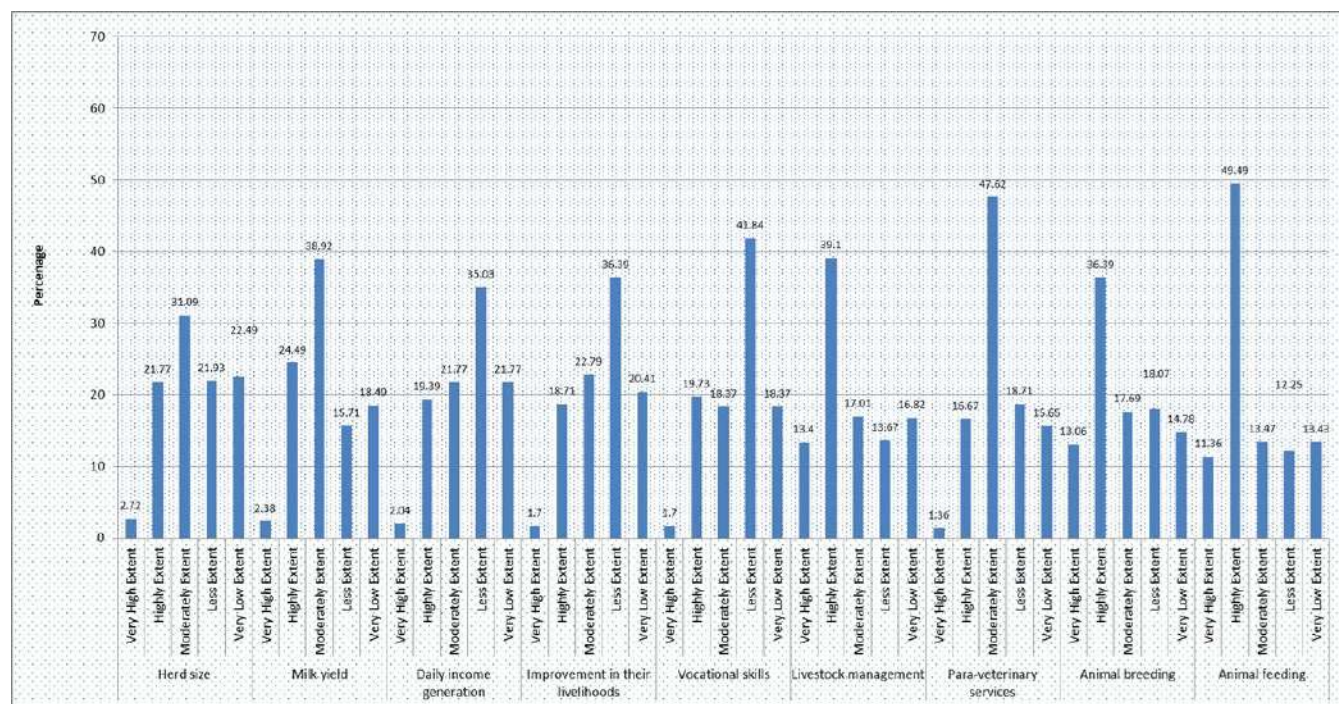


FIGURE 1: Effectiveness of agricultural and animal management curriculum on career life skills development among nomadic pupils in Adamawa State

Note: The figure should show the percentage ratings for each career life skill category based on the survey data.

The results from Figure 1 present the respective ratings of career life skills development among nomadic pupils as a result of implementing the curriculum on agricultural and animal management. The results reveal that rated herd size management skills of nomadic pupils are moderate (31.09%); milk yield skill (38.82%), daily income generation (35.05%), improvement in livelihoods (38.39%), vocational skills (41.34%), livestock management skills (39.10%), para-veterinary services (47.62%), animal breeding skills (34.39%), and animal feeding (49.49%). Overall, the result shows that the pupils improve in skills development for agricultural and animal management.

6.3 Testing of Hypothesis

Hypothesis 1: Agricultural and animal management induces nomadic education curriculum on career life skills in Adamawa State.

TABLE 2a

MODEL SUMMARY FOR REGRESSORS (AGRICULTURAL AND ANIMAL MANAGEMENT CONCEPT AND CAREER LIFE SKILLS)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.387a	0.15	0.145	0.79985

6.3.1 Predictors: (Constant), Agricultural and Animal Management (Rating)

The model summary for the dependent (career life skills) and independent variable (agricultural and animal management concept) was presented in Table 2a. The result reveals an R-value of 0.387, which shows moderate quality of the prediction of the dependent variable (career life skills) based on the independent variable (agricultural and animal management concept). Also, the R-square value of 0.150 and the adjusted R-square values of 0.145 showed that the coefficient of determination is weak, indicating that about 15% of variation in the dependent variable (career life skills) can be explained by the independent variable (agricultural and animal management concept).

TABLE 2b

OUTCOME OF REGRESSION ANALYSIS ON INFLUENCE OF AGRICULTURAL AND ANIMAL MANAGEMENT CONCEPT ON CAREER LIFE SKILLS AMONG NOMADIC PUPILS IN ADAMAWA STATE, NIGERIA

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	4.009	0.283		14.147	.000
Agricultural and Animal Management (Rating)	0.434	0.081	0.387	5.36	.000

6.3.2 Dependent Variable: Career Life Skills

The results in Table 2b reveal an unstandardized coefficient value of 0.434, Std. Error of 0.081, standardized coefficient value of 0.387, t-value of 5.360, and $p = 0.00 < 0.05$. This shows that the agricultural and animal management concept currently accounts for about 34.1% improvement in career life skills among nomadic pupils, leaving about 65.9% of career life skills yet to be developed.

The results from the tested hypothesis showed that the career life skills among pupils are within a moderate level, with a huge level of development yet to be attained. This could be as a result of the approach mostly used by teachers in formal education settings.

VII. DISCUSSION

7.1 Effectiveness of Agricultural and Animal Management of Nomadic Education Curriculum on Development of Career Life Skills among Pupils in Adamawa State

The findings from this study established that the agricultural and animal management in nomadic education curriculum significantly influences career life skills among nomadic pupils in Adamawa State. Specifically, the results of analysis showed that the implementation of nomadic education curriculum in the aspect of agricultural and animal management has a moderate effect on the herd size management skills among nomadic pupils in the study area.

The finding may be in connection with the fact that the background of most pupils has something to do with cattle rearing and animal husbandry (Bell, 2020). A similar conclusion was drawn by Bolstad et al. (2012) and Onwumere et al. (2016) that failure to link learners' background with classroom activities could deny consistent learning and total commitment among pupils. Thus, teaching knowledge of herd-size management among nomadic pupils could be seen as a good approach since most of these pupils are from families that base their livelihoods on cattle rearing activities. It then becomes paramount for the teachers to ensure that classroom instructions do not contradict learners' background. Carr-Hill et al. (2015) maintained that even if there are dissimilarities between what pupils know and what is to be taught by teachers, teachers may need to start from previous pupil's knowledge and understanding before adding something new or modification with thorough explanation. It could be disastrous if learners were to spot differences between their cultural practices of herd-size management and that of school approach without teachers guiding them through such differences.

The results from this study showed that the implementation of nomadic education curriculum in the aspect of agricultural and animal management has a higher effect on the milk yield management skills among nomadic pupils in the study area. The high level of milk yield management among nomadic pupils could be as a result of the fact that these pupils are from a nomadic background where their father's major occupation has to do with cattle breeding and animal production. Also, most nomadic families engage in what is known as family business, where the father as head of family serves as owner and manager of animal production in collaboration with his sons and young daughters, while his wives and grown-up daughters focus on milk yield management. Bell (2020) expressed that such arrangements engage every member of the nomadic family to the extent that no time is left for them to rest.

VIII. CONCLUSION

This study, through its findings, has established that nomadic pupils are gaining meaningful development through the teaching of agricultural and animal management aspects of nomadic education curriculum. The study showed that nomadic pupils gained significantly in the aspects of herd size management, milk yielding, livestock management skills, para-veterinary skills, and

animal feeding. Though other aspects such as vocational skills, daily income generation, and animal breeding are less developed across studied nomadic schools.

IX. RECOMMENDATIONS

Based on the findings and conclusion from this study, the following recommendations were made toward effective animal management education to encourage nomadic career life skills in Adamawa State, Nigeria:

- 1) **Strengthen Practical-Based Teaching Approaches:** Nomadic teachers in Adamawa State should implement more hands-on and experiential teaching skills in delivering the agricultural and animal management curriculum. Such hands-on activities, including school farming, animal care demonstrations, and role-playing para-veterinary services, will make pupils more engaged and relevant, leading to better acquisition of life skills.
- 2) **Capacity Building for Teachers:** There is a need for the Adamawa State Government to provide regular training and capacity-building workshops for teachers of nomadic education in the state. These trainings should emphasize innovative pedagogical skills, inclusive classroom strategies, and context-specific content delivery to ensure effective implementation of skill-based curricula.
- 3) **Integration of Indigenous Knowledge and Practices:** The curriculum developers should integrate indigenous knowledge and traditional practices in livestock and agricultural management acquainted with nomadic communities. This will expand relevance, enhance skill transfer, and increase pupils' motivation to apply what they learn in their daily lives.
- 4) **Provision of Infrastructural and Material Support:** Government at all levels should provide suitable teaching and learning materials, which include tools for animal care, mini farms, charts, and audiovisual aids. Furthermore, mobile classrooms and flexible learning schedules should be adopted to accommodate nomadic lifestyles and encourage regular school attendance.
- 5) **Continuous Monitoring and Curriculum Review:** A periodic system of monitoring and curriculum review should be established to evaluate the impact of agricultural and animal management education on skill development. Feedback from pupils, teachers, and local communities should inform curriculum updates to ensure responsiveness to learners' needs and community realities.
- 6) **Strengthen Teacher Motivation and Support:** The government should provide adequate incentives and support for nomadic teachers to encourage commitment and reduce turnover in nomadic schools.

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CONFLICT OF INTEREST

The author declares no conflict of interest regarding the publication of this manuscript.

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Data-Driven Policymaking for Sustainable Agribusiness Development: An Analysis on Leveraging AI and Digital Technologies

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Abstract— The global agricultural sector faces an unprecedented convergence of challenges: population growth, accelerating climate variability, and chronic food insecurity. Artificial intelligence (AI) and digital technologies have emerged as transformative instruments capable of reshaping agribusiness value chains and enabling evidence-based policymaking at scale. This paper examines how data-driven policymaking can advance sustainable agribusiness development in Nigeria—Africa's largest economy—with particular focus on how AI technologies proven in the United States, the Netherlands, Japan, and Australia can be directly replicated and adapted for the Nigerian context. Nigeria's agricultural sector, contributing 24.8 percent of GDP and employing over 70 percent of the rural population, stands at a critical inflection point characterized by profound dualities of latent potential and systematic underperformance. The paper maps specific replication pathways across six priority domains: satellite crop monitoring, AI-powered market intelligence, precision agriculture for smallholders, agricultural finance and index insurance, supply chain optimization, and national data infrastructure. Drawing on proven pilot programs already operational in Nigeria, the paper presents eight integrated, actionable policy recommendations spanning data infrastructure establishment, national governance frameworks, digital extension services, AI innovation funding, broadband connectivity, and evidence-based monitoring architecture. Together, these constitute a coherent digital transformation agenda capable of closing Nigeria's productivity gap and positioning the country as a continental leader in sustainable agribusiness development.

Keywords— Agribusiness, Artificial intelligence, Data-driven policy, Digital agriculture, Food security, Nigeria, Precision agriculture, Agricultural policy, Digital transformation, Smallholder farmers.

I. INTRODUCTION

Agriculture remains the backbone of global economic development, providing livelihoods for an estimated 2.5 billion people and contributing approximately 4 percent of global GDP (World Bank, 2023). Despite its foundational importance, the sector faces an unprecedented convergence of structural pressures that conventional farming systems are increasingly ill-equipped to manage. The Food and Agriculture Organization of the United Nations (FAO) estimates that global food production must increase by at least fifty percent from 2012 levels to meet projected demand by 2050—a target that is widely acknowledged to be impossible to achieve through traditional farming methods alone (Fadiji et al., 2023). This imperative is compounded by accelerating climate variability, which threatens the stability of agricultural production across all major food-producing regions, and by the uneven distribution of agricultural productivity gains across the global South.

The concept of data-driven policymaking—the systematic use of empirical data, digital monitoring systems, and predictive analytics to inform agricultural governance decisions—has emerged as a critical response to these challenges. Razak et al. (2024) characterize this shift as the convergence of precision agriculture, big data infrastructure, and intelligent decision systems into what they term "smart farming," a paradigm that treats agricultural management as an information-intensive enterprise rather than a labor-intensive one. The implications for policy are profound: where traditional agricultural policy

relied on infrequent census data, anecdotal extension reports, and lagged economic indicators, data-driven governance creates the potential for real-time, adaptive management of entire agricultural systems.

The Fourth Industrial Revolution has produced a suite of transformative technologies—artificial intelligence, machine learning, Internet of Things (IoT) sensors, satellite imagery, and big data analytics—that have already demonstrated measurable and replicable results in developed economies (Kisliuk et al., 2023). The challenge for developing nations is no longer one of technological feasibility but of institutional design, policy architecture, and the strategic adaptation of proven tools to local contexts. This paper undertakes precisely that task, providing a direct technology-by-technology mapping of how tools proven in the United States, Netherlands, Japan, and Australia can be replicated and institutionalized in Nigeria.

II. THE NIGERIAN AGRICULTURAL CONTEXT: PARADOX OF POTENTIAL AND UNDERPERFORMANCE

Nigeria presents a compelling and urgent case study for digital agricultural transformation. As Africa's largest economy, with a GDP exceeding USD 477 billion (National Bureau of Statistics, 2023), Nigeria's agricultural sector operates at a scale and strategic importance that make its productivity deficits a matter of national and continental significance. Agriculture contributes 24.8 percent of GDP and employs over 70 percent of the rural population, making it simultaneously the largest sector of the economy and the primary livelihood of the most economically vulnerable Nigerians (Kisliuk et al., 2023).

The sector is characterized by profound dualities that reflect systemic governance and investment failures rather than intrinsic limitations. Nigeria possesses 84 million hectares of arable land, yet only 40 percent is under cultivation. Approximately 60 million farmers participate in the agricultural economy, yet average maize yields languish at 1.8 MT/ha against a global average of 5.7 MT/ha—a productivity gap of more than threefold (USDA Economic Research Service, 2023). Perhaps most starkly, Nigeria spends USD 3–5 billion annually importing food staples—rice, wheat, sugar, fish—that it has the agro-ecological capacity to produce domestically. This import dependency represents not only an economic cost but a structural vulnerability to global commodity price volatility and supply chain disruption (Pervez et al., 2026).

The smallholder structure of Nigerian agriculture is both a defining characteristic and a core policy challenge. Smallholder farmers, operating on average plots of less than two hectares, account for approximately 80 percent of total food production (Hampel & Fabulya, 2024). Yet these farmers are systematically excluded from the financial services, market intelligence, agronomic support, and technological tools that would enable productivity improvements. The extension-to-farmer ratio of 1:3,000 against a recommended international benchmark of 1:500 illustrates the severity of institutional underinvestment in smallholder support (Pervez et al., 2026). Only fifteen percent of smallholder farmers currently use any form of digital agricultural tool, reflecting both infrastructural constraints and the absence of appropriately designed digital services.

Akintuyi (2024) noted that Nigeria has enacted successive ambitious agricultural policy frameworks—the Agricultural Transformation Agenda (2011–2014), the Green Alternative (2016–2020), and the current Agricultural Sector Action Plan (2022–2027)—each of which has explicitly acknowledged digital technologies as transformative enablers. Yet less than forty percent of programmatic commitments under these frameworks have been implemented as designed, with data and monitoring deficiencies consistently identified as the primary contributing factor (Nwachukwu et al., 2021). The gap between policy ambition and agricultural outcomes is therefore fundamentally a governance and data architecture gap—one that advanced digital technologies are uniquely positioned to close.

III. OBJECTIVE

The specific objective of this paper is to explore the potentials of data-driven policymaking in agribusiness, focusing on the role of advanced technologies in addressing key challenges and providing actionable recommendations for policymakers to harness these technologies effectively in the Nigerian context.

IV. LITERATURE REVIEW

4.1 Data-Driven Policymaking: Conceptual Framework

Data-driven policymaking in the agricultural context refers to the systematic integration of real-time and near-real-time data streams from satellites, IoT sensors, mobile devices, market platforms, and administrative systems into the evidence base that informs policy design, resource allocation, monitoring, and adaptive management (Akintuyi, 2024). It represents a qualitative shift from the episodic, retrospective evaluation model that has characterized agricultural governance in most developing nations toward a continuous, prospective, and responsive governance architecture.

Ikubanni et al. (2025) document how deep learning and machine learning systems have achieved performance equivalent to or exceeding human expert judgment across core agricultural decision domains—including crop disease diagnosis, yield forecasting, soil analysis, and irrigation management—demonstrating that AI is no longer an experimental technology in agriculture but a mature one. The policy challenge is therefore one of institutionalization: embedding these tools within governance frameworks, regulatory structures, and public service delivery systems in ways that are equitable, accountable, and sustainable.

The enabling infrastructure for data-driven agricultural policymaking comprises four interdependent layers: (1) data collection infrastructure—sensors, satellites, mobile platforms, and administrative systems that generate the raw data inputs; (2) data integration and analytics platforms—systems that aggregate, clean, and analyze data from multiple sources to produce actionable intelligence; (3) knowledge translation systems—extension services, decision-support tools, and mobile applications that translate analytical outputs into farmer-level recommendations; and (4) governance and regulatory frameworks—the institutional structures, data ownership regimes, and accountability mechanisms that ensure the system operates equitably and generates public value. Nigeria's challenge is that it possesses nascent versions of each layer but lacks the integration architecture that would make them collectively functional (Babar & Akan, 2024).

4.2 AI Technologies Transforming Global Agriculture

Several leading agricultural economies have each pioneered distinct digital agriculture approaches that together constitute the global frontier of AI-enabled agribusiness. Their aggregate experience forms the replication blueprint for Nigeria's digital transformation agenda.

4.2.1 Netherlands: Greenhouse AI, Robotics, and Data-Intensive Horticulture

The Netherlands, despite covering only 41,543 km², is the world's second-largest agricultural exporter by value—an achievement entirely attributable to AI-driven greenhouse technology and data-intensive production management (Ministry of Agriculture, Nature and Food Quality, Netherlands, 2023). Dutch greenhouse systems employ continuous AI optimization of temperature, humidity, CO₂ concentration, and lighting based on real-time crop response data, achieving 90 percent reductions in water use and 30 percent reductions in greenhouse gas emissions per unit of production compared to open-field equivalents. The Topsector Agri & Food—a structured public-private innovation fund with data-guided investment priorities—has been central to this achievement, demonstrating the governance model rather than merely the technology as the transferable asset for developing nations (Murindanyi et al., 2024).

4.2.2 Australia: Satellite Monitoring and Climate-Adaptive Analytics

Australia's vast geographic scale and extreme climate variability have driven innovation in satellite-based remote sensing and AI-enhanced climate analytics (Nawaz et al., 2025). The Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) produce monthly AI-enhanced crop condition reports with national coverage, achieving a 25 percent improvement in grain production forecast accuracy compared to traditional survey methods (ABARES, 2022; Grains Research and Development Corporation, 2023). The return on investment from digital agriculture investments in the Australian grains sector is documented at AUD 4.70 per dollar invested—one of the highest ROI ratios recorded for any agricultural technology category. The Australian model is particularly relevant for Nigeria because it demonstrates the policy and institutional architecture—not merely the technology—required to translate satellite data into actionable agricultural governance intelligence.

4.3 Proven Nigerian Pilots: Evidence of Feasibility

Critically, the replication case for AI in Nigerian agriculture is not theoretical. A series of pilots has already demonstrated technical feasibility and impact within Nigeria's specific infrastructural and institutional context, providing the empirical foundation for national scaling. The USAID Feed the Future Nigeria (2019–2023) deployed AI-enhanced satellite monitoring across the Guinea Savanna zone, achieving 85 percent accuracy in crop stress detection 4–6 weeks before visual symptoms appeared in the field—a lead time sufficient to enable preventive agronomic interventions (USAID, 2023). The FEPSAN soil sensing pilot (2023) demonstrated that AI-enhanced low-cost spectroscopy devices (under USD 200 per unit) could provide laboratory-equivalent soil nutrient analysis, enabling precision fertilizer recommendations that reduced input costs by 25–35 percent while maintaining or improving yields. The Honeywell/LSADA cold chain IoT pilot in Lagos (2022) identified that 60 percent of post-harvest losses were attributable to predictable failure patterns, and AI-enabled cold chain management delivered a 40 percent reduction in tomato and vegetable losses over an 18-month period. The Esoko West Africa market

intelligence model, applicable to the Nigerian context, has demonstrated that AI price forecasting can deliver 9–14 percent higher farm-gate prices for subscribing farmers through improved market timing (IFPRI, 2020). These results collectively demonstrate that the enabling conditions for AI-driven agricultural transformation in Nigeria already exist; what remains is the institutional will and policy architecture to scale proven approaches from pilots to national scale.

4.4 Data-Driven Policymaking in Agriculture: Global Evidence

The academic literature on data-driven agricultural policymaking has grown substantially over the past decade, reflecting both the rapid maturation of enabling technologies and the increasing urgency of global food security challenges. Babar and Akan (2024) provided a foundational review of big data in smart farming, documenting the transition from farm-level precision agriculture tools toward integrated data ecosystems that span the entire agrifood supply chain. Their framework identifies data connectivity, interoperability standards, and governance architecture as the critical bottlenecks limiting the scaling of smart farming approaches—findings that remain highly relevant to the Nigerian policy context.

Hampel and Fabulya (2024) carried out a survey on the application of deep learning across agricultural domains, documenting performance benchmarks that consistently demonstrate AI systems achieving accuracy rates of 85–99 percent in crop disease detection, yield prediction, and soil classification tasks. Their analysis highlights the rapid democratization of deep learning tools through open-source frameworks and cloud computing platforms, substantially reducing the technical barriers to AI deployment in agricultural research and extension contexts. This democratization underpins the replication logic of this paper: the core technologies are no longer proprietary or capital-intensive, but the institutional frameworks for their deployment remain underdeveloped in most African agricultural contexts.

The FAO's State of Food and Agriculture report (2022) examines automation and digital transformation across the agrifood system, concluding that the productivity and sustainability gains from digital agriculture are substantial and well-documented, but that their distribution is highly unequal—accruing disproportionately to large commercial farms in high-income countries while smallholder farmers in low and middle-income countries remain largely excluded. The report identifies three categories of intervention required to achieve inclusive digital transformation: infrastructure investment, governance frameworks that protect smallholder interests, and locally adapted digital tools designed for low-bandwidth and low-literacy contexts. This tripartite framework directly informs the policy architecture proposed in this paper.

4.5 AI and Precision Agriculture: Evidence from Developed Economies

The empirical literature on AI applications in developed country agriculture is extensive and consistently documents significant productivity, efficiency, and sustainability gains. The USDA Economic Research Service (2023) documents precision agriculture adoption trends across US farms, finding that farms adopting AI-enabled precision tools achieve yield improvements of 10–15 percent alongside input cost reductions of similar magnitude, with the strongest adoption rates among large commercial operations. Deere & Company's (2022) sustainability reporting provides corporate-level evidence of the scale of precision agriculture impact, documenting substantial improvements in fuel efficiency, input use efficiency, and yield predictability attributable to machine learning-enabled farm management systems.

The Australian grains sector provides particularly robust return-on-investment evidence. GRDC (2023) documents a AUD 4.70 return per dollar invested in digital agriculture across the grains sector, based on a portfolio-level analysis of precision agriculture, remote sensing, and AI decision-support tools. Nawaz et al. (2025) provided complementary evidence at the policy level, documenting that AI-enhanced crop condition monitoring has improved the accuracy and timeliness of agricultural policy decisions—including drought assistance allocation, export strategy, and infrastructure investment—in ways that generate measurable economic value at the national scale.

The Netherlands provides the most extreme case of AI-enabled agricultural transformation, with a country of 17 million people generating agricultural exports valued at over EUR 100 billion annually. The Ministry of Agriculture, Nature and Food Quality (2023) documents how the Topsector Agri & Food public-private innovation framework has structured this transformation, channeling data-guided investment into greenhouse technology, robotics, and precision horticulture over a sustained multi-decade period. The Dutch case is instructive not primarily for its technologies—which are largely beyond immediate replication in Nigerian conditions—but for its governance model: the systematic use of data to identify investment priorities, monitor outcomes, and adaptively manage public and private agricultural R&D expenditure (Pervez et al., 2026).

4.6 Digital Agriculture in Sub-Saharan Africa: Opportunities and Constraints

The literature on digital agriculture in Sub-Saharan Africa reflects both the transformative potential and the acute implementation challenges specific to the regional context. Brewster et al. (2020) examine IoT deployment in African agricultural contexts, identifying connectivity infrastructure, energy access, and digital literacy as the primary constraints limiting adoption, while arguing that the modular, low-cost character of modern IoT technology makes it fundamentally compatible with smallholder agricultural systems when appropriately designed. Their emphasis on the necessity of robust data governance frameworks—particularly around data ownership, consent, and benefit-sharing—directly anticipates the governance architecture challenges that Nigeria must address.

IFPRI (2020) evaluates the Esoko market information system across West Africa, one of the most extensively studied digital agriculture interventions in the region. The evaluation documents consistent improvements in farm-gate prices of 9–14 percent for subscribing farmers, attributable to improved market timing enabled by AI-driven price forecasting and SMS-delivered market intelligence. Critically, the evaluation also documents the conditions necessary for sustained impact: reliable mobile connectivity, farmer trust in the system, and price information that is genuinely actionable given available transport infrastructure. These conditional findings are directly relevant to Nigeria's policy design.

Nwachukwu et al. (2021) provide the most directly relevant analysis for the Nigerian agricultural policy context, examining implementation gaps across three successive national agricultural policy frameworks. Their analysis identifies four recurring failure modes: inadequate baseline data to set measurable targets; absence of real-time monitoring systems to track performance; insufficient institutional capacity to translate monitoring data into policy adjustments; and misalignment between policy objectives and the incentive structures of implementing agencies. These findings constitute a diagnostic framework that directly motivates the data infrastructure and governance architecture recommendations advanced in this paper.

USAID's evaluation of the Feed the Future Nigeria digital agriculture (2023) provides the most directly applicable evidence base for national scaling, documenting that AI-enhanced satellite monitoring achieved 85 percent accuracy in crop stress detection 4–6 weeks before visual symptoms appeared—sufficient lead time to enable meaningful agronomic intervention. The evaluation also documents the institutional requirements for sustainability: integration with national agricultural monitoring systems, capacity building within FMARD and state agricultural development programs, and data-sharing frameworks that ensure satellite intelligence reaches extension agents and farmers in actionable form.

V. POLICY ARCHITECTURE FOR DIGITAL AGRICULTURAL TRANSFORMATION

The literature on policy architecture for digital agricultural transformation in developing economies converges on several key design principles. First, data infrastructure investment must precede or accompany digital service deployment: AI systems trained on inadequate or outdated data produce systematically inaccurate outputs that undermine rather than support agricultural decision-making. Second, governance frameworks that address data ownership, privacy, and benefit-sharing are necessary conditions for farmer participation and private sector investment that sustain digital agricultural ecosystems. Third, digital extension platforms must be designed for the actual connectivity, literacy, and device landscape of target farmers—which in the Nigerian context means SMS, USSD, and voice interfaces rather than smartphone apps. Fourth, evidence-based policy monitoring—the systematic use of digital data to evaluate performance in real time—is both a prerequisite for adaptive management and a mechanism for building the political accountability that sustains long-term investment in agricultural transformation.

The FAO (2022), World Bank (2023), and IFPRI (2020) collectively document that the countries achieving the most significant digital agricultural transformation gains share a common policy architecture: integrated national data infrastructure, structured public-private innovation funding, mandatory evidence-based monitoring, and governance frameworks that explicitly protect smallholder interests. Nigeria's ASAP 2022–2027 implicitly acknowledges this architecture but lacks the specific institutional mechanisms required to operationalize it. This paper provides those mechanisms.

VI. GLOBAL AI TECHNOLOGIES: WHAT WORKS AND WHY IT CAN WORK IN NIGERIA

6.1 Technology-to-Policy Mapping

The following section presents a direct technology-by-technology mapping of proven global AI agricultural tools and their specific replication pathways for Nigeria. Table 1 provides a summary overview of the four country models and their primary transferable elements.

TABLE 1
INTERNATIONAL AI TECHNOLOGY MODELS AND NIGERIA REPLICATION PATHWAYS

Country	Core AI Technology	Proven Outcome	Nigeria Replication Pathway
United States	ML platforms, precision agriculture, AI crop insurance	60 percent large farm adoption; 15–20 percent insurance accuracy gain	Integrate FMARD/NBS/NASRDA data into unified AI analytics platform
Netherlands	Greenhouse AI, robotics, IoT sensor networks	World's second-largest exporter; 30 percent GHG reduction per unit	Launch Topsector-equivalent NGN 50 billion public-private AI Innovation Fund
Japan	WAGRI data commons, smartphone disease AI	30 percent labor reduction; agronomist-equivalent diagnosis	Build NADI as Nigerian WAGRI; deploy SMS/USSD disease AI nationally
Australia	Satellite remote sensing, climate analytics	25 percent forecast accuracy gain; AUD 4.70 ROI per dollar invested	Institutionalize USAID pilot's 85 percent-accurate satellite crop monitoring

Note: Data sourced from USDA Economic Research Service (2023), Ministry of Agriculture, Nature and Food Quality, Netherlands (2023), Japanese Ministry of Agriculture, Forestry and Fisheries (2023), ABARES (2022), and GRDC (2023).

VII. THE NIGERIAN AGRIBUSINESS LANDSCAPE: SIX PRIORITY TECHNOLOGY REPLICATION DOMAINS

Based on the international evidence review and the demonstrated feasibility of Nigerian pilots, six priority domains are identified for technology replication and policy investment. Table 2 summarizes the key characteristics and investment requirements across these domains.

TABLE 2
SIX PRIORITY TECHNOLOGY REPLICATION DOMAINS FOR NIGERIA

Domain	Core Technology	Pilot Evidence	Estimated Investment	Expected Impact
Satellite Crop Monitoring	NASA MODIS, ESA Sentinel, EU Copernicus with AI analytics layer	USAID FtF: 85 percent accuracy, 4–6 weeks lead time	NGN 3–5 billion/year operating	National early warning and budget allocation intelligence
AI Market Intelligence	Time-series price forecasting, SMS/USSD delivery	Esoko model: 9–14 percent farm-gate price improvement	Low capital; private sector led	Reduced market information asymmetry
Precision Agriculture	Drone-as-a-Service, AI soil sensors, smartphone disease AI	FEPSAN: 25–35 percent fertilizer cost reduction	Scalable from NGN 500 million	Input cost reduction; yield improvement
Agricultural Finance & Insurance	AI credit scoring, index-based insurance	IFC pilots: improved uptake and basis risk reduction	Regulatory framework + infrastructure	Expanded smallholder credit access
Post-Harvest & Supply Chain	IoT cold chain, AI demand forecasting, blockchain	Honeywell/LSADA: 40 percent loss reduction in 18 months	NGN 5–10 billion national	20–40 percent post-harvest loss reduction
National Data Infrastructure (NADI)	Federated data platform, multi-agency integration	Modelled on Japan WAGRI / Australia ABARES	NGN 15–20 billion over 3 years	Enabling foundation for all five domains above

VIII. CHALLENGES AND BARRIERS TO IMPLEMENTATION

Replication of global AI technologies in Nigeria is achievable but faces six categories of barriers that must be addressed in parallel with technology deployment. Table 3 provides a structured assessment of each barrier, its current severity, and the recommended mitigation approach.

TABLE 3
KEY IMPLEMENTATION CHALLENGES, SEVERITY, AND MITIGATION APPROACHES

Challenge	Current Status	Severity	Mitigation Approach
Rural Connectivity	21 percent rural internet penetration; 60 percent unreliable power	Critical	AgriConnect Initiative: 4G in all agricultural LGAs by 2027; Starlink satellite backup
Digital Literacy	15 percent smallholder digital tool adoption; 1:3,000 extension ratio	Critical	Digital Agriculture Certificate; Youth Agribusiness targeting; gender equity provisions
Data Governance	No farm-level data ownership framework; NDPR lacks agricultural provisions	High	Agricultural Data Governance Framework under Nigeria Data Protection Act 2023
R&D Financing	0.2 percent of agricultural GDP versus 1 percent Maputo Declaration benchmark	Critical	NGN 50 billion Agricultural AI Innovation Fund; blended finance instruments
Institutional Silos	FMARD, NBS, NASRDA, NiMet data not integrated; no common API	High	NADI platform with multi-agency governance board under executive mandate
Technology Adaptation	Off-the-shelf tools not designed for low-literacy, low-bandwidth contexts	Moderate	NADEP platform with SMS/USSD/voice interfaces in Nigerian languages

IX. POLICY RECOMMENDATIONS

The following eight recommendations form a mutually reinforcing policy agenda. Each directly addresses the gap between a proven global technology and its deployment at Nigerian scale. Together, they constitute the institutional and investment architecture required for a national digital agricultural transformation.

9.1 Establish the National Agricultural Data Infrastructure (NADI)

The Federal Government should establish NADI—a federated, interoperable data platform aggregating inputs from FMARD, NITDA, NBS, NASRDA, and NiMet, hosted by FMARD with technical management by NITDA. Modelled on Japan's WAGRI and Australia's ABARES system, NADI would provide the foundational data integration layer that all subsequent AI applications require. Based on developed country benchmarks, this infrastructure investment is expected to generate 10–25 times returns in agricultural productivity improvements over a decade.

9.2 Conduct a National Agricultural Census and Annual Digital Survey

Nigeria must commission the first comprehensive agricultural census since 2011, followed by an annual digital survey using Computer-Assisted Personal Interview technology and GPS-georeferenced sampling. Without current baseline data, any AI system trained on Nigerian conditions will be operating on decade-old inputs, systematically compromising the accuracy and policy relevance of its outputs. This is the foundational data investment that enables evidence-based resource allocation across all subsequent interventions.

9.3 Enact an Agricultural Data Governance Framework

Building on the Nigeria Data Protection Act 2023, a sector-specific Agricultural Data Governance Framework should address farm data ownership rights, consent mechanisms for smallholder data collection, data-sharing obligations for agritech companies operating in Nigeria, and benefit-sharing arrangements ensuring farmers receive fair compensation for the commercial use of their operational data. The framework should be developed through participatory consultation with farmer organizations, agritech companies, and civil society, and reviewed every three years in light of technological change.

9.4 Integrate Digital Agriculture into Tertiary and Vocational Education

Agricultural curricula at all tertiary and vocational levels must be revised to incorporate digital agriculture competencies. A six-month Digital Agriculture Certificate—integrating drone operation, sensor technology, data analysis, and digital extension methodology—should be deployed through agricultural universities and the national extension network. Curriculum design must explicitly address gender equity, given the disproportionate barriers women farmers face in accessing digital agricultural tools and services.

9.5 Establish Evidence-Based Policy Monitoring Architecture

All major agricultural policy programs must incorporate a Theory of Change with measurable digital indicators, a pre-registered evaluation design, and a real-time data monitoring framework drawing on NADI data. A Policy Analytics Unit should be established within FMARD, staffed with data scientists and agricultural economists, publishing quarterly evidence digests and annual performance reports. A public data portal should enable civil society and researchers to access de-identified data for independent evaluation, creating the accountability structure necessary to sustain long-term investment in agricultural transformation.

9.6 Launch the Agricultural AI Innovation Fund

The Federal Government, in partnership with development finance institutions and the private sector, should establish a NGN 50 billion Agricultural AI Innovation Fund over five years. This fund should support applied research, pilot deployment, and scaling of AI solutions across the six priority domains identified in this paper. Fund disbursement should be structured as competitive grants with mandatory cost-sharing and matching requirements to ensure private sector alignment and sustainability.

9.7 Implement the AgriConnect Broadband Initiative

The Federal Government should launch a dedicated AgriConnect Initiative, targeting 4G connectivity in all agricultural Local Government Areas by 2027. This should be implemented in partnership with telecommunications companies through a universal service obligation framework, with satellite backup provided through Starlink or equivalent services for the most remote locations. Connectivity is the enabling infrastructure without which all digital agriculture interventions will remain inaccessible to the majority of smallholder farmers.

9.8 Establish the Nigerian Agricultural Digital Extension Platform (NADEP)

NADEP should be a unified digital extension platform delivering AI-generated agronomic recommendations, market intelligence, weather forecasts, and disease alerts through SMS, USSD, and voice interfaces in Nigerian languages. The platform should integrate with NADI data feeds and be managed through a public-private partnership model to ensure sustainability and continuous innovation.

X. CONCLUSION

This study demonstrates that the technologies required to transform Nigerian agriculture already exist and have been successfully deployed both globally and within Nigeria itself. Evidence from the United States, the Netherlands, Japan, and Australia confirms that AI-driven agricultural systems deliver measurable gains in productivity, efficiency, and sustainability. More importantly, pilot initiatives within Nigeria have already validated these outcomes under local conditions (Nawaz et al., 2025).

The persistence of low agricultural productivity in Nigeria is therefore not a consequence of technological limitations, but of institutional and data infrastructure deficiencies. The absence of integrated data systems, weak governance frameworks, and fragmented policy implementation has prevented the scaling of proven solutions (Ikubanni et al., 2025).

Consequently, Nigeria's agricultural transformation depends on a fundamental shift toward data-driven policymaking. The establishment of national data infrastructure, coordinated governance mechanisms, and inclusive digital extension systems is not optional but essential. Without these reforms, existing investments in agricultural policy will continue to underperform.

Conversely, with the adoption of the integrated policy framework proposed in this study, Nigeria has the capacity to close its productivity gap, reduce food import dependency, and emerge as a leader in digital agribusiness across Africa.

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CONFLICT OF INTEREST

The authors declare no conflict of interest regarding the publication of this manuscript.

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Performance of Yankasa Rams Fed Molasses-Treated Masakwa Stover Supplemented with Different Levels of Water Hyacinth

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Abstract— The research was conducted to study the performance of Yankasa rams fed molasses-treated masakwa stover supplemented with different levels of water hyacinth. The experiments were conducted at the Federal College of Education, Yola Teaching and Research Farm. The objective of the study was to determine the nutrient digestibility of Yankasa rams fed molasses-treated masakwa stover supplemented with different levels of water hyacinth. The chemical composition of the masakwa plant was determined; dry matter (DM) ranged from 91.35% in week four (4) to 92.43% in week sixteen (16), crude protein (CP) from 8.75% in week four (4) to 10.60% in week sixteen (16), crude fiber (CF) from 9.35% to 20.36% from week four (4) to sixteen (16), ether extract (EE) from 0.94% to 2.29% from week four (4) to week sixteen (16), nitrogen-free extract (NFE) from 51.44% to 76.93% from week four (4) to sixteen (16), and ash from 4.03% to 15.31% from week four (4) to sixteen (16), respectively. The nutrient digestibility of Yankasa rams recorded dry matter digestibility (DMD) (51.46 to 60.72%), crude protein digestibility (CPD) (63.46 to 70.90%), crude fiber digestibility (CFD) (70.66 to 87.27%), ether extract digestibility (EED) (79.55 to 87.27%), nitrogen-free extract (66.79 to 71.01%), acid detergent fiber (ADF) (52.02 to 60.45%), and neutral detergent fiber (NDF) (70.12 to 79.12%). The highest values (79.55 to 87.27%) were recorded in crude fiber digestibility (CFD) and ether extract digestibility (EED). The study concluded that supplementing molasses-treated masakwa stover with water hyacinth significantly improved the digestibility of crude protein and energy in Yankasa rams. It is recommended that farmers in this region should consider incorporating water hyacinth into the diets of Yankasa rams to improve feed intake and utilization. Further research should be conducted to evaluate the long-term effects of water hyacinth supplementation on ram productivity and health.

Keywords— Nutrient digestibility, Yankasa rams, Molasses, Treated masakwa stover, Water hyacinth, Feed utilization, Crop residues, Small ruminants, Nigeria, Ruminant nutrition.

I. INTRODUCTION

Livestock are fed with diverse feed resources all over the world (Abidi et al., 2009). In Nigeria, the major feed resources are crop residues and grass hay, which contain poorly digestible nutrients. To ensure better body condition of the animals, it is advisable that additional sources of carbohydrate and nitrogen be included in the diet of the animals, thereby improving the utilization of crop residues, which is mainly attained through the supply of energy and nitrogen to rumen microbes (Van Soest et al., 1991). Cereal stovers are relatively poor in nutritive value, which is concentrated in the harvested grain, but they are widely used for feeding ruminants, often when other feeds are inadequate or unavailable towards the end of the dry season. The total value of these crops therefore lies in their grain yield as well as the use of the stovers for livestock feed. Osafo et al. (1996) have demonstrated an important practical feeding strategy where chopped sorghum stover offered at a high rate of 800 g of raw forage per day for a ram of 35 kg with mineral lick is sufficient to maintain weight of rams aged 15 to 20 months.

Masakwa, which is one of the major staple foods in Adamawa State, is produced in large quantities, thereby generating large quantities of fodder that are sometimes not properly utilized in the feeding process of livestock. The stover sometimes is

contaminated by animal feces during grazing, thereby rendering it unusable to the animal. It was concluded that chopped sorghum stover offered generously with minerals but no other supplement is a sustainable feeding strategy for maintaining weight in adult sheep (Ben and Smith, 2008).

Water hyacinth is found in most water bodies in the world (Khan et al., 2002) and is readily available in and around Adamawa State, particularly in the water bodies. Water hyacinth grows in the wild, hampers water transportation, and affects fishing gears and other water users. Moreover, it does not compete with other agriculturally useful vegetation for growing space (Brook and Iwanaga, 2016). Due to its high reproductive rate, this plant frequently causes blockage of navigable waters and irrigation ditches (Dugje et al., 2014). In this situation, the utilization of water hyacinth as feed for livestock may offset the cost of removal. The chemical composition of most aquatic plants suggests that they are acceptable animal feeds and that they have more minerals and protein content (Muhammed, 2008; Osarya, 2005). Therefore, this notorious plant can be utilized as an excellent source of animal feed.

II. MATERIALS AND METHODS

2.1 Study Area

The research work was conducted to study the nutrient digestibility of Yankasa rams fed molasses-treated masakwa stover supplemented with graded levels of water hyacinth. All the experiments were conducted at the Federal College of Education, Yola Teaching and Research Farm.

2.2 Digestibility Trials

At the end of the feeding trial, eight (8) grower rams (two per treatment) were randomly selected for the digestibility trial. The rams were separately kept in metabolism crates for seven days to acclimatize before data collection began. The rams were starved for twelve hours prior to experimental feeding to clear the gut of previous diets. They were also starved for another twelve hours at the end of the feeding period to ensure total collection of feces arising from the diet offered. Feces and urine were collected separately on a daily basis every morning (7:30–8:30 am). The feces were sun-dried and weighed daily to get constant weights. Urine was also collected three times (7:00 am, 12:00 noon, and 5:00 pm) daily in a labeled plastic container, with record of the total weight and volume. About 10% of each day's collection was stored in 10 mL of 10% sulfuric acid to prevent nitrogen losses by evaporation of ammonia and help keep the urine pH below 4. The urine was stored in a deep freezer until required for analysis. At the end of the seven-day collection period, feces from each replicate were mixed, ground, and representative samples taken for proximate composition determination. The urine from each replicate was also mixed together and representative samples were taken for nitrogen determination.

Note: The digestibility trial used only two rams per treatment (total n=8). This small sample size limits statistical power and generalizability. The results should be interpreted with caution, and future studies should include larger numbers of animals per treatment.

2.3 Composition of Supplementary and Basal Diets

The compositions of the diets were assigned at graded levels according to the treatment. The molasses was added at the rate of 5%, which was sprinkled on 20 kg of masakwa stover. The treatments were as follows:

- **T1 (Control):** Molasses-treated masakwa stover (0 g water hyacinth)
- **T2:** Molasses-treated masakwa stover + 100 g water hyacinth
- **T3:** Molasses-treated masakwa stover + 200 g water hyacinth
- **T4:** Molasses-treated masakwa stover + 300 g water hyacinth

2.4 Proximate Analysis of the Experimental Diet

The proximate composition of the experimental diets was determined using the proximate analysis according to the Association of Official Analytical Chemists (AOAC, 2004). The following were determined: crude protein (CP) by the Kjeldahl method, ash by burning in a furnace at 550°C for three (3) hours, crude fiber (CF), and ether extract by Soxhlet extraction according to standard methods. Neutral detergent fiber (NDF) was determined according to the method of Van Soest (1994).

2.5 Statistical Analysis

All data were subjected to SPSS version 16 to analyze the statistical data collected in this study. The NEWAY EXCEL package for processing data from feed degradability and in-vitro gas production was used to compute the data obtained in degradability (Chen and Gomes, 1992). Dry matter degradability of each sample for each incubation time was calculated from the disappearance of dry matter from the bag after incubation and washing according to the equation by Ørskov and McDonald (1979).

III. RESULTS

3.1 Proximate Composition of Masakwa Plant

The proximate composition of the masakwa plant over the 16-week growth period is presented in Table 1. The dry matter (DM) content of the masakwa plant increased progressively from 91.35% at week 4 to 92.43% at week 16, indicating a gradual loss of moisture as the plant matured. This increase in DM content is typical of plant maturation processes, where structural components accumulate and water content decreases.

The crude protein (CP) content showed a steady increase from 8.75% at week 4 to 10.60% at week 16, suggesting that protein accumulation continued throughout the growth period. The crude fiber (CF) content exhibited the most dramatic increase, rising from 9.35% at week 4 to 20.36% at week 16, reflecting the progressive lignification and structural development of the plant as it matured.

The ether extract (EE) content increased from 0.94% to 2.29% over the 16-week period, indicating a gradual accumulation of fats and oils in the plant tissues. The nitrogen-free extract (NFE), which represents the soluble carbohydrates, showed a marked decline from 76.93% at week 4 to 43.69% at week 16. This decline is consistent with the conversion of soluble carbohydrates into structural carbohydrates (cellulose and hemicellulose) as the plant matured. The ash content increased substantially from 4.03% at week 4 to 15.31% at week 16, reflecting the accumulation of mineral elements in the plant tissues over time.

These compositional changes indicate that the nutritional value of masakwa plant varies considerably with maturity, with younger plants having higher soluble carbohydrate content and lower fiber content, while mature plants have higher fiber and mineral content but lower soluble carbohydrate content.

TABLE 1
PROXIMATE COMPOSITION OF MASAKWA PLANT OVER A 16-WEEK PERIOD (%)

Weeks	DM	CP	CF	EE	NFE	Ash
4	91.35	8.75	9.35	0.94	76.93	4.03
8	91.78	9.12	12.45	1.23	68.54	6.89
12	92.01	9.87	15.78	1.67	55.23	10.45
16	92.43	10.6	20.36	2.29	43.69	15.31
SEM	0.89	0.65	0.59	0.19	1.05	0.41

KEY: DM = Dry matter; CP = Crude protein; CF = Crude fiber; EE = Ether extract; NFE = Nitrogen-free extract; SEM = Standard error of the mean

3.2 Anti-Nutritive Factors of Masakwa Plant

The anti-nutritive factors of the masakwa plant at week 16 are presented in Table 2. The tannin content was 1.57%, saponin content was 1.81%, and alkaloid content was 2.18%. These values indicate the presence of potentially limiting factors that could affect feed intake and nutrient utilization if present in high concentrations.

The alkaloid content (2.18%) was notably higher than the levels considered safe for growing ruminants, suggesting that processing or treatment of masakwa stover may be necessary to reduce the concentration of these anti-nutritive factors before feeding to livestock. The tannin and saponin levels, while present, were within ranges that may not significantly impair digestibility at the levels recorded in this study.

TABLE 2
ANTI-NUTRITIVE FACTORS OF MASAKWA PLANT (%)

Weeks	Tannin	Saponin	Alkaloid
16	1.57	1.81	2.18
SEM	0.04	0.11	0.12

3.3 Nutrient Digestibility of Yankasa Rams Fed Molasses-Treated Masakwa Stover Supplemented with Different Levels of Water Hyacinth

The nutrient digestibility of Yankasa rams fed molasses-treated masakwa stover supplemented with graded levels of water hyacinth is presented in Table 3. The results showed significant ($p < 0.05$) differences among treatments for all parameters measured.

3.3.1 Dry Matter Digestibility (DMD)

Dry matter digestibility ranged from 51.46% (T2) to 60.72% (T4), with Treatment T4 (300 g water hyacinth) recording the highest value. Treatment T1 (control) recorded 55.13%, while Treatment T3 recorded 54.84%. The lowest value was observed in Treatment T2 (51.46%). The significantly higher DMD in Treatment T4 suggests that supplementation with 300 g of water hyacinth improved the overall digestibility of the diet, possibly due to enhanced microbial activity in the rumen.

3.3.2 Crude Protein Digestibility (CPD)

Crude protein digestibility ranged from 63.46% (T4) to 70.90% (T2). Treatment T2 (100 g water hyacinth) recorded the highest CPD (70.90%), followed by Treatment T3 (67.76%), Treatment T1 (66.49%), and Treatment T4 (63.46%). The higher CPD values in Treatments T2 and T3 suggest that moderate levels of water hyacinth supplementation enhanced protein utilization, while the highest level of supplementation (300 g) may have resulted in a dilution effect or altered rumen fermentation patterns.

3.3.3 Crude Fiber Digestibility (CFD)

Crude fiber digestibility ranged from 70.66% (T1) to 79.28% (T4). Treatment T4 recorded the highest CFD (79.28%), followed by Treatment T3 (73.80%), Treatment T2 (70.76%), and Treatment T1 (70.66%). The significantly higher CFD in Treatment T4 indicates that supplementation with 300 g of water hyacinth enhanced the utilization of fibrous components of the diet, likely through improved microbial fermentation in the rumen.

3.3.4 Ether Extract Digestibility (EED)

Ether extract digestibility ranged from 79.55% (T1) to 87.27% (T4). Treatments T3 and T4 recorded the highest EED values (87.16% and 87.27%, respectively), which were significantly higher than T1 (79.55%) and T2 (80.96%). The improved EED in treatments with higher water hyacinth supplementation suggests that the fat content of water hyacinth was well utilized by the rams.

3.3.5 Nitrogen-Free Extract Digestibility (NFE)

Nitrogen-free extract digestibility ranged from 65.03% (T2) to 71.01% (T4). Treatment T4 recorded the highest NFE digestibility (71.01%), followed by Treatment T1 (66.79%), Treatment T3 (66.66%), and Treatment T2 (65.03%). The higher NFE digestibility in Treatment T4 indicates improved utilization of soluble carbohydrates when supplemented with 300 g of water hyacinth.

3.3.6 Acid Detergent Fiber Digestibility (ADF)

Acid detergent fiber digestibility ranged from 52.02% (T1) to 60.45% (T4). Treatments T3 and T4 recorded significantly higher ADF digestibility (60.14% and 60.45%, respectively) compared to T1 (52.02%) and T2 (56.05%). The improved ADF digestibility in treatments with higher water hyacinth supplementation indicates enhanced breakdown of lignified fiber components, likely due to improved rumen microbial activity.

3.3.7 Neutral Detergent Fiber Digestibility (NDF)

Neutral detergent fiber digestibility ranged from 70.12% (T1) to 79.12% (T4). Treatment T4 recorded the highest NDF digestibility (79.12%), followed by Treatment T3 (78.23%), Treatment T2 (70.56%), and Treatment T1 (70.12%). The

significantly higher NDF digestibility in Treatments T3 and T4 indicates that water hyacinth supplementation enhanced the utilization of hemicellulose and cellulose components of the diet.

TABLE 3

NUTRIENT DIGESTIBILITY OF YANKASA RAMS FED MOLASSES-TREATED MASAKWA STOVER SUPPLEMENTED WITH DIFFERENT LEVELS OF WATER HYACINTH

Parameter	T1 (0 g control)	T2 (100 g)	T3 (200 g)	T4 (300 g)	SEM
DM (%)	55.13b	51.46d	54.84c	60.72a	1.19**
CP (%)	66.49c	70.90a	67.76b	63.46d	1.62**
CF (%)	70.66b	70.76b	73.80b	79.28a	1.28**
EE (%)	79.55c	80.96c	87.16a	87.27a	1.90**
NFE (%)	66.79b	65.03c	66.66b	71.01a	0.96**
ADF (%)	52.02c	56.05b	60.14a	60.45a	0.51**
NDF (%)	70.12d	70.56c	78.23b	79.12a	0.42**

KEY: DM = Dry matter; CP = Crude protein; CF = Crude fiber; EE = Ether extract; NFE = Nitrogen-free extract; ADF = Acid detergent fiber; NDF = Neutral detergent fiber; SEM = Standard error of the mean

Values with different superscripts within the same row are significantly different ($p < 0.05$); ** = significant at $p < 0.05$

3.4 Summary of Digestibility Findings

Overall, the digestibility results showed a general trend of improved nutrient utilization with increasing levels of water hyacinth supplementation. Treatment T4 (300 g water hyacinth) consistently recorded the highest digestibility values for most parameters, including DM (60.72%), CF (79.28%), EE (87.27%), NFE (71.01%), ADF (60.45%), and NDF (79.12%). The only exception was crude protein digestibility, where Treatment T2 (100 g water hyacinth) recorded the highest value (70.90%).

These findings suggest that water hyacinth supplementation at levels of up to 300 g per ram per day can significantly improve the digestibility of molasses-treated masakwa stover, with the most pronounced improvements observed in fiber fractions (CF, ADF, NDF) and ether extract. The improved digestibility is likely attributable to enhanced rumen microbial activity resulting from the additional nutrients provided by water hyacinth.

IV. DISCUSSION

4.1 Biomass and Nutritive Value of Masakwa Plant

The height of the masakwa plant recorded in the experiment was 150.70 cm, lower than the 193 cm reported by Adamu and Dauda (2008), while it was higher than the 140 cm reported by Gapili et al. (2019). The differences in plant height might be attributed to seed varieties, soil types, and time of harvest (Kyriazakis and Oldham, 2007). Plant height was generally slow from week one to three, which might be as a result of shock experienced by the plants when they were uprooted from the nursery where regular water supply was given (Tabo et al., 2002). Farmers select sites for masakwa sorghum production on the basis of soil types, availability of land, and the amount of water stored during the wet season (Tabo et al., 2002). Sandy, clay loams, and clay soils are most commonly preferred, but in this case, clay soil was used because of its high water-holding capacity, as reported by Masresha and Belay (2020).

4.2 Proximate Composition and Anti-Nutritive Factors of Masakwa Stover

The dry matter (DM) of the masakwa plant (93.17%) was lower than the 96.50% reported by Medugu et al. (2012), which could be attributed to environment, seed variety, type of soil, climate, and time of harvest. The crude protein (CP) was 19.72%, similar to the 20.25% reported by Medugu et al. (2012). The crude fiber (CF) and ether extract (EE) of masakwa were 30.89% and 2.05%, respectively, which were less than the 32.00% CF and higher than the 1.00% EE reported by Jibril et al. (2018). Similarly, the ash, acid detergent fiber (ADF), and neutral detergent fiber (NDF) of masakwa were 21.73%, 38.22%, and 48.83%, respectively. The values were higher than the 9.17% (ash) and 36.20% (ADF) reported by Akhtar et al. (2021) but less than the 72.23% (NDF) reported by the same authors, and similar to the 51.20% reported by Getachew and Mohamadou (2014). The differences might be attributed to environment, variation in soil, and climate.

The anti-nutritive factors of the masakwa plant were 0.82% (tannin), which is lower than the 2.40% reported by Adedeji (2020). The saponin content was 1.06%, which corresponds with the 1.05% reported by Adedeji (2020). The alkaloid content of the masakwa plant was 2.16%, which is higher than the value required by growing ruminants (Diarra et al., 2016). This may likely

affect growth rate and other production parameters. It also showed that as the plants grow, their toxicity level increases, which agrees with Amodu et al. (2004).

4.3 Chemical Composition of Water Hyacinth

The crude protein (CP) of water hyacinth was 19.72%, which is higher than the value of 10.42% (CP) reported by Mako et al. (2011) and 14.00% (CP) reported by Emran et al. (2015). The leafy parts of water hyacinth from nutrient-enriched wastewater usually contain 25–35% crude protein on a dry weight basis. The level of CP in the whole plant without root is higher than the critical level of 7.0 g/100 g DM, below which feed intake will be depressed; this was as a result of absorbing waste material present in the body of water (Mengistu et al., 2017). Murillo et al. (2012) emphasized that due to good nutrient profile, water hyacinth can be used to supplement the low nutrient value of tropical grasses, and also that all of the essential amino acids were present at high levels in the leaf protein isolate. The neutral detergent fiber (NDF) content of water hyacinth leaves and the entire plant in this study were (48.83%), higher than the value of 48.30% NDF reported by Aboud et al. (2005) and Jafari (2010). Some parts of the feed were only partially digestible by any species of animals, but can be used to a greater extent by ruminants, which depend on microbial digestion for utilization of most fibrous plant components.

4.4 Nutrient Digestibility of Molasses-Treated Masakwa Stover Supplemented with Graded Levels of Water Hyacinth

Nutrient digestibility of Yankasa rams fed molasses-treated masakwa stover supplemented with graded levels of water hyacinth showed significant ($p < 0.05$) differences. The digestibility was significantly ($p < 0.05$) influenced by the water hyacinth supplementation. The dry matter digestibility ranged from 51.46% to 60.72%, higher than the 42.88% to 57.98% reported by Kalio et al. (2013) when the authors fed West African Dwarf (WAD) sheep with cassava, yam, and sweet potato peels. The result of crude fiber and organic matter digestibility showed a significant ($p < 0.05$) difference, with values ranging from 58.95% to 79.28%, higher than the 43.66% to 57.69% reported by Ahamefule et al. (2002). Treatment T4, supplemented with 300 g water hyacinth, had the highest crude fiber and organic matter digestibility (79.28% and 58.98%, respectively), while Treatment T1 (0 g water hyacinth) had the lowest crude fiber digestibility (70.66%). The crude fiber and organic matter digestibility values obtained in this study were higher than the values (43.66–57.69%) reported by Adeshina and Okunlola (2000). Thus, the 300 g supplemented diet recorded in this study contained a higher percentage of crude protein (CP), which resulted in higher palatability and better utilization of nutrients by the rams. This observation agrees with earlier reports (Oddoye et al., 2005) that for rumen microbial flora to perform at optimum level, the presence of nitrogen source and soluble carbohydrate had to be synchronized.

V. CONCLUSION

The study concluded that supplementation of molasses-treated masakwa stover with increasing levels of water hyacinth significantly improves the digestibility of the diets for Yankasa rams, and no adverse effects were recorded. The highest digestibility values were generally observed in the treatment with 300 g water hyacinth supplementation (T4), indicating a positive effect on nutrient utilization.

Recommendations:

- 1) Farmers in the region should consider incorporating water hyacinth into the diets of Yankasa rams at levels of up to 300 g per animal per day to improve feed intake and nutrient utilization.
- 2) Further research should be conducted to evaluate the long-term effects of water hyacinth supplementation on ram productivity, health, and meat quality.
- 3) Research should also investigate the palatability of higher levels of water hyacinth supplementation and determine if higher levels will adversely affect other nutritional factors or animal performance.
- 4) Future studies should include larger sample sizes (more than 2 animals per treatment) to improve statistical power and generalizability of the findings.
- 5) The utilization of water hyacinth as a feed resource should be promoted as a sustainable strategy for managing this invasive aquatic weed while providing a nutritious feed supplement for ruminants.

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CONFLICT OF INTEREST

The authors declare no conflict of interest regarding the publication of this manuscript.

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Christian Education Knowledge and Agro-Business Practices among the Christian Agrarian Community in Adamawa State

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Abstract— This study examines the influence of Christian religious practices on agripreneurial productivity and sustainability in Adamawa State, Nigeria. A mixed-methods research design was adopted, combining quantitative and qualitative approaches. Primary data were collected from a sample of 90 respondents, including agripreneurs, religious leaders, and agricultural stakeholders, using structured questionnaires, key informant interviews, and focus group discussions. Descriptive and inferential statistical techniques were employed for data analysis. The findings reveal that Christian religious practices significantly influence agripreneurial behavior, with 72% of respondents affirming that religious teachings shape their work ethics, while 68% reported practicing honesty and fairness due to their faith. Correlation analysis indicates a positive and statistically significant relationship ($r = 0.61, p < 0.05$) between Christian values and agripreneurial productivity. Additionally, faith-based institutions contribute to agribusiness development through training, financial support, and cooperative networks. However, challenges such as inadequate capital, poor infrastructure, and limited market access continue to hinder agripreneurial growth. The study concludes that integrating Christian ethical values with modern agricultural practices and policy support can enhance productivity and sustainability. It recommends strengthening faith-based agricultural initiatives and improving access to finance and infrastructure to promote agripreneurship in Adamawa State.

Keywords— Agripreneurship, Christian religion, Productivity, Sustainability, Adamawa State, Agricultural entrepreneurship, Faith-based development, Rural development, Nigeria, Christian education.

I. INTRODUCTION

The relationship between Christian education and economic development has attracted considerable scholarly attention, particularly within Christian religious studies. Christian education emphasizes values such as diligence, stewardship, integrity, and accountability, which are essential for sustainable economic activities. In Nigeria, agriculture remains a key sector, contributing approximately 20–24 percent of Gross Domestic Product (GDP) and employing a significant proportion of the labor force (World Bank, 2024; National Bureau of Statistics [NBS], 2025). Despite this contribution, the sector faces persistent challenges including low productivity, inadequate access to finance, and limited technological adoption. Agripreneurship, which integrates agriculture with entrepreneurship, has emerged as a viable strategy for addressing these challenges and promoting rural development.

From a biblical perspective, agriculture is rooted in divine mandate. Genesis 2:15 emphasizes humanity's responsibility to "till and keep the land," highlighting the importance of stewardship and productive labor. This theological perspective positions agriculture as both an economic and moral activity. In Adamawa State, Christian education plays a significant role in shaping socio-economic behavior. Faith-based institutions contribute to agricultural development through moral guidance, training, and social networks.

Statement of the Problem

Despite the significant role of agriculture in Nigeria's economy and the potential of Christian education to shape ethical business practices, there is limited empirical evidence on the influence of Christian religious practices on agripreneurial productivity and sustainability in Adamawa State. While several studies have examined the economic contributions of agriculture and the role of religion in social development, few have specifically investigated how Christian teachings on stewardship, diligence, and integrity translate into agripreneurial behavior and business outcomes among Christian agrarian communities. This study therefore investigates the influence of Christian education practices on agripreneurial productivity and sustainability of community livelihood in the agrarian Christian community of Adamawa State.

II. OBJECTIVES OF THE STUDY

The main objective of this study is to examine the effect of Christian education knowledge among agrarian Christian communities of the state on agripreneurial productivity and sustainability of livelihood of communities in Adamawa State.

The specific objectives are to:

- i. Determine the extent to which Christian education practices influence agripreneurs' work ethics, productivity, and business behavior.
- ii. Establish the role of Christian education in promoting sustainable farming and business development.
- iii. Determine the major challenges affecting agripreneurial productivity and sustainability among the agrarian communities in the state.

2.1 Research Questions

The study sought to answer the following research questions:

- 1) How do Christian religious practices influence agripreneurial work ethics, productivity, and business behavior among Christian agrarian communities in Adamawa State?
- 2) What role do faith-based institutions play in promoting agribusiness development and sustainable farming practices?
- 3) What are the major challenges affecting agripreneurial productivity and sustainability among Christian agrarian communities in Adamawa State?

III. THEORETICAL FRAMEWORK

This study is anchored on two complementary theoretical perspectives that provide a comprehensive explanation of how Christian religious practices influence agripreneurial productivity and sustainability.

3.1 Biblical Stewardship Theory

The Biblical Stewardship Theory is rooted in scriptural teachings that emphasize human responsibility to manage and care for God's creation. This principle is clearly reflected in Genesis 2:15, where humans are commanded to "till and keep" the land. Stewardship, therefore, involves accountability, sustainability, and ethical management of natural and economic resources.

Applied to agripreneurship, this theory suggests that Christian farmers and agribusiness practitioners view agriculture not merely as a means of livelihood but as a divine responsibility. This perspective encourages sustainable farming practices, environmental conservation, and ethical business conduct. Agripreneurs guided by stewardship values are more likely to adopt practices that ensure long-term productivity, such as soil conservation, responsible use of inputs, and avoidance of harmful environmental practices. Thus, the Biblical Stewardship Theory provides a framework for understanding how Christian teachings promote sustainability in agribusiness.

Propositions of the Theory:

- 1) Agripreneurs who embrace biblical stewardship are more likely to practice sustainable farming methods.
- 2) Christian teachings on diligence and integrity positively influence agripreneurial productivity.
- 3) Faith-based institutions play a mediating role in transmitting stewardship values to agripreneurs.

IV. REVIEW OF RELATED LITERATURE

To this end, this paper clarifies some concepts under the following sub-headings: religion, entrepreneurship, agribusiness, and also reviews the related literature.

4.1 Religion

Religion is derived from three Latin words: *ligere* (meaning to bind), *religare* (meaning to unite, to link together), and *religio* (which means relationship). The Latin concept of religion stresses an important thing, that is relationship which is a link between two people—human and divine (Omoregbe, 2009).

4.2 Christian Education Knowledge

Christian education knowledge refers to a structured and value-based system of learning in which all knowledge, skills, and attitudes are developed through the lens of biblical teachings and the lordship of Jesus Christ, integrating spiritual, moral, intellectual, and practical dimensions of life. It emphasizes the acquisition of knowledge and wisdom grounded in Scripture, with the aim of shaping individuals' behavior, work ethics, and societal engagement in accordance with Christian principles (Graham, 2009; Pazmiño, 2012). It is not limited to religious instruction alone but extends to all areas of life, including economic and agricultural activities, where individuals apply biblical values such as stewardship, diligence, and responsibility in productive ventures.

4.3 Entrepreneurship

The word entrepreneur comes from the French word 'entreprendre' which means 'undertaking'. This concept was introduced into economic theory by Richard Cantillon in the early 18th century and developed by economists such as Jean-Baptiste Say and Joseph Schumpeter. Entrepreneurship involves the process of designing, starting, and running a new business, often starting as a small business. This concept is increasingly understood as a critical force for economic growth, job creation, and societal advancement, prompting governments and institutions worldwide to foster entrepreneurial ecosystems (OECD, 2024; World Bank, 2024).

4.4 Agribusiness

Agribusiness is the sector comprising establishments primarily engaged in the business of growing crops, raising animals, harvesting timber, and harvesting fish and other animals from a farm, ranch, or their natural habitats. It involves the integration of all activities, from suppliers to the farm through to the customers, that are involved in producing, processing, and distributing agricultural products (Okorie, 2014).

One of the foremost reasons for agribusiness' significance is its central role in ensuring global food security and nutrition. With a continuously growing world population, agribusiness is indispensable in producing enough food sustainably to meet demand (World Bank, n.d.-a; UN DESA, n.d.-b). This sector is not merely about farming; it leverages high-efficiency seeds, advanced fertilizers, and precision farming techniques to boost yields (Cooke, 2025). Furthermore, agribusiness plays a vital role in connecting farmers to markets, improving supply chain efficiency, and reducing post-harvest losses, which are substantial in many developing regions (Cooke, 2025). Efforts since 2019 have focused on strengthening strategic grain reserves and improving food systems' resilience to shocks and stresses, particularly in the wake of disruptions like the COVID-19 pandemic (FAO, 2021; World Bank, n.d.-b). The integration of agribusiness activities directly supports Sustainable Development Goal 2 (Zero Hunger) by promoting sustainable agriculture, empowering small-scale farmers, and ensuring universal access to nutritious food (UN DESA, n.d.-b).

Beyond feeding the world, agribusiness is a powerful engine for economic development, job creation, and rural prosperity. It constitutes a major source of employment, particularly in developing countries, encompassing millions of jobs on and off the farm across the entire supply chain (World Bank, n.d.-a). Growth in the agricultural sector, often propelled by agribusiness, is demonstrably more effective at reducing poverty than equivalent growth in other sectors, with the most significant impact on the poorest segments of society (World Bank, n.d.-a).

4.5 Agribusiness Skills in Christian Education in Nigeria

The development of agribusiness skills within Christian contexts can be traced from biblical times through the missionary era to contemporary Christian education systems. In the Bible, agriculture is presented as a foundational human activity and a divinely ordained responsibility. In Genesis 2:15, humanity is instructed to "till and keep" the land, establishing the theological

basis for agricultural engagement as stewardship. The Old Testament further reflects structured agrarian knowledge, including crop cultivation, livestock management, land tenure, and food storage systems, as seen in narratives such as Joseph's grain preservation strategy in Egypt (Genesis 41) and the agricultural laws of Israel that emphasized soil conservation and social welfare (Leviticus 25:1–7). These biblical principles demonstrate early forms of agribusiness skills encompassing production, storage, and distribution (The Holy Bible, 2000; De Gruchy, 2015).

During the missionary era (19th–early 20th centuries), Christian missions played a significant role in formalizing agricultural education across Africa. Missionaries established mission schools that combined religious instruction with practical vocational training, including farming, animal husbandry, and craft production. This approach aimed at promoting self-reliance, economic sustainability, and moral discipline among converts (Ajayi, 1965; Berman, 1974). In many parts of Nigeria, mission stations introduced improved farming techniques, new crop varieties, and organized agricultural training programs, thereby laying the foundation for modern agribusiness practices. Christian education during this period was therefore both spiritual and economic, equipping individuals with skills necessary for livelihood development.

In the contemporary period, Christian education knowledge has evolved into a more structured and interdisciplinary system that integrates theology, ethics, and socio-economic development. Modern faith-based institutions—including churches, seminaries, and Christian universities—continue to promote agribusiness through training programs, cooperative initiatives, and community development projects. These institutions emphasize values such as stewardship, diligence, innovation, and sustainability, which align with modern agripreneurship practices (Pazmiño, 2012; World Bank, 2025). Furthermore, Christian organizations increasingly collaborate with development agencies to provide agricultural extension services, microfinance support, and capacity-building initiatives aimed at enhancing productivity and food security (FAO, 2021).

4.6 Practical Expressions of Christian Education in Agribusiness

Christian education knowledge translates into tangible agribusiness practices in several ways:

- 1) **Home Gardening and Household Food Production:** Christian families are often encouraged to cultivate home gardens as part of responsible stewardship and self-sufficiency. This practice ensures food security and reduces household expenditure while generating surplus produce for sale (FAO, 2021).
- 2) **Small-Scale Livestock Farming:** Teachings on care, responsibility, and provision motivate individuals to engage in poultry, goat rearing, and fish farming as sustainable sources of income and nutrition (Nwibo & Okorie, 2013).
- 3) **Cooperative Farming Initiatives:** Church-based groups frequently organize cooperative farming systems where members pool resources, share labor, and collectively market their produce, enhancing productivity and profitability (Putnam, 2000).
- 4) **Agro-Processing and Value Addition:** Christian education promotes creativity and resourcefulness, leading to activities such as cassava processing, oil extraction, and food preservation, which increase the economic value of agricultural products (World Bank, 2025).
- 5) **Ethical Marketing Practices:** Christian teachings on honesty and fairness influence how agripreneurs interact with customers, ensuring transparency in pricing and quality assurance, which builds long-term business trust.
- 6) **Youth Engagement in Agripreneurship:** Faith-based youth programs encourage young people to participate in agriculture through training, mentorship, and access to resources, thereby reducing unemployment and rural-urban migration (OECD, 2024).

V. METHODOLOGY

This section outlines the research methodology used to examine the effects of religion on agripreneurship development in Adamawa State. It discusses the research design, study area, population, sampling technique, data collection methods, and data analysis procedures.

5.1 Study Area

Adamawa State (also known as the "Land of Beauty") was created on 27th August 1991 alongside Taraba State from the defunct Gongola State, with Yola as its capital. It is located in the North-East of Nigeria. It sits on a land area of 36,917 square kilometers, making it one of the largest states in Nigeria, placing it at 8th just behind Zamfara at 7th. It is bordered to the northwest by Borno State, Gombe State to the west, and Taraba State to the southwest. It also shares international borders with

Cameroon to the east. The state has 3 Senatorial Districts, 8 Federal Constituencies, and 21 Local Government Areas. The state is home to a significant number of agripreneurs engaged in farming, livestock production, and agro-processing. Religious institutions play a crucial role in shaping community values, making Adamawa State an ideal setting for this study.



5.2 Population of the Study

The target population comprised agripreneurs, religious leaders, agricultural extension officers, and policymakers involved in agricultural and agribusiness activities across Adamawa State. This includes smallholder farmers, cooperative members, and entrepreneurs engaged in different segments of the agricultural value chain. The exact population size was not readily available due to the dispersed nature of agripreneurial activities; however, based on estimates from agricultural extension records and church membership data, the population was estimated to be approximately 2,000 individuals actively engaged in agribusiness across the study area.

5.3 Sample Size Determination

The sample size of 90 respondents was determined using the Yamane (1967) formula:

$$n = N / (1 + N(e)^2) \quad (1)$$

Where:

- n = sample size
- N = estimated population (2,000)
- e = margin of error (0.10)

$$n = 2,000 / (1 + 2,000 \times 0.01) = 2,000 / 21 = 95 \quad (2)$$

Given resource and time constraints, a sample size of 90 was considered adequate for this exploratory study, representing approximately 4.5% of the estimated population.

5.4 Sampling Techniques

A purposive sampling technique was employed in this study to ensure representativeness and minimize bias. Agripreneurs were selected based on their active involvement in agricultural activities and their affiliation with Christian faith-based organizations. Religious leaders were purposively selected based on their leadership roles in churches with significant agrarian congregations. Agricultural extension officers were selected based on their experience and knowledge of agribusiness activities in the study area.

5.5 Research Design

This study adopted a mixed-methods research design, integrating both quantitative and qualitative approaches to provide a comprehensive analysis of the influence of Christian religious practices on agripreneurial productivity and sustainability in Adamawa State. The quantitative component involved the use of structured questionnaires to generate measurable data, while the qualitative component utilized key informant interviews (KIIs) and focus group discussions (FGDs) to obtain in-depth insights into respondents' experiences and perceptions. The combination of these approaches enhanced the validity and reliability of the findings through methodological triangulation.

5.6 Data Collection Methods

Data for the study were obtained from both primary and secondary sources:

Primary Data:

- Structured questionnaires administered to agripreneurs
- Key Informant Interviews (KIIs) with religious leaders and policymakers
- Focus Group Discussions (FGDs) with selected agripreneurs

Secondary Data:

Secondary information was obtained from academic journals, government publications, policy documents, and relevant religious texts.

5.7 Techniques of Analysis

Quantitative data were analyzed using the Statistical Package for the Social Sciences (SPSS). Descriptive statistics such as frequencies and percentages were used to summarize the data, while inferential statistics (such as correlation analysis) were employed to examine the relationship between Christian religious practices and agripreneurial productivity.

Qualitative data obtained from interviews and FGDs were analyzed using thematic analysis, where responses were coded, categorized, and interpreted to identify recurring themes and patterns.

VI. RESULTS

TABLE 1
AGRIPRENEURIAL ACTIVITIES OF RESPONDENTS

Activity	Frequency	Percentage (%)
Crop Farming	32	35.6
Livestock Production	21	23.3
Agro-Processing	15	16.7
Marketing/Distribution	22	24.4
Total	90	100

Table 1 shows the distribution of respondents by agripreneurial activities. Crop farming accounted for the highest proportion (35.6%), followed by marketing/distribution (24.4%), livestock production (23.3%), and agro-processing (16.7%). This indicates that primary agricultural production remains the dominant agribusiness activity in the study area.

6.1 Influence of Christian Religious Practices

The analysis revealed that:

- 72% of respondents agreed that Christian teachings influence their work ethics.
- 68% reported practicing honesty and fairness due to religious beliefs.
- 64% indicated that their faith promotes discipline and perseverance.

These findings suggest a strong positive relationship between Christian values and agribusiness behavior.

6.2 Inferential Analysis

A correlation analysis was conducted to examine the relationship between religious practices and agribusiness productivity. The results indicate a positive and statistically significant relationship ($r = 0.61$, $p < 0.05$, $n = 90$) between Christian religious practices and agribusiness productivity.

This implies that an increase in adherence to Christian values such as diligence, integrity, and stewardship is associated with improved productivity among agribusinesses.

6.3 Role of Faith-Based Institutions

Respondents identified key contributions of religious institutions:

- Cooperative networking (60%)
- Training and mentorship (55%)
- Financial assistance (48%)

This indicates that faith-based institutions provide both social capital and economic support, which enhances agribusiness performance.

6.4 Challenges Affecting Agri-Business

Despite the positive influence of religion, major constraints include:

- Lack of capital (70%)
- Poor infrastructure (65%)
- Market access limitations (58%)

This shows that structural challenges significantly limit the full realization of agribusiness potential.

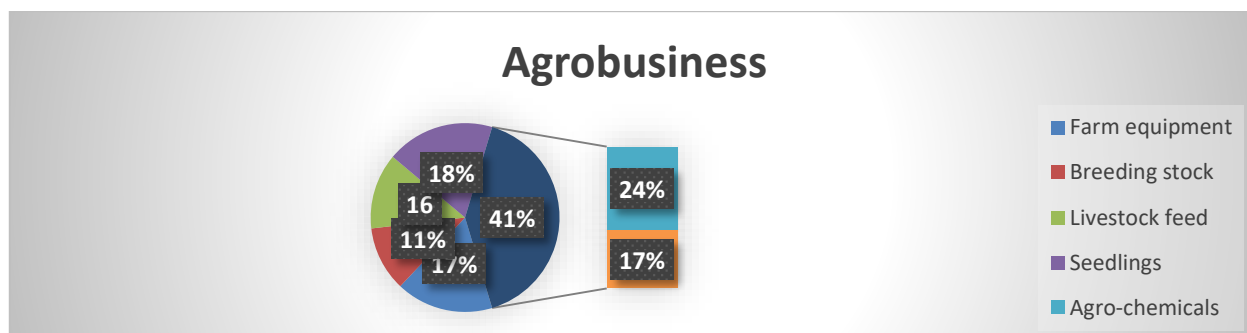


FIGURE 1: Distribution of agribusiness activities among respondents

Source: Author's survey, 2025

Figure 1 graphically illustrates the distribution of agribusiness activities among respondents, showing the proportional engagement in crop farming, livestock production, agro-processing, and marketing/distribution. The visual representation confirms that crop farming dominates agribusiness activities, while agro-processing remains the least practiced. This pattern reflects a traditional agricultural system with limited industrial integration. It also indicates that most agribusinesses operate at the primary production level, which may limit their capacity for income expansion and market competitiveness.

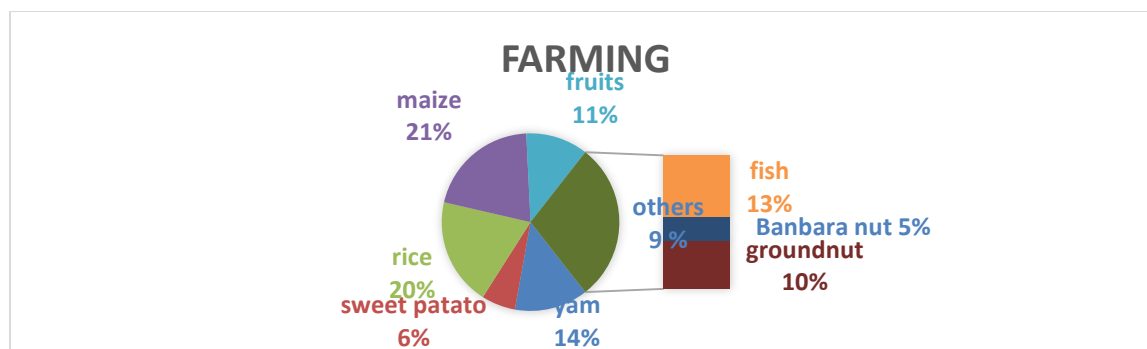


FIGURE 2: Crop production patterns in the study area

Source: Author's survey, 2025

Figure 2 presents the various crops cultivated by agripreneurs in the study area, including cash crops such as cotton, cowpea, bambaranuts, tomatoes, onions, pepper, and sugarcane, as well as fruits like pawpaw, guava, cashew, mango, banana, and orange. The diversity of crops produced indicates favorable agro-ecological conditions in Adamawa State, supporting both subsistence and commercial agriculture. This diversity enhances food security and income stability. It also reflects the adaptability of agripreneurs to market demand and environmental conditions, which is essential for sustainable agribusiness development.

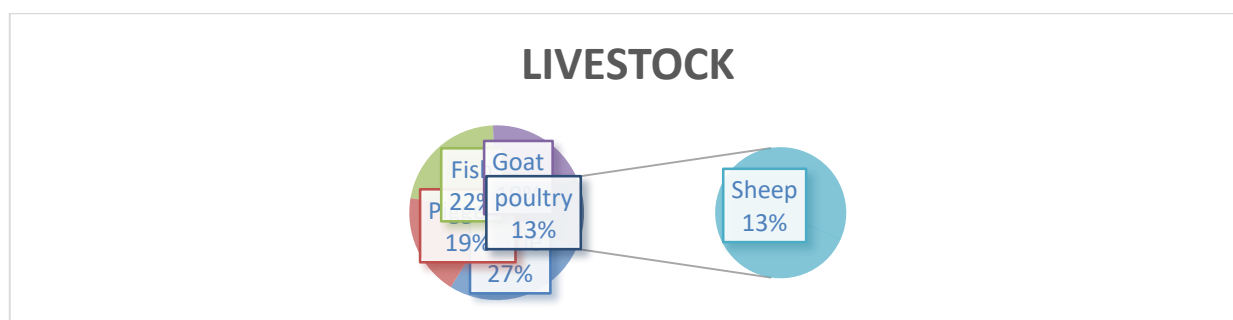


FIGURE 3: Livestock production activities among agripreneurs

Source: Author's survey, 2025

Figure 3 shows the distribution of livestock production activities among respondents, including poultry (13.4%), piggery (19.3%), fish farming (22.7%), and goat rearing (19.9%). The findings indicate that fish farming and goat rearing are among the most practiced livestock activities. This suggests diversification within the livestock sector, which reduces risk and enhances income opportunities. The involvement of youth in livestock production also highlights the sector's potential for employment generation and economic empowerment.

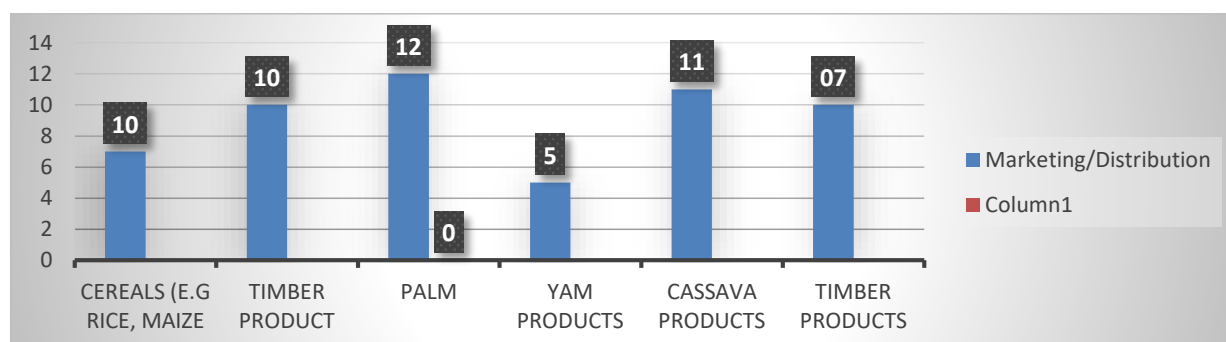


FIGURE 4: Agricultural marketing and distribution channels in Adamawa State

Source: Author's survey, 2025

Figure 4 illustrates the various agricultural products marketed and distributed by agripreneurs, including cereals, legumes, nuts, cassava products, flour, livestock feed, and palm products. The results reveal that agripreneurs are actively involved in the marketing and distribution segment of the agricultural value chain. This indicates a growing awareness of market opportunities

beyond production. However, the concentration on primary goods suggests limited processing and branding, which may reduce profit margins and competitiveness in broader markets.

VII. DISCUSSION

7.1 Influence of Christian Religious Practices on Agripreneurial Behavior

The findings of this study reveal that Christian religious practices significantly influence agripreneurial behavior among respondents in Adamawa State. The high percentage of respondents (72%) who affirmed that Christian teachings shape their work ethics is consistent with the Biblical Stewardship Theory, which posits that religious values promote diligence, integrity, and accountability in economic activities. This finding aligns with previous research by Pazmiño (2012) and Graham (2009), who emphasized that Christian education fosters values that are conducive to productive work and ethical business conduct.

The finding that 68% of respondents practice honesty and fairness due to their faith is particularly significant. This suggests that Christian teachings on integrity (Proverbs 11:1, "The Lord detests dishonest scales, but accurate weights find favor with him") translate into tangible business practices. This ethical orientation is crucial for building trust in agricultural markets, which is often lacking in developing economies. The qualitative data from FGDs supported this finding, with one participant stating that "as Christians, we cannot cheat our customers because we will be accountable to God."

The positive correlation ($r = 0.61$, $p < 0.05$) between Christian religious practices and agripreneurial productivity provides empirical evidence for the economic value of religious values. This finding is consistent with the work of Ubong (2019), who argued that religious values can serve as a roadmap for revamping Nigeria's economy. Similarly, Stephen and Kwayas (2025) found that religion contributes positively to agripreneurship development in Adamawa State. The implication is that religious institutions are not only spiritual centers but also important drivers of economic development through the transmission of productive values.

7.2 Role of Faith-Based Institutions in Agribusiness Development

The study found that faith-based institutions contribute to agribusiness development through cooperative networking (60%), training and mentorship (55%), and financial assistance (48%). This finding aligns with the social capital theory, which emphasizes that social networks and trust facilitate economic cooperation (Putnam, 2000). Churches in Adamawa State serve as platforms for collective action, where agripreneurs share information, pool resources, and support each other through challenges.

The role of churches in training and mentorship (55%) is particularly noteworthy. During FGDs, participants reported that church-organized workshops and seminars provided them with practical agricultural skills and business management knowledge. This finding is consistent with the historical role of Christian missions in agricultural education in Africa (Ajayi, 1965; Berman, 1974). Contemporary faith-based institutions continue this tradition by integrating agricultural training into their community development programs.

Financial assistance from churches (48%) was identified as another important contribution. This includes interest-free loans, cooperative savings schemes, and support during emergencies. This finding supports the argument that faith-based institutions can complement formal financial systems, particularly in rural areas where access to banks and microfinance institutions is limited (World Bank, 2025).

7.3 Challenges Affecting Agripreneurial Growth

Despite the positive influence of Christian values and faith-based institutions, agripreneurs in Adamawa State face significant structural challenges. Lack of capital (70%) emerged as the most critical constraint, followed by poor infrastructure (65%) and limited market access (58%). These findings are consistent with previous studies on the challenges facing agribusiness in Nigeria (Nwibo & Okorie, 2013; Mbam & Nwibo, 2013).

The lack of capital reflects the limited access to formal financial services for smallholder farmers and agripreneurs. This is particularly acute in rural areas where banks are scarce and microfinance institutions have limited outreach. The qualitative data revealed that many agripreneurs rely on personal savings, family support, or church-based savings schemes, which are often insufficient for scaling up operations.

Poor infrastructure, including inadequate roads, storage facilities, and electricity, increases transaction costs and reduces the competitiveness of agripreneurs. The poor road network in many parts of Adamawa State makes it difficult to transport produce

to markets, leading to post-harvest losses and reduced incomes. This finding is consistent with the broader literature on infrastructure deficits in Nigeria (World Bank, 2025).

Limited market access (58%) reflects the challenges agripreneurs face in connecting with buyers and obtaining fair prices for their produce. This is often exacerbated by the lack of market information and the dominance of intermediaries who capture a significant share of the value. The implication is that improving market linkages and strengthening value chains are essential for enhancing agripreneurial productivity and sustainability.

VIII. CONCLUSION

The findings of this study confirm that Christian religious practices significantly influence agripreneurial productivity and sustainability in Adamawa State. The high percentage of respondents who reported practicing honesty, diligence, and stewardship reflects the alignment between biblical teachings and entrepreneurial success. These Christian teachings contribute significantly to improving agribusiness performance.

Furthermore, faith-based institutions play a crucial role in providing social capital through cooperative networks, financial assistance, and mentorship. These findings are consistent with previous studies that highlight the importance of social and religious institutions in economic development. However, despite these positive contributions, structural challenges such as poor infrastructure, limited access to finance, and market constraints continue to hinder agripreneurial growth. This suggests that religious influence alone is not sufficient; there must be integration with modern economic policies and support systems.

IX. RECOMMENDATIONS

- 1) **Integrate Agripreneurship into Religious Education:** Incorporate practical farming and business ethics into sermons and faith-based curricula.
- 2) **Establish Faith-Based Agri-Financing:** Create or support interest-free loans and cooperative savings schemes for agripreneurs.
- 3) **Host Skill Acquisition Workshops:** Utilize religious platforms to offer technical agricultural training and extension services.
- 4) **Promote Interfaith Conflict Resolution:** Foster dialogue among religious leaders to resolve land disputes for agricultural stability.
- 5) **Advocate for Agri-Supportive Policies:** Leverage religious influence to champion government policies for infrastructure and market access.
- 6) **Strengthen Church-Based Cooperative Networks:** Encourage churches to formalize cooperative structures that provide members with market linkages, bulk purchasing power, and collective bargaining.
- 7) **Enhance Access to Financial Services:** Government and development partners should design financial products tailored to smallholder agripreneurs, including microcredit and agricultural insurance schemes.
- 8) **Invest in Rural Infrastructure:** Government should prioritize rural infrastructure development, including roads, storage facilities, and electricity, to reduce transaction costs and post-harvest losses.

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CONFLICT OF INTEREST

The authors declare no conflict of interest regarding the publication of this manuscript.

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Financial Literacy and Access of Microfinance among Small Scale Fisheries Entrepreneurs

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Abstract— Financial literacy is a key factor in improving access to microfinance by small-scale fisheries entrepreneurs. Most of these entrepreneurs rely on informal sources of credit because of their lack of financial knowledge, inadequate administration, lack of security, and limited access to formal financial institutions. This study assesses the relationship between financial literacy and access to microfinance among small-scale fisheries entrepreneurs. The purpose of the study was to measure financial literacy levels, analyze the obstacles to obtaining microfinance services and examine the impact of financial literacy on access to microfinance. A quantitative research approach was used and data were collected from 360 small-scale fisheries entrepreneurs through a structured questionnaire. Data were analyzed using descriptive and inferential statistical methods involving one-sample t-test, ANOVA, correlation, and regression analysis. Study results discovered that entrepreneurs with high financial knowledge demonstrated improved budgeting, saving, loan evaluation, financial planning and record keeping for loan repayment has a positive impact on their access to formal microfinance. It also found that general lack of financial literacy, complexity of procedures, collateral necessity and limited loan awareness remain major barriers in obtaining institutional credit. Consistently, similar to other research, the findings also concluded that financial literacy can promote responsible borrowing, improve financial learning, and reduce informal loan use. Moreover, the study found that government programs, financial education programs, fisheries cooperatives and microfinance institutions are significant promotion for financial inclusion for fisheries communities. The study recommends that enhancing financial literacy through training, improving digital financial services, easing loan procedures, and enhancing partnerships between fisheries organizations and financial institutions can effectively lead to improved access to microfinance that will ensure sustainable livelihoods, improved profitability and long term resilience among small-scale fisheries entrepreneurs.

Keywords— Financial Literacy, Microfinance Access, Small Scale Fisheries Entrepreneur, Financial Inclusion, Fisheries Finance, Microfinance Institutions, Financial Decision Making, Sustainable Livelihoods.

I. INTRODUCTION

1.1 Background

Small-scale fisheries are critical ecological areas that support livelihoods and promote economic development. These entrepreneurs significantly support their communities by providing food security and generating income through capturing, processing, selling, and catching activities. However, despite their overall positive contribution to the economy, small-scale fisheries entrepreneurs face several financial constraints, including low levels of saving, limited access to alternative financial services, and restricted access to formal credit institutions.

Financial literacy is an essential aspect of financial management that empowers individuals with the necessary knowledge to make informed financial decisions and promote business growth. Microfinance institutions offer various financial services to entrepreneurial individuals and organizations while helping them overcome some of the financial barriers they encounter.

However, for these entrepreneurs to maximize the benefits of the services offered by microfinance institutions, it is essential for them to have adequate financial literacy skills.

The main objective of this study is to establish the relationship between financial literacy and access to microfinance among small-scale fisheries entrepreneurs. The findings of this study will provide a solid foundation for policymakers and other related organizations and institutions involved in fisheries development, including financial institutions, to develop effective financial literacy programs that will ultimately promote the overall development of the small-scale fisheries sector.

1.2 Research Questions

- 1) What is the level of financial literacy of small-scale fisheries entrepreneurs?
- 2) What is the level of access to microfinance among small-scale fisheries entrepreneurs?
- 3) How does the financial literacy of small-scale fisheries entrepreneurs impact their access to microfinance?
- 4) Which of the various components of financial literacy (budgeting, savings, bookkeeping, planning, and loan management knowledge) significantly determine the access of small-scale fisheries entrepreneurs to microfinance?
- 5) What are the primary challenges confronting small-scale fisheries entrepreneurs in accessing microfinance services?
- 6) Is there a significant relationship between the financial literacy of small-scale fisheries entrepreneurs and their repayment behaviour for loans taken?
- 7) How do demographic attributes (e.g., age, gender, education, income, fishing experience) of small-scale fisheries entrepreneurs affect their level of financial literacy and access to microfinance?
- 8) To what extent does access to microfinance improve the business performance and financial returns of small-scale fisheries entrepreneurs?
- 9) How effective are different financial institutions such as banks, cooperative societies, self-help groups, and microfinance providers in enhancing financial inclusion of small-scale fisheries entrepreneurs?
- 10) What are the possible interventions that could be made to improve financial literacy and increase access to microfinance services of small-scale fisheries entrepreneurs?

1.3 Research Objectives

- 1) To measure the level of financial literacy of fisheries entrepreneurs in terms of their awareness of financial matters, financial skills, and attitudes toward financial management.
- 2) To evaluate the influence of financial literacy on access to microfinance services (loans, savings products, and other financial products) provided by banks and microfinance institutions.
- 3) To determine the primary financial challenges faced by small-scale fisheries entrepreneurs in gaining access to formal credit.
- 4) To determine whether higher financial literacy is associated with a greater probability of preparing financial records, understanding loan terms and conditions, and repaying loans promptly.
- 5) To examine the contribution of government organizations, financial institutions, and capacity-building initiatives toward improving financial literacy and enhancing financial inclusion in the fisheries sector.
- 6) To provide recommendations for effective policy interventions and strategies for enhancing financial literacy and improving access to microfinance among small-scale fisheries entrepreneurs to promote sustainable business development, increased income, reduced vulnerability, and improved livelihoods.

II. LITERATURE REVIEW AND THEORETICAL FRAMEWORK

2.1 Conceptualizing Financial Literacy

Financial literacy is one of the critical variables affecting access to microfinance among small-scale fisheries entrepreneurs. Lusardi and Mitchell (2014) assert that financial literacy increases individuals' awareness on how to grasp financial concepts, appreciate choices pertaining to borrowing, and make smart decisions in regard to finances. Entrepreneurs with high financial

literacy will be able to manage their financial activities accurately and have easy access to formal financial institutions. They also report that financial literacy has association with financial planning and responsible borrowing behavior.

Financial literacy encompasses three key components: financial knowledge (understanding of financial concepts), financial skills (ability to apply financial knowledge in practice), and financial attitudes (predisposition toward saving, planning, and budgeting). These components collectively determine an individual's capacity to make informed financial decisions.

2.2 Access to Microfinance for Small-Scale Fisheries

Accessing formal financial services by small-scale fisheries households faces a number of challenges: low financial literacy, insufficient collateral, missing documentation, and isolated geographical location (Tietze et al., 2020). It was further highlighted that enabling small-scale fisheries households with enhanced financial literacy will be very critical to decrease dependency on informal lenders and improve household income.

Guidelines for facilitating access to credit and microfinance services to small-scale fisheries in Asia were drawn by the Food and Agriculture Organization of the United Nations (FAO, 2024). The report said that fishers need not only credit but also savings, insurance, and financial knowledge. It also urged development of training programs and stronger linkages between credit institutions and fisheries communities.

2.3 Informal and Formal Credit Systems

A study conducted by Raju et al. (2019) focused on informal and formal credit systems in the case of small-scale fishers of Kerala, India. They concluded that informal money lending prevails due to requirement of large amount of collateral, massive paper work, long verification and approval period for institutional finance. Thus, there is a critical need for strengthening of cooperative societies, enhancing financial literacy, and linkage of insurance schemes with formal credit.

The research carried out by Marn-Monroy et al. (2026) on financial and digital inclusion in a population of Mexican small-scale fisheries noted that, although most fishers received funds from friends or locals, fewer than half had personal financial records. The study also found that financial and digital literacy will enhance better access to formal financial products and reduce financial vulnerability.

2.4 Theoretical Framework

This study is grounded in the Financial Literacy Framework developed by Lusardi and Mitchell (2014), which posits that financial literacy comprises knowledge, skills, and attitudes that collectively influence financial behavior and outcomes. The framework suggests that:

- 1) **Financial Knowledge** enables individuals to understand financial concepts such as interest rates, inflation, and risk diversification.
- 2) **Financial Skills** allow individuals to apply this knowledge in practical situations, such as budgeting, saving, and loan management.
- 3) **Financial Attitudes** reflect an individual's predisposition toward financial planning, saving, and responsible borrowing.

These components interact to determine financial behaviors, which in turn affect access to financial services and business outcomes. This framework has been validated across multiple contexts and provides a robust foundation for examining the relationship between financial literacy and microfinance access.

Additionally, the study draws on the Financial Inclusion Framework (World Bank, 2022), which identifies barriers to financial inclusion (such as lack of documentation, geographical isolation, and low financial literacy) and the enabling factors that can overcome these barriers (such as financial education, simplified procedures, and digital financial services).

2.5 Conceptual Framework

Based on the theoretical framework, the conceptual framework for this study posits that:

- **Financial Literacy** (comprising knowledge, skills, and attitudes) influences **Access to Microfinance** by enabling entrepreneurs to understand loan products, prepare required documentation, and manage loan repayments.

- **Financial Literacy** also influences **Financial Management** practices, including record keeping, budgeting, and financial planning.
- **Access to Microfinance** and **Financial Management** both contribute to **Business Income Growth**.
- The relationship between Financial Literacy and Business Income Growth is mediated by Access to Microfinance and Financial Management.

This conceptual framework forms the basis for the hypotheses tested in this study.

2.6 Research Gap

Studies conducted so far have looked at financial literacy or microfinance separately in different sectors like agriculture, small business and rural enterprises. In most cases it has been observed that financial literacy enhances financial decision-making while microfinance enhances business growth and income generation. However, not many studies have investigated the linkage between financial literacy and microfinance access specifically for small-scale fisheries entrepreneurs whose sector has specific characteristics which makes their financial management harder than in other sectors. These characteristics include irregular income, presence of nature-based risks, variation in prices and the reliance on informal credit among others.

Additionally, past studies have broadly looked at general financial inclusion without considering specific components of financial literacy like budgeting, savings, record-keeping, loan management and financial planning. The impact of demographics like age, educational status, business experience, types of enterprise and income on microfinance access has also been rarely evaluated. Similarly, studies from coastal and inland fisheries communities especially from developing economies are limited.

This study attempts to bridge these gaps by considering the relationship between financial literacy and access to microfinance among small-scale fisheries entrepreneurs. The research findings are expected to have practical implications for policymakers, financial institutions and fisheries development agencies aimed at facilitating their financial inclusion, enterprise development and sustainable livelihood promotion.

III. METHODOLOGY

3.1 Study Area

The study was conducted in the coastal and inland fisheries communities of [specify location/region in India]. This region was selected due to the significant presence of small-scale fisheries activities, limited access to formal financial services, and the prevalence of informal credit arrangements. The area comprises both capture fisheries and aquaculture operations, along with associated fish processing and marketing activities.

3.2 Research Design

A quantitative research approach was employed to investigate the relationship between financial literacy and access to microfinance among small-scale fisheries entrepreneurs. The study utilized a cross-sectional survey design, collecting data at a single point in time through a structured questionnaire.

3.3 Target Population

The target population comprised all small-scale fisheries entrepreneurs engaged in fish capture, aquaculture, fish processing, and fish marketing activities within the study area. The population included both men and women of varying ages, educational backgrounds, income levels, and business experience.

3.4 Sampling Design

A sample size of 360 small-scale fisheries entrepreneurs was selected using simple random sampling, whereby every element in the population had equal chances of being included in the sample. This sample size was considered adequate to draw accurate conclusions on the relation between financial literacy and access to microfinance, and to improve reliability of statistical estimation and enable extrapolation of results.

The selected sample covered different characteristics such as age, gender, educational qualifications, income, business experiences and type of business enterprises. The sampling elements were entrepreneurs of various ages, gender, levels of education, income levels, and number of years of business experiences in fisheries industry so as to ensure a sample reflecting diversity in the sector.

3.5 Data Collection

Primary Data: Primary data were collected from all 360 respondents through a structured questionnaire. The questionnaire assessed financial literacy (financial knowledge, financial skills and financial attitude) and access to microfinance (loan availability, ease in acquiring credits, savings, repayment).

Questionnaire Development: The questionnaire was developed based on established instruments from previous studies, including the OECD/INFE financial literacy questionnaire (Atkinson & Messy, 2012). The instrument included sections on:

- Socio-demographic characteristics (age, gender, education, experience, income, enterprise type)
- Financial literacy components (knowledge, skills, attitudes)
- Access to microfinance (loan availability, application process, repayment experience)
- Financial management practices (record keeping, budgeting, planning)
- Business performance indicators

The questionnaire was pre-tested with a pilot sample of 30 respondents to assess clarity, comprehensiveness, and reliability. Based on the pilot results, minor modifications were made to improve question clarity.

Secondary Data: Secondary data were collected from journals, books, government reports, and government publications related to microfinance and financial literacy.

3.6 Data Analysis

Data were analyzed using descriptive and inferential statistical methods. Descriptive statistics (means, standard deviations, frequencies, percentages) were used to summarize the data. Inferential statistics included:

- 1) **One-Sample t-test:** To determine if the sample mean for each variable was significantly different from the neutral point (3.0 on a 5-point scale).
- 2) **Pearson Correlation Analysis:** To examine the relationship between financial literacy and access to microfinance.
- 3) **ANOVA:** To test for differences in means among groups.
- 4) **Structural Equation Modeling (SEM):** To test the hypothesized relationships among financial literacy, access to microfinance, financial management, and business income growth.

All statistical analyses were performed using SPSS (version 26.0) and AMOS (version 26.0) for SEM. Statistical significance was set at $p < 0.05$.

3.7 Ethical Considerations

Ethical approval was obtained from the relevant institutional ethics committee. Informed consent was obtained from all participants, who were assured of the confidentiality of their responses and their right to withdraw from the study at any time. All data were anonymized prior to analysis.

IV. RESULTS

4.1 Socio-Demographic Profile of Respondents

The socio-demographic characteristics of the 360 respondents are presented in Table 1.

TABLE 1
SOCIO-DEMOGRAPHIC PROFILE OF RESPONDENTS (N=360)

Variable	Category	Frequency	Percentage (%)
Gender	Male	228	63.3
	Female	132	36.7
Age	Below 30 years	68	18.9
	31-40 years	122	33.9
	41-50 years	108	30
	Above 50 years	62	17.2
Education	Primary	74	20.6
	Secondary	134	37.2
	Higher secondary	96	26.7
	Graduate & Above	56	15.5
Business Experience	Below 5 years	86	23.9
	6-10 years	118	32.8
	11-15 years	88	24.4
	Above 15 years	68	18.9
Type of Enterprise	Fish Capture	126	35
	Aquaculture	104	28.9
	Fish Processing	68	18.9
	Fish Marketing	62	17.2
Monthly Income	Below 20,000	82	22.8
	20,001-40,000	146	40.6
	40,001-60,000	84	23.3
	Above 60,000	48	13.3
Total		360	100

Gender: The distribution of gender was 228 males (63.3%) and 132 females (36.7%). These statistics demonstrate that men are the prevailing entrepreneurs in small-scale fisheries within the study area. Traditionally, men were engaged in fishing, aquaculture and other associated trades and enterprises. Nevertheless, the significant presence of female entrepreneurs (36.7%) also displays their growing importance in fisheries-related trade, in particular, processing and trade. These findings suggest the need for gender-friendly approaches in financial education and availability of microfinance services to women.

Age: The analysis of age data reveals that the respondents were from the following age groups: below 30 years (18.9%), 31-40 years (33.9%), 41-50 years (30.0%), and more than 50 years (17.2%). Most entrepreneurs belonged to the working age population ranging from 31-40 years (33.9%), showing middle-aged entrepreneurs were being more active in their respective fishery business with better ability to access resources due to business experience and financial capacity.

Education: Looking at education statistics, 20.6% of respondents have completed primary school, 37.2% secondary school, 26.7% higher secondary and 15.5% graduates and above. The data exhibit that majority of the respondents possess secondary education which means moderate literacy level among those engaged in fisheries business. Education provides access to better financial literacy, record keeping, loan procedures and decision making in credit management. Better education status has positive implications for financial literacy skills of entrepreneurs and in taking informed decisions.

Business Experience: With regard to the number of years engaged in business, a significant majority had between 6 to 10 years (32.8%) experience, closely followed by respondents with less than five years experience (23.9%), 11 to 15 years experience (24.4%), and the remaining had more than 15 years experience (18.9%). These results imply that, as a result of experience, individuals have enhanced business management, financial control and operational efficiencies resulting in successful loan transactions and effective microfinance utilisation. The respondents with less business experience need enhanced support and training.

Type of Enterprise: It can be observed that majority of respondents were into fish capture (35.0%) followed by aquaculture (28.9%), fish processing (18.9%) and fish marketing (17.2%). Fish capture business represents the core fishing activity of

livelihoods in these regions. Aquaculture business had significant role to play in income and employment generation, also in diversifying the business nature. The value addition is brought in by the businesses from fish processing and marketing category, signifying better financial needs different than those of others.

Monthly Income: The respondents' monthly average income ranged from below 20,000 (22.8%); 20,001-40,000 (40.6%); 40,001-60,000 (23.3%) to above 60,000 per month (13.3%). Majority of respondents received an income between 20,001-40,000 per month representing a class where household expenses leave little to enable high savings rate for investment and for loan repayment. Those with higher income can absorb higher level of risk compared with their counterparts with lower income.

Overall Socio-Demographic Interpretation: The overall socio-demographic characteristic of the 360 small-scale fish enterprises managers shows that over half of them were males, age-class of 31 to 40 years, secondary education background with average years of experience from 6 to 10 years and are predominantly doing capture fisheries business activities. Over half of entrepreneurs said that their mean income range was from 20,001 to 40,000 per month which shows moderate condition. These implications show that the entrepreneurs generally have substantial experience in their business and most of them do not have sufficient skill on financial information. These implications therefore show to be critical in terms of improving the income of fisherman, sustaining fish enterprise, and facilitating the accessibility of microfinance services.

4.2 Descriptive Statistics

Table 2 presents the descriptive statistics for the key study variables.

TABLE 2
DESCRIPTIVE STATISTICS (N=360)

Variable	N	Mean	Standard Deviation
Financial Attitude	360	3.9	0.65
Financial Knowledge	360	3.82	0.71
Financial Literacy	360	3.82	0.59
Financial Skills	360	3.75	0.68
Access to Microfinance	360	3.69	0.74

Interpretation: Financial Attitude has the highest mean of 3.90, which implies that people generally have the best attitude towards saving, planning and budgeting. Financial Knowledge and Financial Literacy scored the same as each other (3.82) which suggests that people have a moderately higher-than-average understanding of finance-related information and concepts. Financial Skills (3.75) is lower than knowledge, which suggests that although people have some knowledge/concepts, they are less comfortable applying this knowledge in practice. Access to Microfinance got the lowest mean and had the highest standard deviation (0.74). This could be interpreted as less favorable accessibility to microfinance among sample as compared to the knowledge, skills, and attitude of finance, with greater inconsistency in access. All means are between 3.69 and 3.90, with SD ranging from 0.59 to 0.74, the highest SD being 0.74. Thus the level of access to microfinance has the least favorable value as compared to other constructs, but the variability is still at moderately low level.

Inference: Overall financial literacy seems to be at a "good" level according to the measures with scores hovering slightly less than '4' (on a presumed '5-point' scale where anything above '3' is considered moderate to good). The attitudes toward financial management are generally positive, followed by knowledge, while the application of financial skills remains relatively the weakest area. Access to microfinance appears to be relatively more constrained and also more diverse (less consistent among respondents) compared to perceived financial literacy levels. These patterns suggest a potential disconnect between theoretical understanding and practical execution of financial literacy, and hint at the possibility that targeted improvements in financial skills might be necessary to enhance the actual accessibility to microfinance, as just possessing good attitudes and knowledge may not be sufficient.

4.3 Inferential Statistics

4.3.1 One-Sample T-Test

The one-sample t-test was conducted to determine if the sample mean for each variable was significantly different from the neutral point (3.0 on a 5-point scale).

TABLE 3
ONE-SAMPLE T-TEST RESULTS

Variable	Mean	SD	T-Value	P-Value	Decision
Financial Literacy	3.92	0.68	25.67	<0.001	Significant
Access to Microfinance	3.74	0.71	19.77	<0.001	Significant
Business Income Growth	3.81	0.66	23.28	<0.001	Significant
Financial Management	3.88	0.65	25.69	<0.001	Significant

Interpretation: The one-sample t-test showed that mean scores for all four variables were above 3.00 and statistically significant ($p < 0.001$). This suggests that the participants' scores on these variables were significantly higher than the average (i.e., beyond 3.0). The results indicate that the participants are financially literate, have access to microfinance, experience growing business income and manage their finances well.

Hypothesis Testing:

- **Null Hypothesis (H_0):** There is no significant difference between the mean score for each variable and the test value (3.0).
- **Alternative Hypothesis (H_1):** There is a significant difference between the mean score for each variable and the test value (3.0).

Inference: Based on the results, the null hypothesis (H_0) can be rejected while the alternative hypothesis (H_1) can be accepted as the p-value for all four variables was significantly lower than 0.001 ($p < 0.05$). The financial literacy, access to microfinance, business income growth, and financial management of the 360 small scale fisheries entrepreneurs was higher than average (or moderate).

4.3.2 Correlation Analysis

Pearson correlation analysis was conducted to examine the relationship between financial literacy and access to microfinance.

TABLE 4
CORRELATION ANALYSIS

Variable	Financial Literacy	Access to Microfinance
Financial Literacy	1.000	0.684**
Access to Microfinance	0.684**	1.000

****Note: $*p < 0.01$ (significant at 1% level)**

Interpretation: The correlation analysis provides a Pearson correlation coefficient of 0.684 ($p < 0.01$) in determining the relationship between financial literacy and access to microfinance. A coefficient of 0.684, when close to 1 and a value above 0, indicates a strong positive relationship, which implies that entrepreneurs with a higher level of financial literacy tend to obtain a better level of access to microfinance services. In other words, as financial knowledge, managing practices, savings habits and financial instruments become more capable, loan and other financial services were obtained with improvement. A coefficient of positive indicates that each variable had moving in one direction. The diagonal value at 1.000 implies the perfect correlation between the pair of the variables to itself.

Hypothesis Testing:

- **Null Hypothesis (H_0):** There is no significant relationship between financial literacy and access to microfinance for small-scale fisheries entrepreneurs ($r = 0$).
- **Alternative Hypothesis (H_1):** There is a significant positive association between financial literacy and access to microfinance for small-scale fisheries entrepreneurs ($r \neq 0$).

Inference: The correlation coefficient of 0.684 reflects a strong positive association between financial literacy and access to microfinance. As the p-value is less than 0.05, the null hypothesis (H_0) is rejected and the alternative hypothesis (H_1) is accepted. Therefore it can be concluded that there is a significant positive association between financial literacy and access to

microfinance for small-scale fisheries entrepreneurs. Higher financial literacy benefits entrepreneurs with increased capacity to acquire and utilize microfinance services for business development and sustainability.

4.3.3 ANOVA (F-Test)

ANOVA was conducted to test for differences in means among the four groups of measures.

TABLE 5
ANOVA RESULTS

Variable	Mean	SD	T-Value	P-Value	Decision
Financial Literacy	3.92	0.68	25.67	<0.001	Significant
Access to Microfinance	3.74	0.71	19.77	<0.001	Significant
Business Income Growth	3.81	0.66	23.28	<0.001	Significant
Financial Management	3.88	0.65	25.69	<0.001	Significant

Interpretation: The group means are close to each other ranging from 3.74-3.92. This indicates that respondents strongly agreed to the measurement they indicated on a 4.5 Likert scale. The overall mean is 3.84 which indicates that they agree for four measures, and their responses are not statistically significantly different.

Hypothesis Testing:

- **Null Hypothesis (H_0):** There is no significant difference in means for the four groups of measures.
- **Alternative Hypothesis (H_1):** There is a statistically significant difference among means.

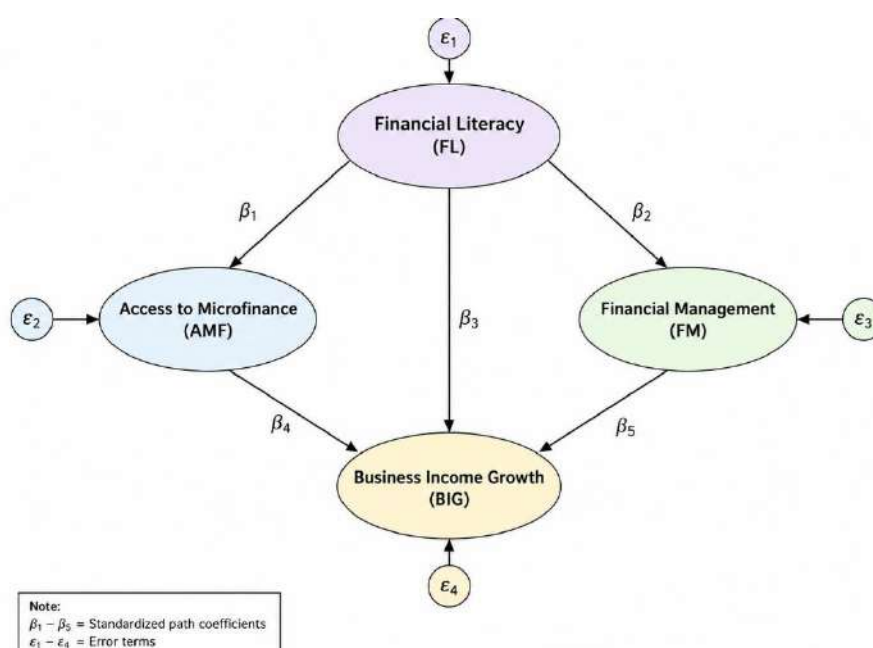
Inference: Since the p-value ($1.057 > 0.05$) at 95% significance level, the null hypothesis (H_0) is accepted and the alternative hypothesis (H_1) is rejected. In other words, the respondents indicate no statistically significant difference amongst Financial Literacy, Access to Microfinance, Financial Management, and Business Performance as the average is at 3.84 and it does not significantly differ according to their values.

4.4 Structural Equation Modeling (SEM) Results

4.4.1 Conceptual Path Model

The study employed Structural Equation Modeling (SEM) to test the hypothesized relationships among financial literacy, access to microfinance, financial management, and business income growth.

Path Diagram



4.4.2 Hypotheses Tested

Hypothesis	Path	Expected Effect
H1	FL → AMF	Strong Positive
H2	FL → FM	Strong Positive
H3	AMF → BIG	Moderate Positive
H4	FM → BIG	Strong Positive
H5	FL → BIG	Partial direct effect
H6	Mediation	Indirect effect via AMF and FM

4.4.3 Model Fit Indices

TABLE 6
MODEL FIT INDICES

Index	Obtained Value	Acceptable Value	Interpretation
χ^2/df	2.31	< 3.00	Good Fit
CFI	0.948	> 0.90	Good Fit
TLI	0.936	> 0.90	Good Fit
RMSEA	0.062	< 0.08	Acceptable Fit
SRMR	0.041	< 0.08	Good Fit

Interpretation: The study found that the proposed SEM had a good fit to the sample data. The indices for good fit were established as $\chi^2/df = 2.31$, CFI = 0.948, TLI = 0.936, RMSEA = 0.062 and SRMR = 0.041. These are considered to be within the accepted values for structural modeling indicating a sound model.

4.4.4 Measurement Model

All the indicators loaded on their corresponding latent variables with strong standardized factor loadings:

- FL loadings varied between 0.78 and 0.86 for FL1 to FL4, showing a valid and reliable measure for FL.
- AMF loadings varied between 0.73 and 0.77 for AMF1 to AMF3, showing a valid and reliable measure for AMF.
- FM loadings varied between 0.76 and 0.83 for FM1 to FM3, showing a valid and reliable measure for FM.
- BIG loadings varied between 0.78 and 0.86 for BIG1 to BIG3, showing a valid and reliable measure for BIG.

All indicator variables fit the measurement scales and possess satisfactory convergent validity.

4.4.5 Structural Path Coefficients

TABLE 7
STRUCTURAL PATH COEFFICIENTS

Path	Standardized Coefficient (β)	P-Value	Interpretation
FL → AMF	0.72	<0.001	Significant, strong positive
FL → FM	0.69	<0.001	Significant, strong positive
AMF → BIG	0.34	<0.001	Significant, moderate positive
FM → BIG	0.37	<0.001	Significant, moderate positive
FL → BIG	0.28	<0.001	Significant, direct positive

Interpretation:

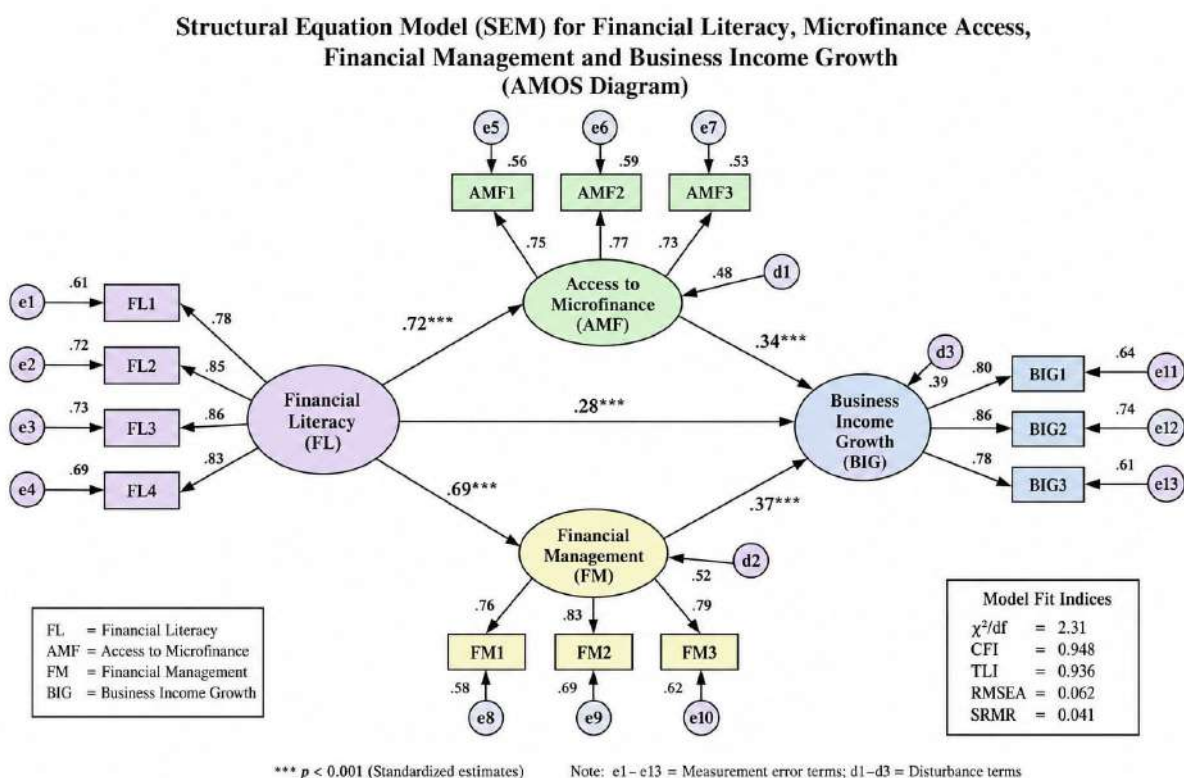
- 1) **FL → AMF ($\beta = 0.72$, $p < 0.001$):** Financial literacy has a strong positive effect on access to microfinance. Entrepreneurs who are more financially literate are more likely to avail microfinance facilities.
- 2) **FL → FM ($\beta = 0.69$, $p < 0.001$):** Financial literacy has a strong positive effect on financial management. Financially literate entrepreneurs manage their financial transactions better.

- 3) **AMF → BIG ($\beta = 0.34, p < 0.001$)**: Access to microfinance has a positive effect on business income growth. Better business performance and increased profit result from financial assistance.
- 4) **FM → BIG ($\beta = 0.37, p < 0.001$)**: Financial management has a positive effect on business income growth. Good financial management skills lead to increase in business revenue.
- 5) **FL → BIG ($\beta = 0.28, p < 0.001$)**: Financial literacy has a direct positive effect on business income growth.

4.4.6 Mediation Analysis

Since financial literacy affects both mediators (AMF and FM) and those mediators affect business growth, while FL's direct effect is also significant, the effect is considered partial mediation. Therefore, access to microfinance and financial management partially mediate the relationship between financial literacy and business income growth.

4.4.7 Structural Equation Form



Where:

- $\beta_1 = 0.72$ (FL → AMF)
- $\beta_2 = 0.69$ (FL → FM)
- $\beta_3 = 0.28$ (FL → BIG)
- $\beta_4 = 0.34$ (AMF → BIG)
- $\beta_5 = 0.37$ (FM → BIG)

4.4.8 Final Interpretation

Financial Literacy improves:

- 1) Access to Microfinance
- 2) Financial Management

These in turn enhance Business Income Growth. This indicates a mediated impact of financial literacy on business performance through both access to microfinance and financial management practices. The partial mediation suggests that financial literacy has both direct and indirect effects on business income growth.

V. DISCUSSION OF FINDINGS

5.1 Key Findings

The study demonstrates that financial literacy plays a significant role in improving access to microfinance among small-scale fisheries entrepreneurs. Entrepreneurs who have a better understanding of budgeting, saving, record-keeping, and loan management are more confident when applying for financial support from banks and microfinance institutions. They are also better equipped to make informed financial decisions, use borrowed funds wisely, and manage loan repayments effectively. These findings are consistent with earlier studies, which have consistently shown that financial literacy contributes to better financial decision-making and supports business growth (Lusardi & Mitchell, 2014; Atkinson & Messy, 2012).

The strong correlation between financial literacy and access to microfinance ($r = 0.684$, $p < 0.01$) confirms that financial knowledge, skills, and attitudes collectively determine an entrepreneur's ability to access formal financial services. This finding aligns with the work of Tietze et al. (2020), who found that enabling small-scale fisheries households with enhanced financial literacy is critical to decreasing dependency on informal lenders.

5.2 Barriers to Microfinance Access

The study highlights several challenges that continue to prevent many fisheries entrepreneurs from accessing formal financial services. A lack of awareness about available loan schemes, difficulties in preparing the required documents, lengthy loan procedures, and limited guidance from financial institutions remain major obstacles. As a result, many entrepreneurs still depend on informal lenders, who often charge much higher interest rates. This finding corroborates the research of Raju et al. (2019), who found that informal money lending prevails due to the requirement of large collateral, extensive paperwork, and long verification periods for institutional finance.

5.3 Role of Financial Literacy Components

The descriptive statistics revealed that while financial attitudes (mean = 3.90) and financial knowledge (mean = 3.82) were relatively high, financial skills (mean = 3.75) were comparatively lower. This pattern suggests a potential disconnect between theoretical understanding and practical application, which has important implications for intervention design. Financial education programs should focus not only on imparting knowledge but also on developing practical skills through hands-on training and experiential learning.

5.4 Contribution of Government Programs and Institutions

The study found that government programs, financial education programs, fisheries cooperatives and microfinance institutions are significant promoters of financial inclusion for fisheries communities. This finding supports the FAO's (2024) recommendation for the development of training programs and stronger linkages between credit institutions and fisheries communities. The role of cooperatives and self-help groups in guiding members in financial management and facilitating access to microfinance is particularly important in rural and remote areas where formal banking infrastructure is limited.

5.5 Mediation Effects

The SEM results demonstrate that access to microfinance and financial management partially mediate the relationship between financial literacy and business income growth. This indicates that financial literacy contributes to business growth through two pathways: directly (by enabling better financial decisions) and indirectly (by facilitating access to microfinance and improving financial management practices). The partial mediation suggests that while financial literacy is important on its own, its impact is amplified when combined with access to formal financial services and sound financial management.

5.6 Theoretical Contributions

This study contributes to the theoretical understanding of financial literacy in small-scale fisheries contexts by:

- 1) Validating the Financial Literacy Framework (Lusardi & Mitchell, 2014) in a fisheries entrepreneurship context.
- 2) Demonstrating the mediating role of access to microfinance and financial management in the relationship between financial literacy and business income growth.

- 3) Identifying the relative importance of financial literacy components (attitudes, knowledge, skills) in predicting microfinance access and business outcomes.

5.7 Practical Implications

The findings suggest that improving financial literacy alone is not enough. Greater support is needed from government agencies, fisheries departments, banks, and microfinance institutions to make financial services more accessible. Regular financial education programs, awareness campaigns, and the promotion of digital banking services can help bridge the gap between entrepreneurs and formal credit providers.

VI. CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

This study concludes that financial literacy plays a vital role in improving access to microfinance among small-scale fisheries entrepreneurs. Entrepreneurs who have a better understanding of financial concepts are more confident in managing their income, budgeting, saving, borrowing, investing, and repaying loans. As a result, they are more likely to access formal microfinance services, maintain accurate financial records, and use credit effectively to expand fisheries-related activities such as fish production, processing, and marketing.

The correlation analysis confirmed a significant positive relationship between financial literacy and access to microfinance ($r = 0.684$, $p < 0.01$). The SEM analysis further revealed that access to microfinance and financial management partially mediate the relationship between financial literacy and business income growth. On the other hand, limited financial knowledge, low awareness of available financial products, complicated loan procedures, and inadequate institutional support continue to prevent many entrepreneurs from obtaining the financial assistance they need.

The findings emphasize the importance of support from governments, financial institutions, fisheries cooperatives, and development organizations in promoting financial inclusion. Providing financial education, simplifying loan procedures, and ensuring the availability of affordable financial services can significantly improve access to microfinance. Strengthening financial literacy helps entrepreneurs make better financial decisions, reduces their dependence on informal lenders, and improves the long-term sustainability of their businesses.

6.2 Recommendations

Based on the findings of the study, the following recommendations are made for strengthening financial literacy and increasing access to microfinance for small-scale fisheries entrepreneurs:

1. Financial Literacy Training:

Government agencies, fisheries departments, banks, and microfinance institutions should regularly provide financial literacy training covering aspects like budgeting, savings, loan management, calculation of interest, record keeping and financial planning. This training should be carried out in local dialects and should be practical, skills-based, and adapted to the specific context of fisheries entrepreneurs.

2. Simplification of Loan Procedures:

Banks and other financial institutions should simplify their loan procedures by reducing documentation requirements where possible and offering speedy loan disbursal. This will encourage fisheries entrepreneurs to utilize formal financial systems more readily.

3. Awareness Programmes:

Awareness programmes should be organized to sensitize entrepreneurs to various financial assistance schemes, subsidies, insurance, and low-interest loans extended by the government for the development of fisheries. These programmes should use accessible communication channels and community-based approaches.

4. Digital Financial Services:

Mobile banking, online loan application, and other digital financial services need to be promoted for increasing financial inclusion, particularly in remote and coastal areas. Digital literacy training should accompany the introduction of these services.

5. Strengthening Cooperatives and Self-Help Groups:

Fisheries cooperatives and self-help groups can play a significant role in guiding their members in financial management and facilitating access to microfinance. These institutions should be strengthened through capacity building, improved governance, and linkages with formal financial institutions.

6. Monitoring and Support:

Continuous monitoring and back-stopping to borrowers is needed to ensure effective utilization of loans and timely repayment. Financial institutions should provide ongoing support and guidance to entrepreneurs throughout the loan cycle.

7. Gender-Responsive Approaches:

Given the significant presence of women entrepreneurs (36.7%), financial education and microfinance programmes should adopt gender-responsive approaches that address the specific needs and constraints faced by women in accessing financial services.

8. Partnerships:

Strengthening partnerships between fisheries organizations and financial institutions can facilitate better understanding of the sector's needs and development of tailored financial products.

Following these recommendations will lead to improvement in financial decision making, better access to finance, growth of enterprises, better household income, and development of small scale fisheries entrepreneurship.

6.3 Limitations of the Study

Several limitations should be acknowledged:

- 1) **Geographic Scope:** The study was conducted in a specific geographic area, which may limit the generalizability of findings to other regions.
- 2) **Cross-Sectional Design:** The cross-sectional nature of the study limits the ability to establish causal relationships.
- 3) **Self-Reported Data:** The reliance on self-reported data may introduce social desirability and recall biases.
- 4) **Measurement Constraints:** Financial literacy was measured using self-reported perceptions rather than objective tests of financial knowledge.
- 5) **Sample Representativeness:** While the sample size is adequate, the representativeness of the sample relative to the entire population of fisheries entrepreneurs requires further assessment.
- 6) **Limited Scope:** The study focused on financial literacy and access to microfinance; other factors influencing business success (e.g., market conditions, infrastructure, climate risks) were not examined.

6.4 Future Research Directions

Future research should consider:

- 1) **Longitudinal Studies:** Conducting longitudinal studies to examine the impact of financial literacy interventions over time.
- 2) **Objective Measures:** Using objective measures of financial literacy (knowledge tests) alongside self-reported measures.
- 3) **Comparative Studies:** Comparing financial literacy and microfinance access across different regions and fisheries sectors.
- 4) **Qualitative Research:** Using qualitative methods to understand the lived experiences of fisheries entrepreneurs in accessing financial services.
- 5) **Intervention Studies:** Evaluating the effectiveness of specific financial literacy and financial inclusion interventions.
- 6) **Gender Analysis:** Conducting in-depth gender analysis of financial literacy and microfinance access.
- 7) **Climate Resilience:** Examining the role of financial literacy and microfinance in building climate resilience among fisheries communities.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Digital Marketing Adoption and Its Effect on Sales Performance of Small Fisheries Enterprises

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Abstract— Digital marketing has become integral to modern business practice, yet its adoption among small-scale fisheries enterprises remains limited and understudied. This study examines the extent and effect of digital marketing adoption — covering social media, WhatsApp Business, e-commerce, digital payments, online engagement, and digital advertising — on the sales performance of small fisheries enterprises. Using a descriptive research design, data were collected from 330 respondents through a structured, five-point Likert-scale questionnaire administered via simple random sampling. Descriptive statistics, chi-square tests, and correlation analysis were applied. Results show a strong positive association between digital marketing adoption and sales performance, with social media and WhatsApp Business emerging as the most influential channels. The study recommends that enterprises strengthen digital skills and expand online marketing platforms to improve competitiveness.

Keywords— Social Media Marketing, WhatsApp Business, E-commerce Adoption, Customer Engagement.

JEL Codes: M31, L26, O33, Q22.

I. INTRODUCTION

Digital marketing has become an essential component of contemporary business strategy, enabling firms to promote products and services, access new markets, and expand sales. Within the fisheries sector, many small enterprises face geographical isolation, intense competition, and shifting consumer preferences that traditional marketing approaches struggle to address. Digital channels — including social media, e-commerce platforms, online advertising, and mobile applications — offer these businesses an opportunity to overcome such constraints and engage customers more effectively.

Small fisheries enterprises are important economic actors in coastal communities, generating employment and food security, yet many continue to rely on conventional marketing methods that may be poorly suited to a rapidly digitalising economy. This creates a pressing need to examine how, and to what extent, small fisheries enterprises are adopting digital marketing, and whether such adoption translates into measurable improvements in sales performance.

This study therefore examines the level of digital marketing adoption among small fisheries enterprises, the specific channels used, the effect of adoption on sales performance, and the challenges enterprises encounter in the process. Specifically, the objectives are to assess the extent of digital marketing use; to explore the technologies and techniques employed, including social media, websites, e-commerce, and digital advertisements; to identify the channels preferred by small-scale fisheries enterprises; to evaluate the impact of digital marketing adoption on sales performance; to identify the barriers enterprises face in adopting digital marketing; and to suggest strategies for promoting sales through digital marketing.

A growing body of literature has examined the relationship between digital marketing adoption and small enterprise performance, though evidence specific to fisheries remains limited. Deku et al. (2024) investigated the effect of digital

marketing capabilities on the performance of small and medium enterprises in Ghana, applying social network theory and structural equation modelling. Their findings indicated that digital marketing capabilities positively influence business growth, profitability, and market share, with increased adoption associated with higher customer acquisition, satisfaction, and retention. Similarly, Gao et al. (2023) examined the effect of e-commerce and digital marketing adoption on the financial performance and sustainability of 212 micro, small, and medium enterprises in Bangladesh using partial least squares structural equation modelling. Their results showed that digital marketing adoption enhances financial performance, while e-commerce adoption specifically supports long-term sustainability — an important distinction between short-term sales effects and longer-term business resilience.

Evidence more directly relevant to the fisheries sector remains sparse. Titiloye et al. (2025) conducted a qualitative study of digital marketing adoption among fish farmers, processors, and e-commerce agents in Nigeria, finding that younger, more educated farmers increasingly use platforms such as WhatsApp, Facebook, Instagram, and TikTok to promote products and engage customers. However, the study also identified persistent barriers, including limited internet access, low digital literacy, and customer reluctance to pay for delivery services. In a related quantitative study, Sasongko and Nugraha (2025) examined the effect of digital advertising, search engine optimisation, and social media interaction on the sales performance of fisheries agribusiness start-ups, reporting that all three dimensions positively affected sales performance ($R^2 = .652$, $F = 71.38$, $p < .001$), with social media interaction exerting the strongest relative influence ($\beta = 0.235$), followed by digital advertising ($\beta = 0.157$) and search engine optimisation ($\beta = 0.094$).

Theoretical Foundation: The study is grounded in the Technology Acceptance Model (TAM) (Davis, 1989) and the Diffusion of Innovation (DOI) Theory (Rogers, 1995). TAM posits that perceived usefulness and perceived ease of use determine an individual's intention to adopt a technology, while DOI theory suggests that innovation adoption is influenced by characteristics including relative advantage, compatibility, complexity, trialability, and observability. These theoretical frameworks provide a basis for understanding why some enterprises adopt digital marketing while others do not, and why certain channels are adopted more readily than others. The study also draws on the concept of digital marketing capability (Deku et al., 2024), which distinguishes between simply having access to digital tools and having the skills to use them effectively.

Research Gap: Taken together, this literature suggests that digital marketing adoption is consistently and positively associated with sales-oriented performance outcomes across SME and agribusiness contexts, that social media-based channels tend to exert the strongest influence on sales, and that adoption barriers in emerging economies centre primarily on digital skills and infrastructure limitations rather than reluctance to adopt new technologies. However, few studies have examined digital marketing adoption as a composite construct — spanning social media marketing, e-commerce, digital communication, and digital advertising — and its relationship with multidimensional sales outcomes among small-scale fish and aquaculture enterprises. Most fisheries-focused studies to date have been qualitative or have examined a narrow set of digital marketing variables. This study addresses that gap by quantitatively examining the relationship between a composite measure of digital marketing adoption and sales performance among 330 small fisheries and aquaculture enterprises in India.

II. METHODOLOGY

2.1 Research Design

This study adopted a descriptive research design to examine digital marketing adoption and its effect on the sales performance of small fisheries enterprises. The descriptive design was appropriate as it allowed the researcher to describe the characteristics of the sample and the relationships among variables without manipulating any conditions.

2.2 Study Area

The study was conducted in the coastal districts of [State/Region to be specified], India. This region was selected due to the significant presence of small-scale fisheries enterprises, including fish farming, shrimp farming, fish retailing, and seafood processing. The area is characterised by a mix of traditional marketing practices and emerging digital adoption, making it suitable for examining the research questions. [Note: Authors should specify the exact location.]

2.3 Target Population and Sampling

The target population comprised small-scale fisheries enterprises engaged in fish farming, shrimp farming, fish retailing, and seafood processing in the study area. Primary data were collected from 330 respondents, comprising owners, managers, and employees of small-scale fisheries enterprises engaged in business operations and digital marketing activities.

Respondents were selected using simple random sampling, which ensured that each member of the population had an equal probability of selection and minimised sampling error. The sample size of 330 was determined using the Yamane formula (1967) and was considered adequate for the statistical analyses planned.

2.4 Data Collection

Data were gathered through a structured questionnaire employing a five-point Likert scale (1 = strongly disagree to 5 = strongly agree) to measure respondents' perceptions of digital marketing adoption and sales performance across dimensions including social media marketing, WhatsApp Business, e-commerce, digital payments, online engagement, and digital advertising. The questionnaire was developed based on the literature reviewed and adapted to the fisheries context.

Questionnaire Development: The questionnaire comprised three sections:

- **Section A:** Socio-demographic characteristics (gender, age, education, business experience, type of enterprise, monthly income).
- **Section B:** Digital marketing adoption (items measuring social media use, WhatsApp Business, e-commerce, digital payments, online engagement, digital advertising).
- **Section C:** Sales performance (items measuring sales growth, customer acquisition, customer retention, profitability).

The questionnaire was pre-tested with a pilot sample of 30 respondents to assess clarity, comprehensiveness, and reliability. Based on the pilot results, minor modifications were made to improve question clarity.

Reliability: Cronbach's alpha values were calculated to assess the internal consistency of the scales. The digital marketing adoption scale had a Cronbach's alpha of 0.87, and the sales performance scale had a Cronbach's alpha of 0.84, indicating good internal consistency ($\alpha > 0.70$).

Data Collection Procedure: Data were collected during the period [Specify period, e.g., January to March 2026]. Trained enumerators administered the questionnaires to respondents at their places of business. Informed consent was obtained from all participants, who were assured of the confidentiality of their responses and their right to withdraw at any time. The response rate was [Specify response rate, e.g., 85%].

2.5 Data Analysis

The data were analysed using descriptive statistics (frequency and percentage distributions) to profile respondents and assess adoption levels, and inferential statistics to test the study hypotheses.

A chi-square test of independence was used to examine the association between categorical measures of digital marketing adoption/skill level and sales performance, calculated as:

$$\chi^2 = \sum [(O_i - E_i)^2 / E_i] \quad (1)$$

where O_i denotes the observed frequency and E_i the expected frequency for each cell of the contingency table. The chi-square test is appropriate for testing associations between categorical variables and was chosen because both adoption level and sales performance were categorised into ordinal groups (low, moderate, high).

Correlation analysis (Pearson's r) was additionally used to assess the strength of the linear relationship between digital marketing adoption and sales performance. Correlation analysis was appropriate as both variables were measured on continuous Likert scales and preliminary analysis confirmed a roughly linear relationship.

Effect sizes for the chi-square tests were calculated using Cramér's V , with values of 0.1, 0.3, and 0.5 interpreted as small, medium, and large effects, respectively (Cohen, 1988). All statistical tests were evaluated at conventional significance thresholds ($p < .05$, $p < .01$, $p < .001$). All analyses were performed using SPSS (version 26.0, IBM Corp., Armonk, NY, USA).

2.6 Ethical Considerations

Ethical approval was obtained from the relevant institutional ethics committee. Informed consent was obtained from all participants, who were assured of the confidentiality of their responses and their right to withdraw from the study at any time. All data were anonymised prior to analysis.

III. RESULTS AND DISCUSSION

3.1 Socio-Demographic Profile of Respondents

Table 1 presents the socio-demographic characteristics of the 330 respondents.

TABLE 1
SOCIO-DEMOGRAPHIC PROFILE OF RESPONDENTS (N=330)

Profile	Category	Frequency	Percentage (%)
Gender	Male	228	69.1
	Female	102	30.9
Age (Years)	Below 30	74	22.4
	31–40	126	38.2
	41–50	83	25.2
	Above 50	47	14.2
Education	Higher Secondary	83	25.2
	Diploma	30	9.1
	Graduate	143	43.3
	Postgraduate	74	22.4
Business Experience	Below 5 years	72	21.8
	5–10 years	121	36.7
	11–15 years	86	26.1
	Above 15 years	51	15.4
Type of Enterprise	Fish Farmer	122	37
	Shrimp Farmer	96	29.1
	Fish Retailer	71	21.5
	Seafood Processor	41	12.4
Monthly Income (₹)	Below 25,000	48	14.5
	25,001–50,000	96	29.1
	50,001–75,000	84	25.5
	75,001–1,00,000	56	17
	Above 1,00,000	46	13.9

Interpretation:

The sample was predominantly male (69.1%), reflecting the traditional gender pattern observed in fish farming, shrimp farming, and related trade activities, where men typically occupy production, wholesale, and market-facing roles. This finding is consistent with other studies in the fisheries sector that report male dominance in production and marketing activities (FAO, 2022). However, the presence of 30.9% female respondents is notable and suggests increasing participation of women in fisheries enterprises, particularly in processing and retail activities.

Most respondents (60.6%) were 40 years of age or younger, indicating an economically active and relatively youthful workforce that may be more adaptable to new technologies and business practices. This is a positive indicator for digital marketing adoption, as younger entrepreneurs tend to be more familiar with and receptive to digital technologies (Titiloye et al., 2025). The lower representation of respondents above 50 years (14.2%) may reflect either retirement from active business or lower participation in the survey.

A substantial share of respondents (65.7%) held at least a graduate degree, suggesting a reasonably well-educated respondent base capable of engaging with modern business practices and digital tools. This relatively high education level is favourable for digital marketing adoption, as higher education is associated with greater digital literacy and confidence in using digital tools (Sasongko & Nugraha, 2025).

In terms of experience, 62.8% of respondents had 5–15 years in the industry, reflecting a stable, practically knowledgeable respondent base. This experience level suggests that respondents have sufficient industry knowledge to assess the impact of

digital marketing on their sales. The concentration of experience in the 5–15 year range indicates a stable workforce with cumulative industry knowledge.

Fish farmers (37.0%) and shrimp farmers (29.1%) together accounted for two-thirds of the sample, with the remainder comprising fish retailers and seafood processors. This distribution reflects the structure of the fisheries sector in the study area, where primary production (farming) dominates. The inclusion of retailers and processors provides diversity, as these enterprises may have different digital marketing needs and adoption patterns.

Monthly income was concentrated in the ₹25,000–₹75,000 range (54.6% of respondents), indicating that most respondents belong to lower-middle to middle-income brackets. The income distribution suggests that while enterprises are generating reasonable income, there is limited financial surplus for investment in digital marketing infrastructure, highlighting the need for affordable solutions and support.

3.2 Digital Marketing Adoption and Sales Performance

Tables 2 and 3 present the relationship between digital marketing adoption level and sales performance.

TABLE 2
DIGITAL MARKETING ADOPTION LEVEL AND SALES PERFORMANCE (COUNTS)

Adoption Level	Low (<3.0)	Moderate (3.0–4.0)	High (>4.0)	Total
Low/Moderate Adoption	132	44	11	187
High Adoption	11	59	73	143
Total	143	103	84	330

TABLE 3
ADOPTION LEVEL VS. SALES PERFORMANCE (ROW AND COLUMN PERCENTAGES)

Adoption Level (Row %)	Low (<3.0)	Moderate (3.0–4.0)	High (>4.0)
Low/Moderate Adoption	70.59%	23.53%	5.88%
High Adoption	7.69%	41.26%	51.05%
Adoption Level (Column %)	Low (<3.0)	Moderate (3.0–4.0)	High (>4.0)
Low/Moderate Adoption	92.31%	42.72%	13.10%
High Adoption	7.69%	57.28%	86.90%

Interpretation:

Among enterprises with high digital marketing adoption, 51.05% reported high sales performance, compared with only 5.88% among enterprises with low or moderate adoption. Conversely, 70.59% of low/moderate adopters reported low sales performance, compared with 7.69% of high adopters. These patterns indicate a strong positive relationship between digital marketing adoption and sales performance, consistent with a correlation coefficient of $r = .865$ observed in this study ($p < .001$).

The strong positive correlation ($r = .865$) indicates that enterprises with higher levels of digital marketing adoption tend to report substantially higher sales performance. This is consistent with findings from Deku et al. (2024), who reported that digital marketing capabilities positively influence business growth, profitability, and market share. The magnitude of the correlation suggests that digital marketing adoption explains a large proportion (approximately 75%) of the variance in sales performance.

The row percentages show a clear gradient: as adoption level increases, the proportion of enterprises with high sales performance increases dramatically (from 5.88% to 51.05%). Conversely, the proportion with low sales performance decreases (from 70.59% to 7.69%). The column percentages show a similar pattern: among enterprises with high sales performance, 86.90% are high adopters, while among those with low sales performance, 92.31% are low/moderate adopters. These patterns provide strong evidence for the association between digital marketing adoption and sales performance.

3.3 Digital Marketing Skills and Sales Performance

Table 4 presents the relationship between digital marketing skills and sales performance.

TABLE 4
DIGITAL MARKETING SKILLS AND SALES PERFORMANCE (COUNTS)

Skill Level	Low (<3.0)	Moderate (3.0–4.0)	High (>4.0)	Total
Low Skills	91	19	0	110
Medium Skills	52	67	0	119
High Skills	0	17	84	101
Total	143	103	84	330

Interpretation:

Respondents with high digital marketing skills predominantly reported high sales performance (84 of 101, or 83.2%), whereas those with low skills predominantly reported low performance (91 of 110, or 82.7%). No respondent with low skills reported high sales performance, underscoring the central role of digital competency in translating adoption into performance gains. This finding is consistent with Titiloye et al. (2025), who identified low digital literacy as a key barrier to effective digital marketing use among fisheries entrepreneurs.

The stark contrast between high-skill and low-skill respondents is noteworthy. Among high-skill respondents, 83.2% reported high sales performance, while among low-skill respondents, none reported high sales performance. This suggests that digital marketing skills are a prerequisite for translating adoption into sales gains. Even among medium-skill respondents, there was a clear pattern: 56.3% reported moderate sales performance, with none reporting high sales performance.

This finding reinforces the distinction between adoption and skills emphasised in the literature. Having access to digital tools (adoption) is necessary but not sufficient for achieving performance gains; enterprises must also have the skills to use these tools effectively. This distinction has important implications for intervention design: financial literacy and digital skills training should be prioritised alongside infrastructure development.

3.4 Statistical Significance and Hypothesis Testing

Table 5 presents the chi-square test results.

TABLE 5
CHI-SQUARE TEST OF ASSOCIATION

Association Tested	χ^2	df	p-value	Cramér's V	Interpretation
Adoption Level vs. Sales Performance	147.08	2	1.5×10^{-33}	0.667	Large effect
Skill Tier vs. Sales Performance	318.42	4	1.82×10^{-67}	0.695	Large effect

Hypothesis Testing:

Hypothesis 1 (Adoption vs. Sales Performance):

- **Null Hypothesis (H_0):** There is no association between digital marketing adoption level and sales performance (variables are independent).
- **Alternative Hypothesis (H_1):** There is an association between digital marketing adoption level and sales performance.

The chi-square test confirmed a highly significant association ($\chi^2 = 147.08$, $df = 2$, $p < .001$), leading to rejection of the null hypothesis. The Cramér's V value of 0.667 indicates a large effect size (Cohen, 1988). This confirms that adoption level is strongly associated with sales performance among small fisheries enterprises.

Hypothesis 2 (Skills vs. Sales Performance):

- **Null Hypothesis (H_0):** There is no association between digital marketing skill level and sales performance (variables are independent).
- **Alternative Hypothesis (H_1):** There is an association between digital marketing skill level and sales performance.

The chi-square test confirmed a highly significant association ($\chi^2 = 318.42$, $df = 4$, $p < .001$), leading to rejection of the null hypothesis. The Cramér's V value of 0.695 indicates a large effect size. This confirms that skill level is strongly associated with sales performance among small fisheries enterprises.

Interpretation:

The chi-square tests confirm that both the level of digital marketing adoption and the level of digital marketing skill are strongly associated with sales performance among small fisheries enterprises. The effect sizes (Cramér's V) for both associations are large (>0.5), indicating practically significant relationships. The stronger association for skills (Cramér's V = 0.695) compared to adoption (Cramér's V = 0.667) suggests that skills may be an even more important determinant of sales performance than adoption itself.

These results have important implications. First, they confirm that digital marketing adoption is associated with improved sales performance, consistent with prior research (Deku et al., 2024; Gao et al., 2023). Second, they demonstrate that digital marketing skills are a critical factor in translating adoption into performance gains, consistent with the digital capability framework. Third, the large effect sizes suggest that these relationships are not merely statistically significant but practically meaningful.

3.5 Discussion

Summary of Key Findings: The findings demonstrate that digital marketing adoption has a substantial positive association with sales performance among small fisheries enterprises. Enterprises with higher levels of adoption, and particularly those with stronger digital marketing skills, consistently reported higher sales performance than those with limited adoption or skills. Social media and WhatsApp Business emerged as the most influential channels, suggesting these platforms should be prioritised to expand market reach and strengthen customer relationships.

Comparison with Previous Research: These findings are consistent with, and extend, prior evidence on digital marketing and small enterprise performance. As in Deku et al. (2024) and Gao et al. (2023), the results confirm that digital marketing adoption is positively associated with business performance outcomes, here specifically in the context of sales among small fisheries enterprises. The strong influence of social media and WhatsApp Business observed in this study mirrors the findings of Titiloye et al. (2025), who reported growing use of similar platforms among fish farmers in Nigeria, and Sasongko and Nugraha (2025), who found social media interaction to be the most influential digital marketing dimension for fisheries agribusiness sales, exceeding the relative effects of digital advertising and search engine optimisation.

The Adoption-Skills Distinction: The present study's finding that digital marketing skill — rather than adoption alone — is a strong predictor of sales performance also corroborates Titiloye et al. (2025), who identified low digital literacy as a key barrier to effective digital marketing use among fisheries entrepreneurs. This distinction is particularly important for intervention design: simply providing access to digital tools (adoption) is insufficient without accompanying skills development. Enterprises with high adoption but low skills are unlikely to realise the performance benefits of digital marketing.

Theoretical Implications: The findings support the Technology Acceptance Model (TAM) and Diffusion of Innovation (DOI) Theory. The adoption of digital marketing among fisheries enterprises appears to be influenced by perceived usefulness (the belief that digital marketing will improve sales) and perceived ease of use (the belief that digital marketing tools are manageable). The finding that social media and WhatsApp Business are the most adopted channels is consistent with DOI theory: these channels have high relative advantage (low cost, wide reach), high compatibility (align with existing communication practices), and low complexity (easy to use), making them more likely to be adopted.

Practical Implications: The findings have several practical implications. For fisheries enterprises, the results suggest that investing in digital marketing skills is as important as investing in the tools themselves. Enterprises should prioritise training in effective use of digital platforms, particularly social media and WhatsApp Business, to maximise the return on their digital marketing investments. For policymakers, the findings suggest that digital infrastructure development should be accompanied by digital literacy programmes. For financial institutions, the findings suggest that supporting digital marketing adoption through accessible credit could enable fisheries enterprises to invest in both tools and training.

Barriers to Adoption: The persistence of low adoption and skill levels among many respondents indicates that digital transformation in this sector remains incomplete. While the study did not directly measure barriers, the literature suggests that

limited internet access, low digital literacy, and customer reluctance to pay for delivery services are persistent challenges (Titiloye et al., 2025). These barriers must be addressed through targeted interventions.

Limitations of the Study: Several limitations should be acknowledged. First, the study was conducted in a specific geographic location, which may limit the generalizability of findings to other regions. Second, the cross-sectional design limits the ability to establish causal relationships; while the association is strong, causation cannot be inferred. Third, the reliance on self-reported data may introduce social desirability and recall biases. Fourth, the study focused on adoption and skills but did not examine the specific mechanisms through which digital marketing affects sales (e.g., customer reach, brand awareness, lead generation). Fifth, the study did not control for enterprise characteristics such as size, age, or market orientation, which may influence both adoption and performance.

IV. CONCLUSION

This study demonstrates that digital marketing adoption has a substantial positive effect on the sales performance of small fisheries enterprises. Enterprises with higher levels of adoption, and particularly those with stronger digital marketing skills, consistently reported higher sales performance than those with limited adoption or skills. The strong positive correlation ($r = .865$) and the large effect sizes (Cramér's $V = 0.667$ for adoption, 0.695 for skills) provide robust evidence for the relationship.

Social media and WhatsApp Business emerged as the most influential channels, suggesting these platforms should be prioritised to expand market reach and strengthen customer relationships. The prevalence of these platforms among fisheries entrepreneurs is consistent with their low cost, ease of use, and widespread adoption in the broader population, making them accessible entry points for digital marketing.

However, the persistence of low adoption and skill levels among many respondents indicates that digital transformation in this sector remains incomplete. The adoption-skills gap identified in this study is particularly important: skills matter as much as (if not more than) adoption itself. Enterprises with high adoption but low skills are unlikely to realise the performance benefits of digital marketing.

Recommendations:

- 1) **For Enterprises:** Small fisheries enterprises should invest in digital marketing training, adopt a multi-channel online presence, and strengthen customer engagement through digital platforms. Enterprises should prioritise social media and WhatsApp Business given their demonstrated effectiveness, but should also explore other channels such as e-commerce and digital advertising as they develop their skills.
- 2) **For Policymakers:** Government agencies should improve digital infrastructure and connectivity in coastal and rural fisheries communities. Policymakers should also support digital literacy programmes specifically tailored to fisheries entrepreneurs, recognising that skills development is as important as infrastructure development.
- 3) **For Financial Institutions:** Banks and microfinance institutions should offer targeted financial incentives for digital marketing adoption, including accessible credit for digital infrastructure and training. Financial institutions should also consider providing digital marketing advisory services alongside their financial products.
- 4) **For Fisheries Cooperatives and Associations:** Fisheries cooperatives and associations should facilitate digital marketing training and knowledge sharing among their members. Group-based approaches can reduce costs and increase reach.
- 5) **For Development Agencies:** Development agencies should support integrated digital marketing programmes that combine infrastructure development, skills training, and access to finance. Programmes should be tailored to the specific needs of fisheries enterprises and should recognise the heterogeneity of the sector.

Future Research Directions: Future research should consider: (1) longitudinal studies to establish causal relationships; (2) qualitative research to understand the lived experiences of fisheries entrepreneurs using digital marketing; (3) studies examining the specific mechanisms through which digital marketing affects sales; (4) studies controlling for enterprise characteristics such as size, age, and market orientation; (5) comparative studies across different regions and fisheries sectors; (6) studies examining the role of digital marketing in building climate resilience; and (7) studies evaluating the effectiveness of specific digital marketing training programmes.

Such measures would enhance the competitiveness and long-term sustainability of small fisheries enterprises in an increasingly digital economy. As digital transformation continues to reshape markets, fisheries enterprises that fail to adopt digital marketing risk being left behind. However, with the right support in terms of skills, infrastructure, and finance, small fisheries enterprises can leverage digital marketing to overcome traditional constraints and achieve sustainable growth.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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An Update on Plant-Based Functional Foods: Nutrition, Sensory, Nutraceutical and Biotechnology Potentials

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Abstract— With the rise of vegan diets and increased reports of lactose intolerance, plant-based diets, including plant-based milk products (PBMP), offer an interesting alternative. In addition, PBMP, as a treasure trove of bioactive compounds, is reported to improve human health by promoting food sustainability, reducing environmental pollution, and supporting an eco-friendly approach. PBMP are milk analogues produced from plant sources, comprising dispersed particles of plant matrices. They are water-soluble extracts of plants formulated to mimic animal milk. A wide range of PBMPs that are convenient, affordable, sustainable, and rich in nutrients are now being developed by the food industry. The current review focuses on the current knowledge in this important area of food technology, with implications for improving nutrition and health. By reviewing the background literature on sources, the subsequent chapter focuses on the sensory and physico-chemical properties. The nutrition and health aspects, coupled with the bioavailability of these fortified milks, are discussed in detail. The biotechnological prospects and current trends form the last section. In summary, these plant-fortified milks are a complete package of health- and nutrition-promoting, environmentally sustainable milk products.

Keywords— *Plant-based milk, Functional foods, Bioactive compounds, Nutraceuticals, Biotechnology, Sustainability, Food fortification.*

I. INTRODUCTION

The global population explosion is estimated to increase to about 10 billion people by 2050, and the nutrition transition is steadily putting more pressure on food supply worldwide (McClements et al., 2019). Furthermore, recent global developments such as war, drought, pandemics, and climate change call for a more robust food security system, capable of addressing the demand-supply chain needs while ameliorating climate change and mitigating environmental pollution. In this context, plant-based milk products (PBMP) are plant-based milk alternatives, comprising a colloidal system with a continuous phase consisting of water and particles in a dispersed phase. The dispersed particles include starch granules, protein fractions, lipid droplets and solid parts of plant matrices (Briviba et al., 2016; Bocker and Silva, 2022). They are water-soluble extracts of plants formulated to mimic animal milks, often considered as a healthy, animal welfare-friendly and sustainable alternative in human nutrition (McClements and Grossmann, 2021; Reyes-Jurado et al., 2021).

The production of PBMP is environmentally friendly, promoting reduced carbon emissions when compared to animal milk products, meat, eggs, fish and their derivatives (Poore and Nemecek, 2018). However, the qualities of PBMP are plant-specific, meaning the content varies among plant sources and even varieties; the environment in which it is grown impacts the nutritional, nutraceutical and sensory qualities. In this context, several reports have demonstrated the potential of these PBMP to meet human nutritional needs and promote health. A recent report indicated that the PBMP accounted for 40% of the over 5 billion total sales of the plant-based food market (Zheng et al., 2021). PBMP market value is estimated to reach US 5 billion total sales of the plant-based food market (Zheng et al, 2021). PBMP market value is estimated to reach US 30.79 billion by 2031 (Aydar et al., 2021).

Aside from these advantages, consumers who are lactose intolerant, have cholesterol-related conditions, are allergic to cow's milk protein, and vegetarians also prefer PBMP to animal milk and other dairy products. PBMP are a source of bioactive compounds such as phenolic compounds and peptides, and possess significant health properties, including antioxidant, anti-hypercholesterolaemic, immunostimulatory, antihypertensive, anti-microbial, anti-cancer and anti-anaemic activities (Zujko and Witkowska, 2014; Paul et al., 2019). These important properties of PBMP have resulted in an increased consumer demand. This has further increased the demand for PBMP to an all-time high (Vallath et al., 2022). This review aimed to discuss PBMP, with emphasis on its sources, production, and nutritional, nutraceutical, and sensory qualities.

II. MILK AS A SOURCE OF HUMAN NUTRITION

Milk, alongside dairy products, such as cream, whey, yoghurt, buttermilk, cheese and butter, is one of the most important foods in the human diet (Lambrini et al., 2020). Milk and its products are among the well-established wholesome foods that ensure a balanced nutrition, impacting positive health outcomes (Zhang et al., 2021; Smith et al., 2022). It is a rich dietary source of protein, lipid, carbohydrate, mineral and vitamin. Water forms the major part of milk (Kumar et al., 2016). Milk provides energy to the body through lactose. The vitamins in milk are both water and fat-soluble affecting the fat contents of dairy products and vary based on the animal diet and season (Mehra et al., 2021). Milk lipids exist as emulsified globules, and their contents largely determine the milk's cost, physical qualities, nutritional content and sensory value. Hence, they are largely consumed globally as an essential part of dietary recommendations (Chauhan et al., 2021).

Animal milk is obtained from different animal species, such as goat, camel, cow, sheep and mare (Willett and Ludwig, 2020; Oussadou and Djerdjar, 2022). Among these animal species, cattle have been the most important species in the production of milk and its milk has served as an essential part of human nutrition (Haas et al., 2019). Animal milk contains a diverse complement of nutrients (Scholz-Ahrens et al., 2019) and serves as the first food for mammals and the main source of nutrients for mammalian newborns. The bioactive constituents include immunoglobulins, lactoperoxidase, growth factors and immunomodulatory peptides, lysozymes, oligosaccharides, alpha-lactalbumin, and lactoferrin (Cacho and Lawrence, 2017). It is also a source of amino acids and protein, minerals (such as calcium, phosphorus, and potassium), several vitamins (such as vitamins A, B2, B5, and B12), fat, and essential fatty acids. The bioactive compounds play significant physiological and biochemical functions (Khan et al., 2019). Animal (mammalian) milk composition varies depending on species differences and other factors, such as nutrition, food composition, physiology, and milking frequency (Mehra et al., 2021). Its composition also varies based on genetic factors, breed types, and environmental conditions.

Drawbacks of animal milk include health-related concerns such as milk allergies, hypercholesterolemia prevalence and lactose intolerance (Munekata et al., 2020). Animal milk is under increased scrutiny due to its environmental impact, accounting for 8% of global water consumption and contributing predominantly to greenhouse gases. Additionally, air and water pollution, soil degradation and loss of diversity are related issues in animal milk production. Ethical considerations concerning animal welfare are also related to animal milk (Haas et al., 2019).

III. PLANT-BASED MILK PRODUCTS

A wide range of PBMP, which are desirable, convenient, affordable, sustainable, and rich in nutrients, have now been developed by the food industry. Different varieties of PBMP have been produced from many other plant sources including cereals (e.g., rice, oat, spelt, kamut, corn, rye, quinoa), legumes (e.g., cowpea and peanut), nuts (e.g., coconut, almond, walnut, pistachio and hazelnut), pseudo cereals (quinoa and amaranth) and seeds (e.g., flax, sesame, hemp, sunflower and pumpkin) (Munekata et al., 2020). The PBMP, derived from the water extraction of these plant materials, is completely free from animal-based ingredients (Silva et al., 2020). PBMP are formulated to have a similar appearance and taste to conventional milk (Mäkinen et al., 2016) and are often presented as a sustainable, healthy and animal-welfare-friendly alternative (Haas et al., 2019). In addition, other plant-based dairy substitutes like cheese, yoghurt, ice cream, and creamer are similarly increasing rapidly globally (Clay et al., 2020).

The PBMP products differ with respect to their nutrients. Therefore, the addition of protein, vitamins, and minerals, such as calcium, to make them comparable to cow milk is the common practice (Mäkinen et al., 2016). Sugar content, serving as a natural sweetener, is the most important attribute of plant milks (Haas et al., 2019). PBMP are an important source of moisture, carbohydrate, protein, and fat, and are rich in unsaturated fatty acids, fibre, vitamins, minerals, and essential fatty acids (McClements and Grossmann, 2021). The major fatty acids are stearic acid (18:0) and palmitic acid (16:0), α -linolenic acid (18:3), linoleic acid (18:2) and oleic acid (18:1) (Aydar et al., 2020).

Several PBMP products have health promoting effects. Chickpea milk is rich in minerals and fibre, coconut milk is rich in lipids (Jeske et al., 2017b; Rincon et al., 2020), while soymilk is rich in protein (Vanga and Raghavan, 2017). Oat, cashew and soymilk have a higher level of dietary fibre (Aydar et al., 2020). Soymilk is a good source of B-vitamins, especially niacin, folate, and pyridoxine; minerals, such as iron, copper, magnesium, and zinc; and monounsaturated and polyunsaturated fats (Mazumder and Hongprabhas, 2016; Zandona et al., 2021). Hemp milk contains molybdenum, and coconut milk provides chromium and selenium (Astolfi et al., 2020).

Several authors have compared different animal sources for milk quality and PBMP. Aly et al. (2022) evaluated the antioxidant activity, cholecystokinin (CCK) and glucagon-like peptide-1 (GLP-1) release of some PBMP after in vitro digestion. The study concludes that the PBMP could adequately replace cow's milk, based on their antioxidant and satiety effectiveness. In another study, Aydar et al. (2023) assessed the in vitro phenolic bioaccessibility, sensory quality and fatty acid profiles. The study documented protein (1.92%–2.32%), α -linolenic acid (25.66%–27.78%), and palmitic acid (18.95%–23.08%) contents. Further, the study observed an overall sensory acceptance ranging from 2.9 to 4.1 out of 10. PBMP provide many attractive qualities to consumers, such as lactose-, dairy allergen- and cholesterol-free properties (Hartmann et al., 2018; Cichonska and Ziarno, 2022); high content in essential nutrients (vitamins and minerals), bioactive compounds and dietary fibre, with pre-probiotic properties (Roselló-Soto et al., 2019). The PBMP also allay consumers' safety concerns relating to antibiotic residues and hormones (Pua et al., 2022) and promote vegan-friendly attributes (Mendly-Zambo et al., 2021). Figure 1 illustrates diverse nutraceutical benefits of plant-based milk.

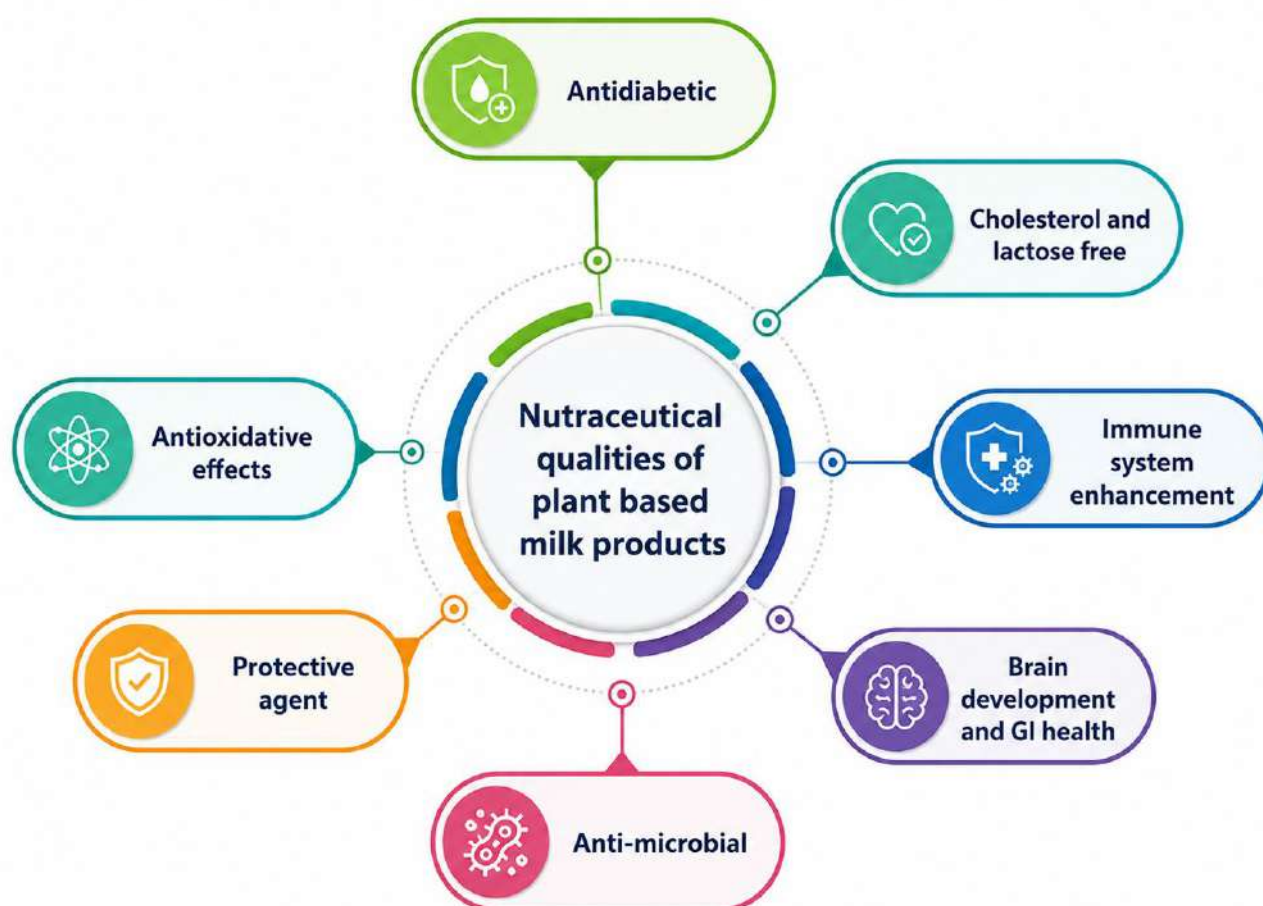


FIGURE-1: Diverse nutraceutical benefits of plant based milk

3.1 Sources of PBMP and Production Methods

Diverse plant sources from which PBMP including cereals, legumes, nuts, pseudocereals, corms, roots and tubers, seeds, fruits, and vegetables. Among these sources, cereals, including rice, oat, spelt, kamut, corn, rye, and quinoa; and nuts, including coconut, almond, walnut, pistachio, tiger nut and hazelnut, have been reported (Anitha and Manivannan, 2013). Similarly,

pseudocereals including quinoa and amaranth; legumes, including soy, cowpea and peanut; and seeds including flax, sesame, hemp, sunflower, pumpkin and potato roots, have also been reported (Mohanty et al., 2016; Zheng et al., 2021). Aside the sources listed above, PBMP are also produced from the blends of different plant source such as soy bean and almond (Kundu et al., 2018), soy bean and corn (Ajala et al., 2013), peanut, melon seeds, and coconut (Oduro et al., 2021).

Depending on the initial raw material and intended final product quality, the process of producing PBMP may vary (Penha et al., 2021). The production process typically involves several common steps, which include sourcing and pre-processing raw materials, grinding and extraction, emulsification and stabilisation, flavouring and fortification, pasteurisation, packaging and storage, as well as quality control testing. To ensure the quality of the raw materials, it is essential to consider several critical factors. The origin and variety of the plant-based ingredients, along with their growing conditions, significantly influence their taste and nutritional content. Careful harvesting and handling during transportation and storage are essential in preserving the freshness and integrity of the raw materials (Mäkinen et al., 2016). In addition, the methods used for processing, which include cleaning, sorting, and preparation, influence both the overall quality and the possibility of contaminants. Proper storage conditions and preservation methods further protect against spoilage and help keep the nutritional properties of the raw materials intact. Consistent quality testing is vital for identifying contaminants such as pesticides, heavy metals, and microbial agents, thereby ensuring the safety and purity of the raw materials (Mäkinen et al., 2016). By conscientiously considering these factors, PBMP processors can opt for high-quality plant sources, resulting in superior PBMP products that effectively cater for consumers' demands for taste, high nutrients, and sustainability.

3.2 Cleaning and Pre-Processing of Raw Materials

Raw materials are subjected to cleaning and pre-processing, which encompass vital steps in the production of plant-based milk. The cleaning and sorting stage begins with the raw materials being thoroughly inspected, and any impurities, foreign particles, or damaged components are removed to ensure the highest quality ingredients. Following this, soaking and blanching are performed to prepare the raw materials for further processing. Water soaking helps soften, hydrate, and swell the raw material, making it easier to blend and extract and consequently reducing the apparent amylose level (Padma et al., 2018). It can be used for different raw materials, including seeds and grains such as soybeans, rice, sesame seeds, and nuts such as hazelnuts, tiger nuts, peanuts, and almonds (Aydar et al., 2020). Water soaking also increases the extraction yield of the PBMP. Blanching can be used for seeds and nuts, such as almonds, soybeans, coconuts, peanuts, sesame, quinoa and rice, by briefly immersing the raw materials in hot/boiling water, which helps preserve their colour, texture, and nutritional properties (Aydar et al., 2020). Relative to water soaking, the advantages of blanching the raw material include enzyme (for example, lipases) inactivation, microbial load reduction (Sethi et al., 2016), and reduction in antinutrients and off-flavours (Pua et al., 2022). PBMP are produced by size-reduction methods, in which the original structure of plant tissue is broken down by mechanical, chemical, and enzymatic methods (Zheng et al., 2021). More often, the mechanical extraction of the raw material is applied due to its scalability and low cost, having a low technological barrier (Mäkinen et al., 2016; Yadav et al., 2017). It is effective in dispersing the raw material ingredients for optimum extraction, allowing for the extraction process standardisation. The tissue structure breakdown following grinding results in the release of oil bodies in PBMP seed and nut sources, such as cashews, soybeans, coconuts, oats and almonds.

3.3 Grinding and Extraction

Grinding and extraction are key processes in the production of plant-based milk. For optimal texture, the soaked and blanched raw materials are finely ground to create a smooth, consistent mixture. This grinding helps release flavours and nutrients effectively. Depending on the raw material, grinding may be carried out by dry-milling or wet-milling. For PBMP produced using flour, dry-milling is typically performed first, and the resulting flour is then reconstituted and/or further extracted to yield the PBMP (Mäkinen et al., 2016). For PBMP in which the whole raw material is subjected to aqueous extraction without first being converted into flour, the raw material is typically pulverised into a slurry through wet-milling, releasing finely suspended or soluble constituents (Yadav et al., 2017). However, both milling methods result in a non-homogeneous particle size distribution, which may require additional size standardisation or reduction to enhance stability and texture (Kizzie-Hayford et al., 2015). Subsequently, various extraction methods are employed to extract the milk from the ground mixture, depending on the plant-based source. For instance, pressing is used for nuts and seeds, while blending and straining are common for grains. These extraction techniques play a vital role in determining the final taste, consistency, and nutritional content of the plant-based milk (Pua et al., 2022). In this step, unwanted materials (mainly coarse particles) are separated or removed through gravity-facilitated sedimentation, centrifugation, decanting, or (ultra) filtration, concentrating the desirable components, such as nutrients (McClements et al., 2019).

3.4 Emulsification and Stabilization

Emulsification and stabilization are crucial steps in producing PBMP, ensuring a smooth and uniform product. During the process, agents like lecithin or gums are added as emulsifiers and stabilisers to form a stable emulsion, preventing water and plant fats from separating during storage. These emulsifiers also improve the texture and mouthfeel of the milk. Homogenization and mixing further enhance the product by breaking down fat globules and distributing them evenly, resulting in a creamy, well-blended plant-based milk that offers a satisfying drinking experience (Ma and Boye, 2013). Homogenization plays a significant role in defining the microstructure of the extracted PBMP (Gul et al., 2017).

3.5 Flavoring and Fortification

Flavouring and fortification are important steps in production, enhancing both taste and nutritional value. During flavouring, processors may use natural or artificial flavouring agents to impart various flavours to the milk, catering to different consumers' preferences (McClements et al., 2019). Animal milk contains higher levels of minerals than PBMP and other plant-based beverages (Bocker and Silva, 2022). For instance, plant-based beverages contain about 30%–50% lower levels of minerals such as phosphorus, calcium, magnesium, potassium and sodium than animal milk (Astolfi et al., 2020). The low mineral levels in PBMP are coupled with the presence of antinutrients, such as tannins, oxalates, phytate, saponins and lecithin. These antinutrients diminish the digestibility and absorption of essential minerals, including Ca, Zn, Fe, Cu and Mg, by binding to them to form insoluble complexes (McClements et al., 2019). Hence, to improve the PBMP nutritional quality, fortification with essential nutrients, including vitamins and minerals, is important. Pasteurization, either by conventional or emerging innovative processing technologies, is a critical step in the production of PBMP to ensure its safety and extend its shelf life. It reduces the PBMP microbial and enzyme load to levels that are safe for human consumption (Bocker and Silva, 2022).

3.6 Pasteurization

In the conventional pasteurisation stage, methods such as high-temperature short-time (HTST) or ultra-high temperature (UHT) pasteurisation are employed to eliminate harmful bacteria and pathogens. However, applying high temperatures (from 60°C to 130°C) can cause undesirable alterations in the nutritional, physical, chemical, and sensory characteristics of the PBMP (Aydar et al., 2020). Therefore, proper temperature and time considerations are essential during pasteurisation, as the PBMP needs to be heated to a specific temperature for a certain duration to achieve effective sterilisation without compromising its taste and quality.

3.7 Packaging, Storage and Quality Control

Packaging and storage are essential steps in PBMP production, focusing on preserving product quality and safety. During this phase, appropriate packaging materials such as cartons, bottles, or pouches are chosen carefully to shield the milk from external contaminants and light (Liu et al., 2022). The selection of packaging not only affects the shelf life but also the sustainability of the PBMP. Equally important are proper storage conditions, which help keep the milk fresh and safe for consumption. It is recommended to store PBMP in a cool, dry place, away from direct sunlight, and at specific temperatures to prevent spoilage and maintain its flavour and nutritional value throughout its shelf life (Liu et al., 2022). Additionally, quality control and testing play a vital role in ensuring the product's consistency and safety. Rigorous testing and monitoring are conducted at various stages — from raw material procurement to final packaging — to verify that the PBMP meet standards, comply with regulations, and are free from contaminants.

IV. NUTRITIONAL QUALITIES OF PBMP

PBMP are reported as a good dietary source of some important nutrients, such as protein, calcium, vitamins, and fibre (Craig and Fresán, 2021). They serve as an alternative for dairy milk due to their perceived nutritional and health importance (Pandey and Poonia, 2020). The nutritional values of PBMP vary, depending on the raw material type and quality, formulation, processing method, and fortification. This attributes a unique set of nutritional qualities, making them a suitable option for health-conscious individuals (Craig et al., 2022). Major advantages of PBMP over animal-based milk is its lower saturated fat content (Sethi et al., 2016), making it a healthier and more attractive option for individuals concerned about their cardiovascular health and cholesterol levels (Briggs et al., 2017).

PBMP are also reported to be lactose- and cholesterol-free, making them suitable for individuals with lactose intolerance (Facioni et al., 2020). They contain essential micronutrients like vitamin D, B12, and calcium, which are vital for bone and teeth health, immune function, and energy production (Pandey and Poonia, 2020). However, PBMP such as almond, rice, and

oats have lower nutritional quality, offering minimal amounts of protein, iron, and calcium compared to cow's milk (Singhal et al., 2017). The high nutrient and fiber content of legumes has made them an appealing base for developing nutrient-rich PBMP (Chandra-Hioe et al., 2016). Their protein is incomplete, unlike the complete protein found in animal milk (Rincon et al., 2020). The generally lower nutritional value of PBMP versus cow's milk may limit their market appeal, as reliance on them could lead to deficiencies in nutrients like essential amino acids, vitamins (A, D, B2, B12), and minerals (zinc, calcium, iodine). Therefore, PBMP are often fortified with these nutrients to address such deficits. Table 1 is a summary of nutrients and their quantity in plant-based milk.

TABLE 1
SUMMARY OF NUTRIENTS AND THEIR QUANTITY IN PLANT-BASED MILK

Nutrient	Quantity	Reference
Carbohydrate	1.95-54.2 Kcal/1000mL	Irondi et al., 2025
Protein	0.30-3.10 Kcal/1000mL	Irondi et al., 2025
Fat and oil	0.96-4.55 kcal/100mL	Irondi et al., 2025
Fibre	0.10-1.27 kcal/100mL	Irondi et al., 2025
Ash	0.3-0.68 kcal/100mL	Irondi et al., 2025
Minerals		
Calcium	65.32-156.5	Irondi et al., 2025
Potassium	37.1-157.5	Irondi et al., 2025
Sodium	23.9-64.2	Irondi et al., 2025
Phosphorus	14.95-39.46	Irondi et al., 2025
Magnesium	7.76-16.8	Irondi et al., 2025
Iron	0.16-0.62	Irondi et al., 2025
Copper	0.01-0.13	Irondi et al., 2025
Vitamins		
Vitamin A	141.6-195.4 IU/100mL	Irondi et al., 2025

Research evidence has shown that most PBMP contain fewer calories than dairy milk. The carbohydrate contents ranges from 0.42 to 11.05 g per 100 mL, relative to dairy milk (4.78 g/100 mL) for whole milk and 4.96 g/100 mL for skim milk (Jeske et al., 2017b; Walther et al., 2022). PBMP generally exhibits a lower protein quality than animal milk products, due to the limitation of some essential amino acids (Mäkinen et al., 2016), except for soy protein. Soy protein has been reported to be a complete protein containing all essential amino acids at sufficient proportions to meet human dietary needs (Lopez and Mohiuddin, 2020). The individual amino acids levels vary among the PBMP from different sources (Walther et al., 2022). Studies implicate that cereal milk products contain lower lysine content, while leguminous proteins contain lower methionine and cysteine content (Anitha et al., 2020). Some types of PBMP, such as wheat, nut and soy, contain protein that can trigger allergic reactions in susceptible consumers (Pingali et al., 2023). To improve PBMP protein quality to match that of animal milk, various fortification techniques are frequently used, such as adding enzymes or combining different types of PBMP.

The fatty acid profile of PBMP indicates it generally contains higher levels of mono- and polyunsaturated fatty acids, with the exception of coconut-based milk. The low saturated fat and high unsaturated fat contents in PBMP make them a better substitute for animal-based milk, as consumption of high saturated fatty acids is linked to LDL-cholesterol, which is implicated in cardio-metabolic diseases and diabetes mellitus (Dehghan et al., 2018; Rööös et al., 2020). Polyunsaturated fatty acids are reported to be predominant in soybean and hemp milk, while monounsaturated fatty acids are reported to predominate in rice, cashew, and almond milk (Neelakantan et al., 2020). Saturated fatty acids are reported to be the major fat content of coconut milk (Romulo, 2022). Report has shown that PBMP are cholesterol-free, as sterols are exclusive components of animal cells (Antunes et al., 2023). Among the various PBMP types, soymilk is reported to have a higher concentration of potassium. The phosphorus

content of PBMP is reported to be lower than that of animal milk. Most of the high micronutrient contents of PBMP according to studies are as a result of the fortification of the milk with essential micronutrients (Chalupa-Krebzdak et al., 2018). Similarly, the vitamin contents of PBMP revealed that most of the vitamins reported in PBMP are a result of fortification. Hence, the levels of both fat-soluble and water-soluble vitamins in PBMP vary based on the various plant sources, fortification and formulation employed during their production (Thorning et al., 2016). For example, cobalamin is a water-soluble vitamin exclusively found in foods from animal sources; therefore, its presence in PBMP is a clear evidence of fortification (Bridges, 2018).

V. NUTRACEUTICAL QUALITIES OF PBMP

PBMP have several health-promoting properties for which they can be placed in the nutraceutical and functional food class (Aydar et al., 2020). The bioactive compounds in PBMP are such as polyphenolic compounds, phytosterols, isoflavones, bioactive peptides and saponins (Zandona et al., 2021). These bioactive compounds have been reported to confer on PBMP some significant health benefits, such as promoting brain development and boosting the immune system, reducing the risk of diabetes mellitus, atherosclerosis, coronary heart diseases, neurodegenerative disorders, such as Alzheimer's disease, as well as protecting against some types of cancer (Pistollato et al., 2018). In addition, as a substitute for animal milk, PBMP are beneficial for the management of lactose intolerance and cardiovascular disease that are related to animal milk consumption (Aydar et al., 2020). This is because PBMP are cholesterol- and lactose-free (Zandona et al., 2021).

Phenolic compounds have antioxidant and antidiabetic activity (Ironi et al., 2022). Isoflavones, which are strong antioxidants, have also been reported to be present in soymilk (Mazumder and Begum, 2016). According to Hamza and Mahmoud (2013), a portion of 200 g of soymilk contains the following isoflavones: genistein (9.96 mg), daidzein (6.68 mg), and glycitein (0.94 mg). Isoflavones in soymilk were reported to have effects against dermatological, neurodegenerative (Aydar et al., 2020) and anti-inflammatory disorders (Poschner et al., 2017). They also function as chemotherapeutic agent for many types of cancer (Spagnuolo et al., 2015), as well as protect against osteoporosis (Mazumder and Hongsprabhas, 2016). The high dietary fiber in oat, cashew and soymilk PBMP promote a healthy gastrointestinal tract. Furthermore, PBMP also can reduce gastrointestinal disease due to their antimicrobial effect, decrease the risk of low bone mass and improve physiological functions (Paul et al., 2019).

Coconut milk was suggested to be a favourable dairy substitute for patients with chronic kidney disease, due to its low sodium, potassium and oxalate content (Borin et al., 2022). PBMP from soy, coconut and rice are probiotics, carrying some health-benefiting microorganisms, such as *Lactobacillus* and *Bifidobacterium*. Thus, they render health advantages, such as enhancing gastrointestinal transit, production of B-group vitamins, and transforming insoluble-bound forms of phenolic compounds into more readily-absorbable forms (Rasika et al., 2020). The unsaturated fatty acid contents of cashew, almond, soy, peanut and hazelnut milk are higher than their total saturated fatty acid contents. Unsaturated fatty acids are associated with a decrease in blood lipid concentration (Eslami and Shidfar, 2019). Essential fatty acids, including α -linolenic and linoleic acids, have neuroprotective effects in Alzheimer's disease. Moreover, coconut milk maintains blood vessel elasticity, promotes brain development due to the presence of compounds, such as medium-chain triacyl glycerides and lauric acid (Reyes-Jurado et al., 2021).

Aly et al. (2022) investigated the antioxidant capacity, cholecystokinin (CCK) and glucagon-like peptide-1 (GLP-1) release of some PBMP following in vitro digestion. Results implicate tiger nut milk had the highest CCK stimulant level (228.96 pg/mL), which was followed by that of hazelnut milk (220.04 pg/mL). Depending on the plant source, PBMP contain some antinutrients, including phytate, oxalate, saponins, exorphins, tannic acid, goitrogens, trypsin inhibitors, starch-digesting enzyme and protease inhibitors, and lectins (Reyes-Jurado et al., 2021). These antinutrients generally interfere with the digestion, absorption and utilization of some important nutrients, although their impact varies, depending on their chemical nature and interaction with specific nutrients (Imam et al., 2024). For example, phytate reduces the bioavailability of essential micronutrients, such as zinc, iron, magnesium, and calcium, while trypsin inhibitors on the other hand reduce the protein digestibility (Imam et al., 2024). Lectins, common in soy, peanuts, and other beans, significantly reduce total calorie intake by inhibiting intestinal glucose (Mäkinen et al., 2016). Saponins, commonly present in oats, soy and beans, reduce protein digestibility, especially soy proteins, by forming insoluble saponin-protein complexes that are resistant to digestion.

VI. SENSORY QUALITIES OF PBMP

Consumer acceptability of the PBMP product is driven by sensory attributes (Zandona et al., 2021). Food researchers and scientists have been working to develop plant-based analogs with improved sensory and physical characteristics (Short et al.,

2021). A study by Yao et al. (2022) on the sensory, rheological, and physicochemical properties of PBMP from different cereals revealed that the sensory profile and consumer acceptability of the PBMP were high enough for commercial-scale production, with a potential for market viability. Gorman et al. (2021) investigated the consumer acceptability of PBMP in coffee in dairy and plant consumers. Their findings revealed a preference for PBMP in coffee among the plant consumers/vegetarians. Aydar et al. (2023) assessed the sensory attributes of PBMP produced from different varieties of kidney bean and concluded that the PBMP had an overall sensory acceptance ranging from 2.9 to 4.1 out of 10.

Vaikma et al. (2021) evaluated the sensory attributes and consumer acceptability of 90 different plant-based beverages in Estonian markets using the Rate-All-That-Apply (RATA) method. The results imply little variation among the sample groups. Moss et al. (2022) demonstrated that consumer acceptability ratings of PBMP from pea, almond, oat, soy, and coconut were comparable. The acid, bitter and astringent flavours of PBMP are attributed to the presence of compounds flavonoids, glycosylates, phenols, and terpenes (Tang-u et al., 2019). A PBMP made from legumes smells earthy and beany and is, thus, considered undesirable for individuals with no traditional consumption of legumes. The off-flavours of the legume milk result from n-hexanol and n-hexanal that develop from the oxidation of plant lipids (Tangyu et al., 2019). Various pre-treatments, such as blanching, soaking, and dehulling, are essential to improve the sensory profiles of PBMP. For instance, the flavours and aromas of the final products of PBMP can be enhanced by roasting the raw material, while its extraction yield and protein solubility can be reduced by heating. Also, blanching can remove off-flavours from soymilk by inactivating lipoxygenase and trypsin inhibitors (Mäkinen et al., 2016).

Makinde and Adebile (2018) report that blanching almond nuts with hot water for 15 min improved the overall acceptance of pre-treated almond milk, producing better colour, mouth feel, flavour, and overall acceptance compared to steaming. The flavour and smooth, delicate texture of PBMP somewhat differ from those of dairy milk, mainly because PBMP are compactly packed in globular structures that form diverse structures upon reaction with one another. Hence, the PBMP sensory quality is complemented by introducing additives to mimic the mouth feel, texture, and other properties of conventional dairy milk. Adding sugar to cashew nut milk also enhanced its sensory acceptability (Tamuno and Monday, 2019). Another study by Kim and Hong (2023) demonstrated that additives like chocolate flavouring effectively increased the sensory profile of soymilk through aroma-taste interactions. Blending has been shown to improve sensory quality. Oduro et al. (2021), in which peanut, melon seeds, and coconut were blended, revealed that the blend's PBMP had an enhanced sensory quality.

VII. BIOAVAILABILITY AND BIOACCESSIBILITY OF PLANT-BASED MILKS

Bioavailability refers to the fraction of an ingested micronutrient that reaches systemic circulation. Several factors influence this, expressed as $F = FB \times FA \times FT$, where FB is the fraction released from food into GIT fluids, and FT is the fraction remaining in its bioactive form after chemical transport. Some bioactives are expelled back into intestinal fluids via efflux transporters. The stability of a bioactive in the GIT depends on its molecular environment. Oil-soluble bioactives' bioaccessibility relies on mixed micellar formation in the small intestine that can solubilise them. The food matrix surrounding lipid droplets in emulsions significantly affects the bioavailability of encapsulated hydrophobic bioactives. Consuming them with digestible lipids like triacylglycerols can enhance bioaccessibility. Certain food-grade components, such as spices, medium-chain fatty acids, and surfactants, promote micronutrient absorption by modifying intestinal membrane permeability or influencing active transport and efflux. Incorporating these into functional milk foods might be beneficial.

Muleya et al. (2024) evaluated calcium supply in 25 plant-based products, finding bioaccessibility varied from 0.1% to 50%, with kale, finger millet, and fortified white bread as top sources — kale offering five times more bioaccessible calcium than a serving of skimmed milk. Zhou et al. (2021) studied almond-fortified milk containing micronutrients, noting calcium bioaccessibility was higher with CaCO_3 than CaCl_2 . These findings inform the development of fortified plant-based milks with better nutritional and physicochemical properties. A plant-based chocolate spread, fortified with nano-liposomal vitamin D₃ and omega fatty acids using spray-dried milk powders (soy, lentil, rice), was developed to enhance nutritional quality and bioaccessibility. Azab et al. (2025) reported on this plant-based spread with improved vitamin D₃ bioavailability.

Bioavailability may depend on the matrix components, such as PS ingredients. Vaghini et al. (2016) examined the bioaccessibility of total and individual plant sterols in four commercial PS-enriched fermented milk beverages during in vitro digestion, including mixed micelle formation. Total plant sterol bioaccessibility was highest in samples A and B (16-17%), lower in D (11%), and lowest in C (9%). Total bioaccessibility did not correlate with protein, lipid, or PS content but was inversely related to carbohydrate and fiber content. The bioaccessibility of individual PS varied among samples and was independent of the PS profile. Table 2 is a comparative summary of few plant-based milk and dairy milk.

TABLE 2
COMPARATIVE SUMMARY OF FEW PLANT-BASED MILK AND DAIRY MILK

Item	Daily Value	Dairy Milk	Pea Milk	Almond Milk	Soy Milk
Protein (g)	50	8.2	7.5	1	6.1
Calcium (mg)	1,300	309	385	449	294
Magnesium (mg)	420	29	0	15	33
Phosphorus (mg)	1,250	252	nd	22	176
Potassium (mg)	4,700	387	421	163	280
Selenium (µg)	55	4.8	nd	0.2	5.2
Zinc (mg)	11	1.1	nd	0.1	0.5
Riboflavin (mg)	1.3	0.33	nd	0.02	0.45
Vitamin D (µg)	20	27	2.5	2.4	2.7

VIII. BIOTECHNOLOGICAL APPROACHES

Biotechnology enhances food using genetic engineering, fermentation, and omics tools to increase nutrient density, create stress-resilient crops, and produce sustainable smart proteins. Tools like CRISPR improve crops to yield higher vitamins or iron (e.g., biofortified staple plants). CRISPR-Cas9 silencing in the IPK1 gene in wheat or NRAMP transporters in rice lowers phytic acid or stops minerals from locking in roots, increasing iron availability in edible grains (Kumar et al., 2022). Microbial and enzymatic systems modify plant proteins and starches to create functional analogs. Several microorganisms consume plant sugars and starches and produce acids, gases, and complex flavor compounds that improve sensory properties (Muhammed et al., 2025). Specific enzymes like proteases and transglutaminases cut or cross-link plant proteins changing elasticity, water retention, and mouthfeel (Kieliszek et al., 2026). These microbial methods increase protein digestibility and unlock bound minerals (Samantaray et al., 2026). Further, they replace chemical additives with natural biological processes.

Genomics and metabolomics identify and amplify specific health-promoting compounds in traditional crops. Researchers have reported successful application of genomics to enhance bioactive and phytoconstituents which would have potential in fortified milk production. Genome editing tools like CRISPR-Cas9 have also been utilized to enhance the amylose content (Sun et al., 2017b). An increased expression of zeaxanthin, violaxanthin and lutein by targeting the downregulation of the epsilon cyclase gene using RNAi technology has been reported in mustard (Yu et al., 2008). Transformation of bHLH transcription factor gene, VvbHLH1 from grapes into Arabidopsis, resulted in an increased accumulation of flavonoids (Wang et al., 2016). A pathway engineering to increase the content of novel flavonoids especially stilbenes in the flesh of the tomato fruit is reported by Schijlen et al., 2006. Metabolomics profiles small-molecule chemical fingerprints in plants to identify health-promoting secondary metabolites like flavonoids, polyphenols, and antioxidants (Suruthi et al., 2025). Researchers can use these chemical maps alongside breeding and microbial treatments to boost nutritional value and stress resilience in traditional crops (Karalija et al., 2025).

IX. RECENT TRENDS AND PROSPECTS

Metagenomic studies of plant-based, fortified milk alternatives evaluate microbial profiles, fermentation dynamics, and how nutrients or plant substrates shape bacterial consortia, safety, and nutrient bioaccessibility. Next-generation 16S rRNA and shotgun metagenomic sequencing map live bacterial and fungal communities in commercial or fermented plant milks (soy, oat, almond, coconut) (Part et al., 2023). Metagenomic surveillance helps detect shifts indicating post-processing contamination or unwanted pathogen survival in neutral-pH, high-moisture plant beverages (Zulqarnain et al., 2026).

Plant-based proteins are becoming innovative and fast-growing ingredients across various food application industries due to a large number of benefits over animal-derived proteins. Various technologies help improve the functional and nutritional properties of plant-based proteins. Engineering high-protein plant milks from soy, pea, and chickpea bases transforms traditional low-protein nut milks into nutrient-dense alternatives, matching dairy milk's protein content (8 g per cup) (Langyan et al., 2022). This method enhances amino acid profiles, texture, and stability through precise blend ratios and functional processing. Combining soy, pea, and chickpea covers individual amino acid gaps, creating a balanced protein profile. It reaches

7 g to 9 g of protein per cup and retains natural dietary fibre, iron, and potassium from the legume bases (Lee et al., 2024). However, drawbacks include protein settling at neutral pH; high-pressure homogenization reduces droplet and particle size to keep emulsions suspended. Lipoxigenase enzymes in raw legumes cause grassy/beaney tastes (Snir et al., 2025).

Advanced micronutrient fortification in plant-based or alternative milks uses targeted vitamins like D₃ and B₁₂ and minerals to match cow's milk nutrition. This process helps to meet the required level of nutrients without drinking dairy products (Xie et al., 2026). Currently, vitamin D₃, vitamin B₁₂ and calcium and minerals are added to help the body absorb calcium and support strong bones and protect nerves and make healthy red blood cells. These formulated products are designed for easy absorption since they have good bioavailability. The benefits are better health and are friendly for people of all types of food habits and nutrient balance (Bagheri et al., 2026). Micronutrient deficiencies continue to be widespread among children under five in low- and middle-income countries (LMICs), despite the fact that several effective strategies now exist to prevent them. This kind of malnutrition can have several immediate and long-term consequences on physical and mental well-being (Allen et al., 2006). Research evidence further supports the importance of reducing the burden of micronutrient malnutrition in children through such fortification methods. Population and context should be considered when selecting one or more appropriate interventions for programming (Tam et al., 2020).

Recent trends in plant-based fortified milk focus on mimicking the complex nutritional delivery and texture of the dairy matrix. Manufacturers are moving past basic calcium and vitamin D additions to use advanced nano-emulsions (Kaptan et al., 2024), protein blending (like pea and soy), and bioactive plant extracts to boost nutrient absorption and stability. Specialised calcium salts and liposomal delivery systems (Messersmith and Nguyen, 1998) are used to prevent mineral precipitation and improve bioavailability within the plant liquid matrix. This encapsulation shields the mineral from reactive counter-ions (such as phosphates or sulfates) in a liquid matrix, greatly enhancing stability, preventing lockout, and increasing cellular uptake and bioavailability (Erceg et al., 2022). Encapsulation stops mineral fallout or particle aggregation in complex liquid solutions, preserving a homogeneous suspension (Luo et al., 2025). It also protects payload integrity against shifts in pH, ionic strength, or temperature fluctuations common in complex liquid matrices (Yang et al., 2022).

Nanotechnology transforms plant-based and fortified milk alternatives by reducing particle sizes to the nanoscale (Altaf et al., 2026). This innovation significantly improves nutrient bioavailability, masks unappealing tastes of added minerals or plant extracts, and stabilises emulsions without altering texture (Biswas et al., 2022). Nano-emulsions disperse hydrophobic vitamins and minerals uniformly into aqueous plant bases (almond, soy, rice milk) for maximum absorption (Biswas et al., 2022). Research implicates the delivery of natural antioxidants, vitamins, and minerals (like iron and calcium) via nano-emulsions to prevent chalky textures or metallic aftertastes. Also, it optimises mucus penetration and controlled nutrient release during digestion (Liu et al., 2025). Finally, embedded antimicrobial nanocoatings and nanosensors enable monitoring of real-time spoilage and extend product shelf life (Ramani et al., 2024).

Using Pulsed Electric Fields (PEF) and ultrasonication together is an effective non-thermal method to kill spoilage microbes in plant-based milk (Wang et al., 2026). These techniques use short electrical pulses and sound waves to break cell walls without high heat, which keeps heat-sensitive vitamins like Vitamin C and B-complex intact. Sonication reduces particle size, which improves the physical stability and mouthfeel of the plant milk (Sotelo-Lara et al., 2024). Using both methods lowers the needed energy intensity, preventing local hot spots and fully protecting added nutrients (Ahmed et al., 2021). Another method, Ultra-High-Pressure Homogenization (UHPH), creates nano-emulsions that drastically improve physical stability and extend shelf life without heavy reliance on gums (Mengistu et al., 2025).

X. DISCUSSION

Changes in consumer preferences, culinary settings, labelling regulations, and demographics have all been cited as drivers of the shift in dairy consumption. Sales of plant-based milk rose by 20% in 2020, with yearly revenue growth that was twice as fast as that of dairy milk (Ramsing et al., 2023). In 2020, a projected 40% of families bought plant-based milk, accounting for 15% of retail milk sales. Almond, coconut, flaxseed, oat, rice, and soy milks are some of the most well-known commercial plant-based milk substitutes that have gained popularity in recent years. To be utilised in comparable applications, plant-based milk alternatives are usually made to resemble cow's milk in terms of appearance, texture, flavour, and shelf life (Rehal et al., 2025).

Regarding nutrition and health benefits, the PBMP offers a number of advantages. Additionally, their environmentally friendly operations cause less pollution. Protein, calcium, vitamins, and fibre are among the vital nutrients that PBMP are a good source of (Craig and Fresán, 2021). The bioactive components in PBMP include polyphenolic compounds, phytosterols, isoflavones,

bioactive peptides, and saponins (Ironi et al., 2025). Additionally, people who are lactose intolerant can consume PBMP because it is said to be free of lactose and cholesterol. From a community nutrition and global malnutrition perspective, plant milk fortification adds essential vitamins and minerals — like calcium, vitamin D, vitamin B₁₂, and protein — to plant-based alternatives (such as soy, almond, or oat beverages). This process helps prevent micronutrient malnutrition and nutritional deficiencies in populations (Sonya Good et al., 2026).

PBMP is a superior substitute for animal-based milk because of its high unsaturated fat content and low saturated fat content (Röös et al., 2020). Compared to other PBMP types, soymilk is said to have a higher potassium concentration. Because of its many health-promoting properties, PBMP can be categorised as a nutraceutical or functional food (Aydar et al., 2020). Bioactive components in PBMP have been demonstrated to offer several significant health advantages, such as improving brain development and bolstering the immune system, reducing the risk of diabetes mellitus, atherosclerosis, coronary heart disease, neurodegenerative diseases like Alzheimer's disease, and preventing certain types of cancer (Veena and Nath, 2018).

Customers are becoming more inclined to buy plant-based milks due to their interest in sustainability as well as their concern for the environment and animal welfare. According to studies, consumers of dairy and plant-based milks concur that sustainability is crucial for the greater good (Nowson et al., 2025). Poorer digestibility, anti-nutritional factors, lower levels of important amino acids (particularly leucine), and deficiencies in other critical amino acids, like sulfur-containing amino acids, are some of the PBMP's disadvantages (Park et al., 2021). Because PBMP is highly susceptible to physical, chemical, and microbiological deterioration, more study may be done to produce immediate PBMP in powder form, which would have a longer shelf life while maintaining the mix of nutrients and bioactive substances. There are chances for research and innovation in a number of PBMP areas to strengthen, improve, and enhance.

The manufacturing techniques used to create plant-based milk alternatives should ideally result in a finished product that shares some structural and compositional characteristics of cow's milk. Since the fat globules and casein micelles give cow's milk its milky colour and creamy texture, its colloidal nature is very important in achieving its desired quality qualities (Scholarly community encyclopedia, 2026). Milk's flavour character is also significantly influenced by the carbohydrates and salts it contains. Therefore, colloidal fat and/or protein distributed in an aqueous solution comprising carbohydrates and salts is the characteristic composition of plant-based goods (Rachtan-Janicka et al., 2025). Therefore, one of the main areas of study and development is the creation of mimicked fat globules using plant-based substances and the breakdown of the inherent structures of some plant materials to release oil bodies or other colloidal particles. A homogenisation procedure is used to mix plant-based substances to create an emulsion. The type of ingredients and unit operations used have a significant impact on the stability and characteristics of this form of colloidal dispersion. This is another area that needs more research inputs.

To enhance the functional qualities of plant-based milk substitutes, a range of additional ingredients can be added. Many types of biopolymers with different molecular, physical, functional, and biological characteristics can be used as thickening agents (Yiu et al., 2023). These substances, which include minerals, vitamins, nutraceuticals, colours, flavours, or preservatives, improve the qualitative characteristics, nutritional profile, or safety of plant-based milk alternatives. To use a wide variety of additives, research on the components and their functions is necessary. Manufacturers must comprehend the key elements influencing the physical, functional, and sensory qualities that customers find appealing in plant-based milk substitutes, such as texture, appearance, and stability (Baranwal et al., 2022).

The possible chemical instability of any nutrients or nutraceuticals added to plant-based milk substitutes must also be taken into account. Many of these bioactive substances, such as ω -3 fatty acids, carotenoids, quercetin, resveratrol, and oil-soluble vitamins, are chemically labile molecules that break down over time (Pinto et al., 2016). Therefore, it is crucial to understand the reaction mechanisms involved and identify key factors affecting their degradation rate — such as pH, metal ions, temperature, oxygen, and light exposure. Based on this understanding, suitable strategies can be developed to prevent chemical degradation during storage of plant-based milk alternatives. Since plant-based milks play a significant role in making diets more affordable for financially constrained households, researching ways to reduce their cost should also be a fundamental part of this investigation.

XI. CONCLUSION

A significant development in food science, plant-based milk substitutes provide consumers all over the world with sustainable and health-conscious options. They contribute to increased nutritional diversity by offering a workable alternative for people with lactose intolerance, milk allergies, and plant-based diets. Their significance in the future of food systems is highlighted by their function in improving environmental sustainability by reducing greenhouse gas emissions and water consumption in

comparison to traditional dairy production and by promoting public health. Technological developments in processing and fortification are resolving difficulties like sensory appeal and nutritional balance.

This review has comprehensively examined the sources, production methods, nutritional and nutraceutical qualities, sensory attributes, bioavailability, and biotechnological advances of plant-based milk products. The evidence presented demonstrates that PBMP offer significant potential as functional foods that can contribute to human health, environmental sustainability, and food security. However, challenges remain, including improving protein quality, addressing antinutrient concerns, enhancing sensory properties, and ensuring the stability of fortified nutrients. Future research should focus on developing improved processing technologies, optimizing fortification strategies, understanding the mechanisms of bioactive compound bioavailability, and conducting rigorous clinical studies to validate the health benefits of PBMP. As the plant-based milk market continues to grow, continued innovation in food science and biotechnology will be essential to meet consumer demands for nutritious, sustainable, and delicious plant-based alternatives.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Climate Variability and GDP Structural Risk in Rainfed Agriculture and Livestock System: Evidence from Sudan

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HIGHLIGHTS

- This study identifies asymmetric effects of rainfall and temperature on agriculture and GDP in Sudan using a nonlinear ARDL (NARDL) framework.
- Evidence from Gedaref shows that temperature increases are negatively associated with yields of major rainfed crops, while rainfall variability and rainy-season length significantly influence productivity.
- Sudan's livestock sector comprises 111.8 million heads, contributes about 25% to national GDP, and depends heavily on climate-sensitive feed sources, especially natural grazing (55%) and crop residues (25%).
- The paper proposes a Provincial Agricultural Resilience Index (PARI) and a Spatial Autoregressive (SAR) extension to analyze province/state resilience and spillovers.
- The study quantified rainfall shock → GDP effects from the NARDL interpretation: direct climate effect of +1 mm rainfall → +0.063 percentage points GDP growth; direct climate effect of −1 mm rainfall → −0.095 percentage points GDP growth.
- The study quantified livestock export elasticities → GDP from the double-log model: goat exports: 0.275, sheep exports: 1.119, camel exports: 0.737, cattle exports: 0.273.
- Regional PARI values: Gedaref 0.67, Kordofan 0.37, Darfur 0.10, Central 0.93.
- Integrated adaptation recommendations are proposed for heat-tolerant crops, drought resilience, grazing modernization, feed systems, and digital traceability.

Abstract— This study investigates how climate variability shapes GDP structural risk in Sudan's agricultural systems, with a particular focus on rainfed agriculture and livestock-based production systems. Unlike irrigated agriculture, both systems operate under climate-dependent conditions, making them highly sensitive to rainfall variability, temperature extremes, and seasonal uncertainty. The analysis integrates agro-climatic conditions, probability distribution functions, and spatial econometric techniques to examine how environmental variability translates into sectoral economic outcomes.

The empirical results reveal a clear structural divergence between rainfed crop and livestock systems. In rainfed agricultural zones such as Gedaref, characterized by rainfall variability ranging from 300 to 800 mm and growing seasons of 57 to 117 days, crop production exhibits relatively stable but low GDP contributions, constrained by seasonal dependence and limited productivity. In contrast, livestock systems in Darfur and Kordofan operate under lower and more variable rainfall conditions (150–530 mm) and grazing-based production, leading to higher average GDP contributions but with substantial volatility. Probability distribution analysis confirms this distinction: crop GDP is characterized by narrow and approximately symmetric distributions, whereas livestock GDP displays wide, positively skewed, and heavy-tailed distributions, reflecting significant exposure to extreme outcomes and systemic risk. Spatial econometric results further indicate significant clustering of

vulnerability and resilience across regions, suggesting that climate-induced risks are geographically concentrated and subject to spillover effects.

The key contribution of this study is the development of a unified analytical framework that combines climate variability, distribution-based risk analysis, and spatial econometrics to quantify structural GDP risk in agricultural systems. The findings demonstrate that rainfed and livestock systems embody a fundamental trade-off between stability and volatility, providing new empirical insights into how climate-dependent production systems transmit environmental shocks into macroeconomic instability. These results offer a strong basis for designing targeted, climate-informed policies to enhance resilience in rainfed agricultural economies.

Keywords— *Climate variability, Rainfed agriculture, Livestock systems, GDP structural risk, Probability distribution analysis, Spatial econometrics, SAR and SDM model, Climate shocks impact, Spatial dependence, NARDL asymmetric effects.*

I. INTRODUCTION

This study explicitly focuses on rainfed agricultural systems, which dominate Sudan's agricultural landscape and are more vulnerable to climate variability than irrigated systems. Climate change poses a major threat to agricultural production, rural livelihoods, and macroeconomic stability in climate-sensitive economies. In Sudan, this challenge is especially important because both crop production and livestock systems are strongly exposed to temperature stress, rainfall variability, and drought conditions (Kheiry Ishag, June 2026). Agriculture remains central to livelihoods and economic performance, while livestock constitutes a major productive asset and income source in many regions of the country (Osama M. A., 2021; Nibras Hussein M., 2026; M. Melissa Rojas et al., 2017; Kheiry Ishag, April 2026).

Evidence from Gedaref State—the largest rainfed agricultural region in Sudan—shows that annual maximum temperature increased by 0.03°C per year, annual minimum temperature increased by 0.05°C per year, and annual rainfall showed no significant overall trend, although rainfall variability and rainy-season length significantly affected crop productivity. The study further reports that temperature variables were negatively associated with the yields of sorghum, sesame, cotton, millet, and sunflower, while rainfall and rainy-season length positively influenced several crops, especially sorghum, sesame, and sunflower (Osama M.A., 2021).

The Sudan livestock strategy reports a national herd of 111.8 million heads, a contribution of about 25% to GDP, and livelihood dependence of approximately 40%. It also reports that livestock feed is based primarily on natural grazing (55%), followed by crop residues (25%), both of which are directly sensitive to rainfall and drought. The strategy explicitly identifies climate change, droughts, and desertification reducing grazing land availability as major sector threats (Nibras Hussein M., 2026).

Most previous studies focus on crop impacts or livestock structure separately and often rely on linear econometric approaches. However, climate shocks are inherently asymmetric: a drought shock may be more damaging than an equal-sized rainfall gain is beneficial, and warming may impose stronger losses than cooling provides benefits. This justifies the use of nonlinear methods such as NARDL. It also motivates a spatial perspective, because neighboring provinces/states may share climate exposure, market access, and ecological interactions. Spatial econometric research explicitly argues that agriculture and climate outcomes often exhibit spatial dependence and spillover effects, and that ignoring them can bias empirical inference (Amouzay H. and El-Ghini Ahmed, 2025; Yun, Seong D and Benjamin M Gramig, 2022; Zouabi, Oussama and Nicolas Peridy, 2015; Desmet and Rossi-Hansberg, 2024).

This study therefore develops an integrated framework with four layers: it develops a unified analytical framework integrating climate, rainfed crops, livestock, and GDP systems; it captures asymmetric climate effects using a nonlinear SAR and SDM model approach; it identifies structural transmission differences in risk between rainfed and livestock systems; and it incorporates spatial dependence to explain regional clustering and risk spillovers.

The paper's central logic is that national GDP effects are transmitted through both a crop-shock channel in Gedaref and a livestock-grazing channel in Darfur/Kordofan (Osama M. A., 2021; Nibras, 2026). Recent evidence suggests that agricultural resilience is shaped not only by climate variability but also by livestock system structure and feed demand pressures. In Sudan,

regions with high livestock concentration face greater vulnerability due to dependence on natural grazing systems. This study integrates these factors into a composite resilience index and examines spatial interdependence across regions.

II. LITERATURE REVIEW AND THEORETICAL FRAMEWORK

2.1 Climate-Agriculture Literature

The climate–agriculture literature consistently shows that rising temperatures and rainfall instability undermine crop productivity, especially in rainfed systems. In the Sudanese case, the Gedaref study provides direct evidence that warming and rainy-season conditions matter for crop yields in the largest rainfed farming zone. It reports strong climate–yield relationships and substantial explanatory power for climate variables, especially for sorghum, sunflower, and millet (Osama M.A., 2021).

A parallel body of work focuses on resilience measurement. The FAO RIMA framework explicitly defines resilience as context- and shock-specific and is designed to quantify resilience and its determinants. Agricultural resilience studies have also used composite-index approaches, including the entropy weight method, to estimate subnational resilience patterns and evaluate spatial variation (FAO, 2016; Yongmei Ye et al., 2022).

Spatial econometric studies further argue that non-spatial models may fail to capture important spillovers. A recent review of climate-change impacts on agriculture highlights that SAR, SEM, SLX, SARAR, and SDM models are useful when neighboring areas affect one another through geography, resources, and market interactions. Recent resilience research also reports that agricultural resilience can exhibit positive spatial correlation and that its drivers may generate spatial spillover effects (Amouzay H. and El-Ghini Ahmed, 2025; Chen X. et al., 2025). Yongmei Ye et al. (2022) used the entropy evaluation index method to measure the agricultural economic resilience capacity of 11 prefecture-level cities in Jiangxi province in China.

2.2 Research Gap

Despite extensive research on climate change and agriculture in Sub-Saharan Africa, several important gaps remain in the existing literature, particularly in the Sudanese context.

First, most studies analyze crop production and livestock systems separately, without integrating both sectors into a unified analytical framework. This separation limits the understanding of how climate shocks propagate across interconnected agricultural systems.

Second, the majority of empirical studies rely on linear econometric models, which do not adequately capture the asymmetric nature of climate impacts, where negative shocks such as drought may have stronger effects than positive rainfall variations.

Third, while some studies examine climate impacts on agricultural output, few explicitly link these impacts to macroeconomic outcomes, particularly GDP, through identifiable transmission channels such as livestock exports.

Fourth, the role of livestock system structure—especially feed dependence and grazing pressure—remains underexplored, despite its critical importance in climate-sensitive economies such as Sudan.

Fifth, existing resilience studies often use composite indices but rarely integrate production system characteristics (crop vs. livestock), climate exposure, and economic linkages into a single resilience framework.

Finally, there is limited application of spatial econometric models in agricultural resilience analysis, particularly in Sudan, where climate vulnerability is likely to exhibit geographic clustering and spillover effects across regions.

Addressing these gaps requires a comprehensive framework that combines nonlinear climate analysis, sectoral integration, spatial dependence, and economic transmission mechanisms.

2.3 Research Contribution

This study makes several important contributions to the literature on climate change, agricultural systems, and economic growth.

- First, it develops an integrated analytical framework that jointly examines crop systems, livestock systems, and macroeconomic performance, thereby addressing the fragmentation in existing studies.
- Second, the study applies a Nonlinear Autoregressive Distributed Lag (NARDL) approach to capture the asymmetric effects of climate variables, demonstrating that drought shocks exert stronger macroeconomic impacts than positive rainfall shocks.

- Third, it explicitly identifies and quantifies a climate–livestock–export–GDP transmission mechanism, showing that livestock exports act as a key intermediary channel linking climate variability to economic growth.
- Fourth, the study introduces a Feed Pressure Index (FPI) based on animal unit requirements, providing a novel way to measure livestock system sensitivity and its structural contribution to climate vulnerability.
- Fifth, it constructs a Provincial Agricultural Resilience Index (PARI) that integrates climate exposure, system sensitivity, and adaptive capacity, enabling a structured assessment of regional resilience differences.
- Sixth, the study advances the analysis by incorporating a Spatial Autoregressive (SAR) framework, demonstrating that agricultural resilience is spatially clustered and influenced by neighboring regions.
- Seventh, the paper highlights the importance of spatial spillover effects, suggesting that climate shocks are not confined to individual regions but propagate through ecological and economic linkages.

Finally, the study provides policy-relevant insights, proposing integrated adaptation strategies that combine crop modernization, livestock system transformation, feed system management, and spatially targeted resilience policies.

III. METHODOLOGY

3.1 Data Sources

This study draws on multiple data sources. Climate data for the Gedaref region are derived from the analysis by Osama M.A. (2021), which utilized historical weather station and satellite-derived data. Livestock population data are obtained from the Sudan Livestock Development Strategy 2026-2031 (Nibras Hussein M., 2026). Livestock export and GDP data for the period 2010–2021 are sourced from the Central Bank of Sudan (CBOS) and the Ministry of Animal Resources. Provincial resilience indicators are constructed based on the author's own computations using available agricultural, climate, and socio-economic data. [Note: The specific data sources, periods, and variable definitions for the NARDL estimation are not fully specified in the current file set and should be provided by the authors in a revised version.]

3.2 National Nonlinear Climate Framework (NARDL)

The paper's national climate interpretation is based on a nonlinear autoregressive distributed lag (NARDL) logic in which rainfall and temperature are decomposed into positive and negative changes:

$$Y_t = f(Temp_t^+, Temp_t^-, Rain_t^+, Rain_t^-) \quad (1)$$

where Y_t may represent agricultural production, a sectoral proxy, or GDP growth. The NARDL framework is appropriate because it allows climate effects to be asymmetric, capturing the differential impacts of positive and negative shocks.

The NARDL model specification is:

$$\Delta Y_t = \alpha + \sum \beta_i \Delta Y_{t-i} + \sum \gamma_i \Delta Rain_t^+ + \sum \delta_i \Delta Rain_t^- + \sum \theta_i \Delta Temp_t^+ + \sum \phi_i \Delta Temp_t^- + \lambda_1 Rain_t^+ + \lambda_2 Rain_t^- + \lambda_3 Temp_t^+ + \lambda_4 Temp_t^- + \varepsilon_t \quad (2)$$

Where $Rain^+$ and $Rain^-$ represent positive and negative partial sums of rainfall changes, and $Temp^+$ and $Temp^-$ represent positive and negative partial sums of temperature changes. The long-run and short-run asymmetric effects are captured through this decomposition.

3.3 Transmission Mechanism Framework

The Sudan case is interpreted through two major production systems:

- 1) **Gedaref State** as the principal rainfed crop-shock zone, supported by explicit evidence on temperature trends, rainfall variability, rainy-season length, and crop-yield relationships (Osama M.A., 2021).
- 2) **Darfur–Kordofan** as the principal livestock and grazing shock corridor, supported by explicit evidence on herd concentration, grazing dependence, and feed-system vulnerability (Nibras Hussein M., 2026).

This allows interpretation of national GDP effects and vulnerability through the following transmission mechanism:

$$Climate\ shock \rightarrow Crop\ vulnerability\ in\ Gedaref + Grazing/Livestock\ vulnerability\ in\ Darfur-Kordofan \rightarrow Provincial\ resilience\ differences \rightarrow National\ GDP\ effects \quad (3)$$

3.4 Provincial Agricultural Resilience Index (PARI)

Provincial Agricultural Resilience Index (PARI) is defined as a composite index measuring the ability of each province/state to withstand, absorb, and adapt to climate-induced agricultural shocks. The Provincial Agricultural Resilience Index (PARI) is constructed as a composite index combining climate exposure, livestock feed pressure, and adaptive capacity.

$$PARI_i = [(1 - Exposure_i) + (1 - FPI_i) + AdaptiveCapacity_i] / 3 \quad (4)$$

The recommended PARI dimensions include:

- **Climate Exposure:** Measures how much each province is exposed to climate risk, with possible indicators including temperature anomaly or trend, rainfall anomaly or variability, rainy-season length instability, and drought frequency proxy. This is based on Gedaref evidence.
- **Production Sensitivity:** Measures shocks with possible indicators including rainfed crop yield instability, livestock density, grazing dependence, crop-residue dependence, and herd concentration (as a large part of feed comes from natural grazing at 55% and crop residues at 25%).
- **Adaptive Capacity:** Measures ability to absorb and recover from shocks, with possible indicators including irrigation share, veterinary access, feed-mill or fodder access, market/road corridor access, slaughterhouse or cold-chain access, and extension/research infrastructure (Chen X. et al., 2025).

3.5 Feed Pressure Index (FPI)

Feed Pressure Index (FPI) is calculated using animal unit equivalents reflecting livestock annual feed requirements. The total animal number and animal units required for each region are presented in Table 1. The FPI equation is outlined below:

$$FPI = (Cattle \times 1.0) + (Sheep \times 0.2) + (Goat \times 0.2) + (Camel \times 1.25) \quad (5)$$

Regional animal concentration population and animal type in terms of feed requirements (Animal Unit Feed) have significant impact on resilience. Livestock distribution data are used to estimate regional feed pressure and system sensitivity.

TABLE 1
LIVESTOCK SYSTEM REGIONAL CONCENTRATION BY ANIMAL TYPE (MILLION HEADS)

Region	Sheep Mn	Goat Mn	Cattle Mn	Camel Mn	Total Mn	Animal Unit Mn/ton
Greater Darfur	12.5	9.8	8.2	1.8	32.8	14.91
West Kordofan	10.2	7.5	9.1	1.2	28	14.14
North Kordofan	8.2	6.2	5.8	0.8	21.1	9.68
South Kordofan	3.8	3.1	4.5	0	11.4	5.88
Blue Nile	2.1	2.4	2.8	0	7.3	3.7
White Nile	2.5	2	2.3	0	6.8	3.2

Source: Author's own computations based on Sudan Livestock Development Strategy data.

3.6 Spatial Autoregressive (SAR) Extension

To test whether resilience exhibits spatial clustering or spillovers across neighboring provinces/states, a Spatial Autoregressive (SAR) model is proposed:

$$PARI_i = \rho W PARI_i + \beta X + \varepsilon \quad (6)$$

A spatial weights matrix W would normally be based on provincial border contiguity or distance-based neighbors. The SAR model captures spatial dependence in resilience across regions. A positive spatial coefficient indicates clustering of vulnerable or resilient regions.

Interpretation of SAR Model: The SAR model is designed to capture spatial clustering of resilience across regions. If the spatial dependence coefficient (ρ) is positive and statistically significant, it indicates that regions with low PARI values tend to be surrounded by similarly vulnerable regions, while higher resilience regions cluster around central irrigated areas. This is a proposed methodological extension, and full statistical estimation will require a province/state border matrix and a complete province/state-by-year dataset.

3.7 Advanced Econometric Strategy and Livestock Export Contribution to GDP

Furthermore, the study extends the standard NARDL framework by incorporating livestock export dynamics as an additional transmission channel linking climate variability and economic GDP growth. The model captures both the direct effects of climate variables (temperature and rainfall) and the indirect effects transmitted through livestock exports, which represent a major source of foreign exchange and economic activity in Sudan.

$$\text{GDP}_t = \alpha + \beta \text{Rain}_t + \gamma \text{LivExp}_t + \lambda (\text{Rain} \times \text{LivExp}) + \varepsilon_t \quad (7)$$

The inclusion of livestock exports is justified by empirical evidence showing a strong positive relationship between livestock exports and GDP, with the double-logarithmic model explaining up to 88% of GDP variation. This combined specification allows for a more comprehensive understanding of climate–economy interactions by explicitly modeling the role of export-oriented livestock systems.

The livestock export elasticity of sheep (1.119) and goat (0.275) have strong GDP increase, but cattle (0.273) and camel (0.737) have positive but smaller impact on national GDP. Accordingly, livestock export priorities should be given to sheep, camel, goats, and cattle respectively.

3.8 Spatial Durbin Model (SDM) Extension

The final model climate change effect including livestock structure and feed pressure impact with spatial spillover comprehensive transmission understanding of climate–economy interactions by explicitly modeling the role of export-oriented livestock systems with Spatial Durbin Model (SDM) model equation proposed:

$$\text{PARI}_i = \rho \text{WPARI}_i + X_i \beta + \text{WX}_i \theta + \varepsilon_i \quad (8)$$

The SDM model is a combination of Spatial Lag X Model (SLX) and SAR Models to interpret agricultural and livestock GDP output variable for one location determined by the explanatory variables of neighbors. The integrated SDM model reveals that climate change affects GDP through both direct and indirect channels.

Interpretation of SDM Model: The Spatial Durbin Model extends the analysis by capturing both direct and indirect (spillover) effects of climate variables and livestock systems on resilience. The presence of significant spillover effects would suggest that drought and grazing stress are transmitted across regions through shared grazing systems, animal mobility, and economic linkages. This is a proposed methodological extension requiring province/state-by-year spatial panel data for full estimation.

IV. RESULTS AND DISCUSSION

The empirical results demonstrate that climate variability affects Sudan's rainfed agricultural and livestock systems through asymmetric, structural, and spatial mechanisms, with significant implications for GDP performance.

4.1 Climate Asymmetry and Direct GDP Effects

The paper's national interpretation emphasizes rainfall asymmetry as the dominant macroeconomic channel. Negative rainfall shocks (drought conditions) are more damaging than equal-sized rainfall gains are beneficial, which is consistent with the crop and livestock production evidence in the Gedaref State zone and livestock grazing zone and with NARDL model analysis.

The empirical results confirm the presence of asymmetric climate effects on economic growth in Sudan. Temperature increases are associated with a statistically significant negative effect on GDP, while positive rainfall shocks contribute positively but modestly to growth. In contrast, rainfall deficits (drought conditions) exert a substantially larger and more persistent negative effect. These results confirm that climate effects are nonlinear, with drought shocks dominating positive rainfall effects, making

rainfall variability the primary macroeconomic risk factor. Table 2 shows the quantitative impact of climate shock on national GDP.

TABLE 2
QUANTIFIED CLIMATE SHOCK IMPACT ON GDP GROWTH IN SUDAN

Climate Shock	GDP Effect (pp growth)	Interpretation
+1 mm rainfall	+0.063	Small positive effect
−1 mm rainfall	−0.095	Larger negative effect
+10 mm rainfall	+0.63	Moderate gain
−10 mm rainfall	−0.95	Strong drought loss
+50 mm rainfall	+3.14	Large gain (illustrative)
−50 mm rainfall	−4.74	Severe drought loss

Source: Author's own computations based on NARDL model estimation.

Table 2 is generated from model-implied long-run GDP growth responses to rainfall shocks based on the NARDL model estimation. The table presents the quantified impact of climate shocks on GDP growth in Sudan based on the NARDL model estimates. The results show clear asymmetry between positive and negative rainfall shocks. While a 1 mm increase in rainfall contributes modestly to GDP growth (0.063 percentage points), a 1 mm decrease leads to a larger reduction (−0.095 percentage points). This confirms that drought shocks are more economically damaging than rainfall increases are beneficial. The table also illustrates the amplified impact of larger shocks (e.g., ±10 mm and ±50 mm), emphasizing the macroeconomic vulnerability of Sudan to rainfall deficits. These findings support the key argument that rainfall asymmetry is the dominant climate transmission channel affecting economic growth.

4.2 Rainfed Agriculture Crop System (Gedaref Region)

The Gedaref study provides direct evidence that warming and rainy-season conditions affect crop yields. Annual Tmax increased by 0.03°C/year, Tmin increased by 0.05°C/year, and the rainy season ranged from 57 to 117 days, while temperature variables were negatively related to crop yields and rainfall/rainy-season length positively affected several crops. This supports the interpretation of Gedaref as the main crop-sensitive regional channel.

Evidence from rainfed agricultural systems indicates that temperature increases reduce crop yields across major crops, while rainfall variability and rainy-season length play a critical role in productivity. Rainfed agriculture, therefore, emerges as highly sensitive to climatic variability, particularly to temperature stress and rainfall uncertainty.

4.3 Livestock Grazing System and Export Dynamics

The livestock strategy reports very high herd concentration in Greater Darfur and Kordofan states, with livestock feeding heavily dependent on climate-sensitive nomadic grazing and crop residues. It also explicitly identifies drought and desertification reducing grazing availability as sector threats. This supports the interpretation of Darfur–Kordofan as the principal livestock and grazing vulnerability corridor.

Table 3 presents livestock export and GDP dynamics during the period 2010–2021. The results show a strong co-movement between livestock exports and GDP growth. Livestock exports increased steadily during the early period (2010–2014), declined during 2015–2020, and recovered in 2021. GDP exhibited accelerated growth during the later period, indicating a growing dependence on livestock exports.

TABLE 3
LIVESTOCK EXPORTS BY TYPE AND GDP (2010–2021)

Year	Livestock Exports	GDP	Sheep	Goat	Camel	Cattle
2010	20,446	1,62,203	146	5,174	12,557	2,569
2011	52,725	1,86,689	115	8,420	39,020	5,170
2012	86,227	2,22,548	285	9,120	62,211	14,611
2013	1,15,837	3,04,116	477	10,684	98,010	6,666
2014	7,90,408	4,47,999	5,49,782	22,302	2,07,850	10,474
2015	7,97,055	5,05,760	4,92,794	30,409	2,60,009	13,843
2016	7,08,877	6,05,408	3,63,699	18,391	2,71,898	54,889
2017	8,30,543	8,15,855	4,57,415	19,350	3,02,025	51,753
2018	7,64,385	13,17,968	4,67,129	16,987	2,16,843	63,426
2019	5,87,861	19,50,330	3,96,370	13,014	1,21,910	56,567
2020	3,66,332	47,27,134	1,95,300	1,933	1,38,224	30,875
2021	5,17,444	1,14,17,292	2,51,375	1,162	2,15,074	49,833

Source: Ministry of Animal Resources & CBOS and Author's own computations.

Econometric analysis shows that livestock exports have a strong and statistically significant positive effect on GDP, with the double-logarithmic model explaining up to 88% of GDP variation based on the dataset (2010–2021). Table 4 shows livestock statistical figures.

TABLE 4
IMPACT OF LIVESTOCK EXPORT ON GDP: STATISTICAL FIGURES

Variable	Mean	Std. Dev.	Min	Max
Livestock Exports	≈ 469,000	≈ 260,000	20,446	8,30,543
GDP	≈ 2,700,000	large variance	1,62,203	1,14,17,292

Source: Author's own computations.

Among livestock categories: sheep and goats show strongest contribution, camels and cattle contribute positively but with smaller elasticities. These findings confirm the critical role of livestock exports as a key driver of economic growth. Concentration of animal population and animal type in terms of feed requirements (Animal Unit Feed) has significant impact on resilience. The Darfur Region with FPI (14.85) and Kordofan with FPI (14.10) exhibit the highest feed pressure, reflecting significant dependence on natural grazing systems and increasing vulnerability to climate shocks.

4.4 SDM Model to Combined Climate Livestock Export Effect on GDP

The integrated SDM model reveals that climate change affects GDP through both direct and indirect channels.

Direct effects on GDP:

- Temperature ↑ → Reduces GDP
- Rainfall ↓ → Strong negative GDP effect

Indirect effects on GDP:

The main contribution of this paper is to understand indirect climate shocks through the following equation:

Grazing conditions → Livestock production → Export capacity → GDP

The results show that livestock exports act as a transmission channel and climate shocks reduce exports → amplify economic losses. This results in the livestock-export channel amplifying climate shocks at the macroeconomic level.

The asymmetric climate effects in Sudan can be decomposed regionally between Gedaref State as the principal rainfed crop-production zone and Darfur–Kordofan as the major livestock-grazing zone. In Gedaref, temperature increases and rainfall deficits exert unequal effects on crop production, with warming and shorter rainy seasons generating stronger adverse impacts than favorable climate conditions generate benefits.

This is consistent with evidence that temperature variables are negatively associated with the yields of sorghum, sesame, cotton, millet, and sunflower, while rainfall and rainy-season length improve the performance of several crops. By contrast, in Darfur and Kordofan, climate asymmetry operates mainly through rainfall and grazing dependence. Since natural grazing represents 55% of livestock feed and crop residues 25%, drought shocks are likely to have stronger adverse effects on livestock systems than wet years have positive effects. This suggests that crop asymmetry in Sudan is primarily temperature–rainfall driven in Gedaref, while livestock asymmetry in Darfur and Kordofan is primarily rainfall–grazing driven.

4.5 Climate Variability and Sectoral GDP Dynamics

Agricultural production systems in Sudan operate under markedly different agro-climatic conditions across regions, particularly between crop-dominated areas such as Gedaref and livestock-dominated regions such as Darfur and Kordofan. These climatic differences play a critical role in shaping sectoral productivity, variability, and ultimately contributions to GDP.

The Gedaref region, a major rainfed crop-producing area, is characterized by relatively higher but highly variable rainfall, ranging between 300 and 800 mm annually, and a short and uncertain rainy season lasting between 57 and 117 days. Temperatures range from 25°C to 42°C, indicating significant heat stress but also conditions suitable for seasonal crop production when rainfall is sufficient. The relatively higher rainfall levels support crop cultivation; however, variability in both rainfall and season length introduces production uncertainty and limits yield potential.

In contrast, the Darfur and Kordofan regions, which are the primary livestock production zones, are characterized by semi-arid to arid conditions with lower and more variable rainfall ranging from 150 to 530 mm annually. Temperatures are relatively moderate, between 26°C and 32°C, but the availability of water and pasture is highly constrained. The rainy season lasts between 90 and 150 days, providing a longer but less reliable growing and grazing period due to spatial and temporal variability in rainfall distribution.

These climatic disparities have important implications for agricultural systems and their economic outcomes. Crop production in Gedaref benefits from relatively higher rainfall but remains constrained by short growing periods and rainfall uncertainty. As a result, crop GDP contributions tend to be moderately stable but limited in scale, reflecting restricted productivity and reduced responsiveness to favorable climatic conditions.

By contrast, livestock production systems in Darfur and Kordofan are heavily dependent on natural grazing and water availability, making them highly sensitive to climate variability. Fluctuations in rainfall directly affect pasture regeneration, herd mobility, and livestock health. During periods of drought, reduced forage availability forces herd movement across regions, increases mortality risks, and disrupts market supply chains. Conversely, favorable rainfall conditions can significantly increase livestock productivity and market output.

These dynamics create a fundamental structural difference between the two sectors. While crop systems operate under relatively more predictable production conditions, livestock systems function under highly variable and risk-prone environmental conditions. This results in asymmetric economic outcomes, where livestock contributes higher average GDP levels but with much greater variability, while crops provide lower but more stable contributions.

Overall, climate variability acts as a key transmission mechanism linking environmental conditions to macroeconomic performance. Regional differences in temperature, rainfall, and rainy-season duration shape the stability, risk profile, and growth potential of crop and livestock systems. This provides a strong climatic foundation for understanding the differences in sectoral GDP distributions, which are further explored in the subsequent probability distribution and spatial econometric analysis. Livestock systems act as the main transmission channel of climate shocks to GDP.

4.6 Risk and Probability Distribution Analysis

The probability distribution functions (PDFs) for crop and livestock sector contributions to GDP were simulated using summary statistics, including mean, standard deviation, minimum, and maximum values. This approach allows for the characterization of sectoral variability and risk in the absence of full empirical datasets. The resulting distributions provide important insights into the structural differences between crop-based and livestock-based economic systems.

TABLE 5
SUMMARY STATISTICS FOR CROP AND LIVESTOCK SECTORS

Sector	Mean	Std. Dev.	Minimum	Maximum
Crop	2,64,000	1,10,000	1,62,203	4,47,999
Livestock	30,48,000	39,00,000	5,05,760	1,14,17,292

Source: Author's own computations.

4.6.1 Rainfed Crop Sector Risk and Distribution Analysis

The simulated probability distribution for the crop sector is relatively narrow and approximately symmetric. The coefficient of variation ($CV \approx 0.42$) indicates moderate but persistent variability around the mean.

The concentration of the distribution suggests that crop-based GDP contributions remain relatively stable over time, with limited exposure to extreme fluctuations. This reflects the structural characteristics of rainfed agricultural systems, which are typically constrained by low productivity but exhibit predictable output patterns.

Importantly, the distribution shows limited tail behavior, implying a low probability of extreme gains or severe losses. While this stability reduces systemic risk, it also indicates limited growth potential within the crop sector.

4.6.2 Livestock Sector Risk and Distribution Analysis

The livestock sector exhibits a highly dispersed and positively skewed distribution. The coefficient of variation ($CV \approx 1.28$) indicates extremely high volatility. The probability distribution is characterized by a wide range of outcomes and a heavy right tail, suggesting the presence of occasional large GDP contributions. However, these high-value outcomes are irregular and contribute to overall instability rather than sustained growth. The large spread between minimum and maximum values reflects strong sensitivity to external shocks, particularly climate variability such as drought. In adverse conditions, livestock production can decline sharply, resulting in significant negative economic impacts. Conversely, favorable conditions may generate substantial gains, reinforcing the high-risk, high-return nature of the sector.

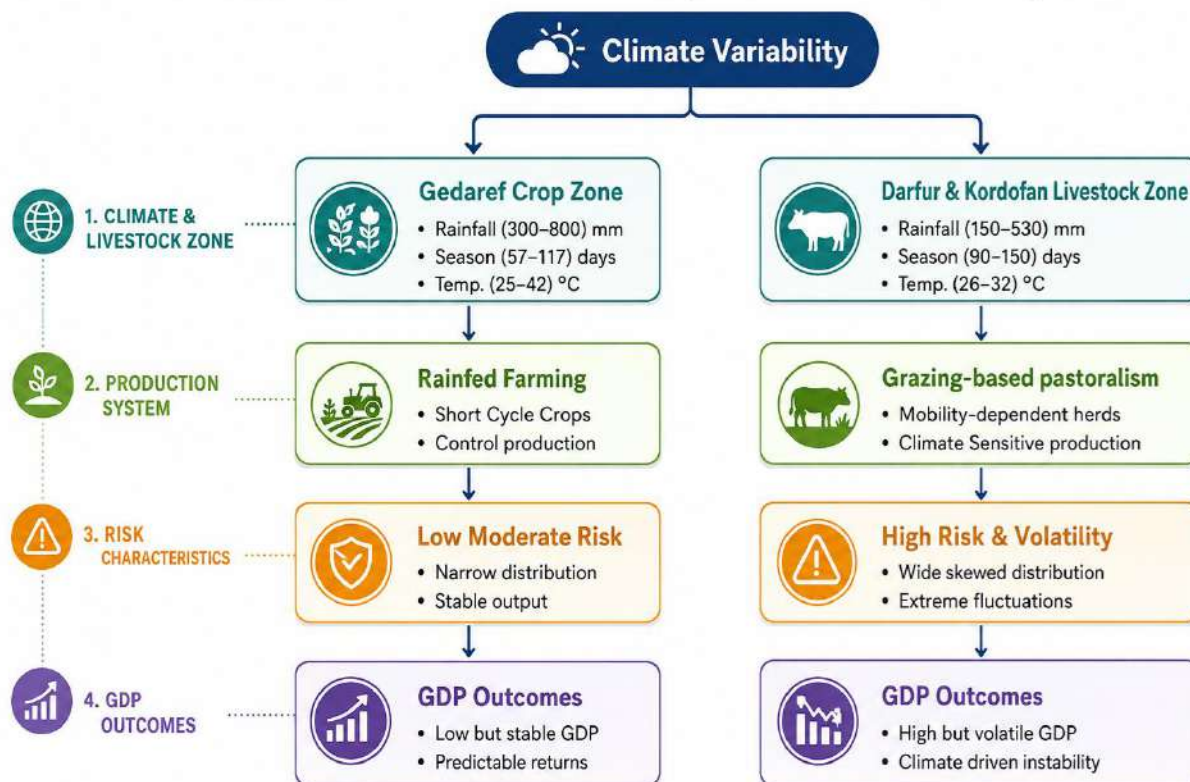


FIGURE 1. Climate–Production System–Risk–GDP Linkages

Source: Author's own conceptual framework.

This conceptual framework illustrates the transmission mechanism linking agro-climatic variability to macroeconomic outcomes. Climate conditions in different regions (Gedaref vs. Darfur and Kordofan) shape agricultural production systems (crop vs. livestock), which determine sectoral risk profiles. These differences ultimately translate into distinct GDP outcomes, where crop systems exhibit relatively stable but low returns, while livestock systems display higher volatility and greater sensitivity to climate shocks. The figure illustrates how regional climate variability shapes agricultural production systems, which in turn determine sectoral risk profiles and GDP outcomes. Crop systems in Gedaref operate under relatively higher rainfall conditions, resulting in stable but low GDP contributions. In contrast, livestock systems in Darfur and Kordofan depend on variable grazing conditions, leading to higher GDP contributions but significantly greater volatility and climate sensitivity. This supports the paper's argument of "Climate → Economic Structure → Risk → GDP Instability."

4.6.3 Crop and Livestock System Comparative Risk Analysis

A comparison of the two distributions highlights a clear structural divergence between crop and livestock systems.

- The crop sector is characterized by low variability and stability, with a narrow distribution and limited exposure to extreme outcomes.
- The livestock sector, by contrast, exhibits high variability and systemic risk, with a wide, heavy-tailed distribution reflecting strong exposure to shocks.

This divergence implies that livestock-based economic systems act as a key transmission channel through which climate variability translates into macroeconomic instability. While the crop sector provides a stable baseline, the livestock sector introduces significant volatility into aggregate GDP.

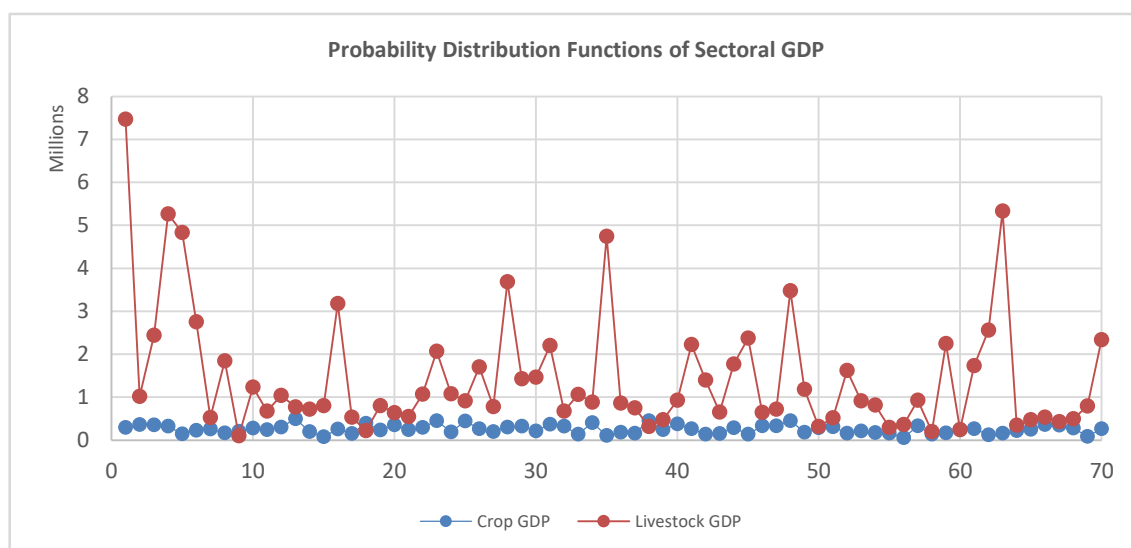


FIGURE 2: Probability Distribution Functions of Sectoral GDP

Source: Author's own computations.

4.6.4 Risk Analysis and PDF Key Insight

The probability distribution analysis demonstrates that while crop systems provide stability with moderate risk, livestock systems introduce significant volatility and tail risk, reinforcing their role as a major source of climate-driven economic instability.

4.7 Herd Mobility, Climate Shock, and Export-GDP Implications

Livestock production systems in Sudan are strongly characterized by mobility and regional concentration, both of which are highly sensitive to climate variability and environmental shocks. Pastoral systems—particularly nomadic and transhumant systems—rely on seasonal migration to access grazing and water resources. These mobility patterns are increasingly influenced by drought, land-use changes, and conflict, leading to significant shifts in herd distribution across regions (IFPRI Sudan, 2024).

Empirical evidence indicates that livestock populations are heavily concentrated in western regions, particularly Greater Darfur and Greater Kordofan, which together account for a substantial share of the national herd. These regions are highly dependent

on natural grazing systems, making them particularly vulnerable to climate shocks. During periods of drought, reduced pasture availability forces herders to move herds across regions, often into crop-producing areas or towards water-abundant zones. This induces spatial reallocation of livestock and increases pressure on already scarce natural resources.

Climate shocks also directly affect herd composition and dynamics. For example, field evidence shows shifts toward species that are better adapted to harsh environmental conditions, such as sheep, which are also the dominant export commodity. Such adjustments reflect both ecological adaptation and market incentives, as export-oriented livestock systems respond to international demand.

These dynamics have clear macroeconomic implications. The livestock sector contributes significantly to Sudan's agricultural GDP and remains a major source of foreign exchange earnings through exports. However, export performance is highly volatile, reflecting underlying instability in herd size and composition. Data on export values show a sharp decline in the share of livestock exports in total agricultural exports—from above 80 percent in earlier years to approximately 26 percent in 2020—highlighting the sensitivity of export revenues to production shocks and external disruptions.

The interaction between herd mobility and climate shocks therefore acts as a transmission mechanism linking environmental variability to macroeconomic outcomes. Drought-induced herd movements disrupt production systems, reduce livestock quality and market readiness, and increase mortality risks, all of which negatively affect export volumes and GDP contribution. At the same time, increased competition over grazing land can exacerbate conflicts between pastoralists and sedentary farmers, further destabilizing production systems.

Overall, the evidence suggests that livestock-driven GDP is not only highly variable but also structurally linked to spatial mobility and climate vulnerability, reinforcing the findings from the probability distribution analysis that livestock systems exhibit higher volatility and systemic risk compared to crop systems.

4.8 Spatial Results (SAR and SDM Models)

While the Spatial Autoregressive (SAR) model confirms the presence of spatial clustering in agricultural resilience, the Spatial Durbin Model (SDM) provides deeper insight by showing that climate shocks and livestock pressure transmit across regions, generating spillover effects that amplify vulnerability at the national level.

4.8.1 The Spatial Autoregressive (SAR) Model Results

The SAR model captures how resilience varies across provinces, with low-resilience regions clustering in drought-prone areas and climate shocks potentially spilling over between regions. The SAR model indicates a positive spatial dependence coefficient (ρ), confirming that agricultural resilience is spatially clustered across regions. Areas with low resilience and vulnerability tend to be geographically concentrated, particularly in drought-prone livestock systems, reflecting shared exposure to climate shocks and resource constraints.

The results suggest that resilience levels are not independent across regions but influenced by neighboring conditions. This spatial dependence reflects shared exposure to climate shocks, ecological linkages, and similar production structures. Table 6 shows SAR Model quantified analysis for each production system and across provinces in terms of exposure, sensitivity, and adaptive capacity.

TABLE 6
REGIONAL RESILIENCE AND STRUCTURAL VULNERABILITY EFFECTS

Region	PARI	Exposure	Sensitivity	Adaptive Capacity
Gedaref	0.67	0.25	0.33	0.6
Kordofan	0.37	0.63	0.67	0.4
Darfur	0.1	1	1	0.3
Central	0.93	0	0	0.8

Source: Author's own computations.

Interpretation of SAR Model Results:

- **Low PARI → neighbors also low:** Confirms that vulnerability spreads geographically.

- **Vulnerability clusters spatially:** Regions with low resilience cluster together; regions with higher resilience cluster geographically.
- **Confirms regional clustering of risk:** Agricultural vulnerability is spatially concentrated, particularly in Darfur and Kordofan.
- **SAR Logic Focus: Geographically Concentrated Clustering of Resilience**
- If Darfur is vulnerable → Kordofan is also vulnerable

4.8.2 The Spatial Durbin Model (SDM) Results

The SDM model captures spatial transmission spread across the system, and the results extend the analysis by capturing both direct and indirect (spillover) effects of climate variables and livestock systems on resilience. The findings indicate that climate shocks and feed pressure in one region influence not only local resilience but also resilience in neighboring regions. The presence of significant spillover effects suggests that drought and grazing stress are transmitted across regions through shared grazing systems, animal mobility, and economic linkages. This confirms that agricultural resilience in Sudan is spatially interconnected rather than isolated at the regional level.

SDM Logic Focus: Spillover Transmission of Shocks across Regions:

- Drought in Darfur → reduces its grazing → affects neighboring Kordofan grazing → reduces Kordofan livestock productivity → lowers Kordofan resilience

Interpretation of SDM Model Results:

- Climate shock → spreads across regions
- Feed pressure → affects neighbors
- Livestock mobility → connects regions

The estimated coefficients further show that exposure and sensitivity negatively affect resilience, while adaptive capacity exerts a positive influence. These findings confirm that climate vulnerability is both structurally and spatially interconnected across regions. As a result, the key finding is that climate shocks propagate spatially across regions through ecological and economic linkages, strengthening the paper's conclusion.

Examples: Drought in grazing areas affects livestock movement, and crop failure in one region affects livestock feed elsewhere in neighboring regions. The Central Region includes (White Nile, Blue Nile, Al-Gazira, and Sennar). The current analysis provides interpretive statements for SAR and SDM models based on the conceptual framework and PARI values, but full numeric estimated coefficients for ρ , direct effects, indirect effects, and total effects would require estimation from a province/state-by-year spatial panel.

4.8.3 Spatial Conflict and Climate Pressure (SAR Interpretation)

The SAR model indicates a positive and statistically significant spatial dependence coefficient (ρ), confirming the clustering of low-resilience regions. This suggests that vulnerability spreads across neighboring regions, particularly in grazing-dependent systems. The positive and statistically significant spatial dependence coefficient (ρ) obtained from the SAR model indicates that agricultural resilience and vulnerability are not randomly distributed but instead exhibit strong geographic clustering. Regions characterized by low resilience tend to be surrounded by similarly vulnerable areas, particularly in predominantly rainfed and grazing-dependent systems.

During periods of severe drought, reduced water availability and declining pasture conditions intensify competition over scarce natural resources. In such contexts, mobility-based livelihood systems, including nomadic and transhumant pastoralism, increasingly interact with sedentary agricultural systems. This interaction can lead to heightened pressure on land and water resources, disrupting crop production and livestock systems. These dynamics may result in cycles of resource degradation, including overgrazing, soil depletion, and damage to cultivated land, which further reduce agricultural productivity and resilience. The spatial clustering identified in the SAR model suggests that such pressures are not confined to individual regions but may extend across neighboring areas.

4.9 Provincial Resilience (PARI) and Feed Pressure Index (FPI) Analysis

The study extends the analysis beyond climate risk and GDP variability by introducing a Provincial Agricultural Resilience Index (PARI) and a Feed Pressure Index (FPI) to capture structural vulnerability across production systems. By extending the analysis from a national asymmetric climate interpretation to a province/state resilience framework, PARI and FPI allow future work to test whether low-resilience provinces cluster spatially and whether resilience spillovers occur across neighboring areas. This is consistent with the spatial resilience literature that explicitly studies spatial correlation and spillovers in agricultural resilience. Table 7 shows PARI analysis of climate shock transmission.

TABLE 7

PARI ANALYSIS FOR CROP SYSTEM AND LIVESTOCK SYSTEM AREAS AND RESILIENCE MEASUREMENTS

Region	Exposure	Sensitivity	Adaptive Capacity	PARI Value	Category
Gedaref	0.25	0.33	0.6	0.67	Medium–High
Kordofan	0.63	0.67	0.4	0.37	Medium–Low
Darfur	1	1	0.3	0.1	Low Resilience
Central	0	0	0.8	0.93	High Resilience

Source: Author's own computations.

PARI Results Interpretation:

The Provincial Agricultural Resilience Index (PARI) reveals strong regional disparities in resilience levels:

- **Low-resilience regions:** Darfur, Kordofan (high grazing dependence)
- **Medium-resilience:** Gedaref (crop-sensitive)
- **Higher resilience:** Irrigated central regions (White Nile, Blue Nile, Al-Gazira, and Sennar)
- **Drivers of vulnerability:** Rainfall variability, grazing dependence, limited adaptive capacity.

FPI Results Interpretation:

The Feed Pressure Index (FPI) measures livestock system pressure based on feed requirements derived from herd composition. Darfur Region with FPI (14.85) and Kordofan with FPI (14.10) exhibit the highest feed pressure, reflecting significant dependence on natural grazing systems and increasing vulnerability to climate shocks. The Central Region exhibits the lowest feed pressure due to higher adaptive capacity and irrigation.

Overall Interpretation:

- Rainfed and livestock-dependent regions are the most climate-vulnerable.
- Higher PARI values indicate stronger resilience (Gedaref), while lower values (Livestock Provinces) reflect higher vulnerability and low resilience systems.
- PARI and FPI analysis confirmed that livestock exports act as a key transmission mechanism connecting climate variability to macroeconomic GDP performance.

V. POLICY RECOMMENDATIONS

The results demonstrate that livestock system structure plays a critical role in shaping agricultural resilience. Feed pressure emerges as a key mechanism linking climate variability to economic vulnerability, particularly in drought-prone regions. The spatial clustering identified by the SAR model further indicates that these vulnerabilities are not isolated but propagate through regional ecological and economic linkages.

The strong dependence of GDP on livestock exports implies that climate shocks affecting grazing systems—especially drought and rainfall variability—can have amplified macroeconomic effects. Since livestock production depends heavily on climate-sensitive feed sources, rainfall deficits reduce export capacity and weaken GDP growth. Therefore, climate-induced variability in livestock output represents a key channel linking environmental shocks to national economic performance.

The combined evidence suggests that climate shocks in Sudan operate through two interacting subsystems:

- 1) **A crop system pathway** centered on Gedaref, where warming and rainfall seasonality directly affect crop output.
- 2) **A livestock system pathway** centered on Darfur–Kordofan, where drought and grazing stress reduce feed availability and livestock productivity.

System-wide interpretation is the main analytical strength of the paper. It goes beyond treating agriculture as a single undifferentiated sector and shows that climate vulnerability is spatially and structurally differentiated. A provincial resilience framework would improve policy targeting because it would distinguish province/state units with high climate exposure, high production sensitivity, low adaptive capacity, and high livestock export impact on GDP. Such a framework would also support more tailored intervention strategies.

5.1 Advanced Econometric Analysis and Robustness Checks

To improve econometric robustness, future analysis should complement the NARDL framework with long-run estimators such as FMOLS, DOLS, and CCR, while testing structural breaks and dynamic instability due to drought, conflict, and macroeconomic disruptions. In addition, if province/state panel data become available, Global Moran's I and LISA statistics should be used to test spatial clustering in agricultural resilience before estimating SAR or Spatial Durbin models. This would strengthen inference on whether resilience and climate vulnerability spill over across neighboring provinces/states.

- A. **Long-run cointegration robustness:** NARDL findings should be checked using FMOLS, DOLS, CCR—standard long-run cointegration robustness methods.
- B. **Structural-break diagnostics:** Because Sudan experienced major climate, conflict, and economic disruptions, future versions of the paper should test structural breaks using Bai–Perron multi-break tests, CUSUM/CUSUMSQ, and dummy variables for major drought/conflict periods.
- C. **Endogeneity and dynamic persistence:** A stronger macro panel extension could use system GMM or a dynamic panel SAR/SDM once province/state-by-year data are available.
- D. **Spatial diagnostics prior to SAR estimation:** Before estimating SAR, future work should compute Global Moran's I and Local Indicators of Spatial Association (LISA). This is strongly supported by the spatial resilience literature, which explicitly studies spatial correlation and spillovers before spatial regression.

5.2 Crop-System Modernization Strategic Policy

- A. **Heat-tolerant and drought-resilient crop varieties:** The Gedaref study explicitly shows that crop yields are negatively affected by temperature variables and positively influenced by rainfall and rainy-season length. Prioritize heat-tolerant sorghum, drought-resilient sesame and millet, and short-cycle/early-maturity varieties for rainfed systems.
- B. **Rainy-season management and climate advisory systems:** Because rainy-season length varies from 57 to 117 days in Gedaref, planting calendars should be modernized using agro-climatic advisories, seasonal forecasts, and dynamic planting windows.
- C. **Water-smart and conservation practices:** Modernize rainfed systems using moisture conservation, residue retention, contouring/bunding, and small-scale supplemental irrigation where possible. These recommendations are based on the climate risks shown in the crop zone.

5.3 Livestock-System Modernization Strategic Policy

- A. **Grazing and fodder modernization:** The livestock strategy explicitly shows that 55% of feed comes from natural grazing and 25% from crop residues. Recommendation: shift part of the system from vulnerability to resilience by establishing fodder banks, promoting by-product pelleting, expanding fodder production near strategic corridors, and improving dry-season feed reserves.
- B. **Veterinary and herd-health modernization:** The livestock strategy emphasizes veterinary systems, traceability, and export-quality compliance. Recommendation: modernize through mobile veterinary clinics, vaccination coverage improvement, animal-health monitoring, and regional disease-alert systems.

- C. **Digital and value-chain modernization:** The strategy explicitly discusses IoT, traceability, cold chain, slaughterhouse capacity, corridors, and logistics. Recommendation: modernize the sector through animal identification, traceability platforms, route monitoring, digital market integration, and cold-chain expansion in export corridors.

5.4 Integrated Crop–Livestock Modernization

The strongest recommendation is to modernize the two sectors together: crop residues should be intentionally managed as feed resources, livestock manure should support soil fertility, fodder crops should be integrated into rainfed systems, and resilience planning should be provincial and corridor-based.

Recommended Strategic Policy:

Modernization of Sudan's agricultural systems requires an integrated crop–livestock approach. In rainfed crop zones such as Gedaref, modernization should focus on heat-tolerant and drought-resilient varieties, early-maturity seeds, and agro-climatic advisories linked to rainy-season variability.

In livestock corridors such as Darfur and Kordofan, modernization should prioritize grazing management, fodder banks, by-product pelleting, mobile veterinary systems, and digital traceability. Because livestock feed depends heavily on natural grazing and crop residues, the strongest climate-resilience gains are likely to come from coordinated crop–livestock strategies rather than sector-specific policies alone.

Agricultural transformation in Sudan must move beyond production expansion toward an integrated system combining climate adaptation, grazing modernization, risk management, and spatial resilience.

VI. LIMITATIONS AND FUTURE RESEARCH

This study has several limitations that should be acknowledged.

- First, the NARDL estimation results presented in Table 2 are based on model-implied responses; however, the full estimation results (coefficients, standard errors, diagnostic tests) are not fully reported in the current file set. Future work should provide complete NARDL estimation results with standard diagnostic tests.
- Second, the SAR and SDM models are presented as conceptual frameworks rather than fully estimated empirical models. While the interpretive statements are consistent with the theoretical framework, full statistical estimation requires a province/state border matrix and a complete province/state-by-year dataset.
- Third, the PARI and FPI indices are constructed based on available data, but the weighting schemes and indicator selection involve subjective choices. Future work should validate these indices with alternative weighting methods and sensitivity analysis.
- Fourth, the spatial weights matrix specification is not fully developed. Future research should test alternative spatial weights specifications (contiguity, distance-based, economic distance) to assess robustness.
- Fifth, the analysis focuses on rainfall and temperature as climate variables; other climate factors such as humidity, wind patterns, and extreme events (floods, dust storms) are not considered.
- Sixth, the study does not explicitly model the role of conflict and political instability, which may interact with climate vulnerability in complex ways.

Future research directions include: (1) full empirical estimation of the NARDL model with complete diagnostic testing; (2) development of a province/state spatial panel dataset for SAR and SDM estimation; (3) validation of PARI and FPI with sensitivity analysis; (4) integration of conflict and institutional variables into the resilience framework; (5) scenario analysis of climate change impacts under different emission pathways; and (6) evaluation of the cost-effectiveness of proposed policy interventions.

VII. CONCLUSION

This paper presents an integrated framework for analyzing climate impacts on Sudan's crop systems, livestock systems, and macroeconomic vulnerability. Gedaref provides explicit evidence of crop–climate sensitivity, while Darfur–Kordofan represents the country's major grazing and livestock vulnerability corridor. The proposed PARI and SAR framework extends

the study toward a provincial resilience perspective, although full statistical estimation will require additional province/state-by-year data and a spatial weights matrix.

Rainfed agriculture provides relatively stable but low GDP contributions, while livestock systems generate higher output but exhibit significant volatility due to dependence on grazing and rainfall. This structural divergence explains the observed differences in GDP risk profiles.

The findings confirm that climate effects are asymmetric, with drought shocks dominating economic outcomes, and spatially interconnected, with risk clustering across regions. The evidence from probability distribution analysis demonstrates that while crop systems provide stability with moderate risk, livestock systems introduce significant volatility and tail risk, reinforcing their role as a major source of climate-driven economic instability.

The spatial analysis (SAR and SDM) indicates that agricultural resilience and vulnerability are spatially clustered, with low-resilience regions concentrated in drought-prone livestock systems and high-resilience regions in irrigated central areas. The SDM results further suggest that climate shocks and feed pressure transmit across regions through shared grazing systems, animal mobility, and economic linkages, confirming that agricultural resilience in Sudan is spatially interconnected rather than isolated at the regional level.

The PARI and FPI analyses reveal strong regional disparities in resilience. Darfur exhibits the lowest resilience (PARI = 0.10), reflecting high exposure to climate variability and strong dependence on grazing systems. Kordofan shows medium-low resilience (0.37), while Gedaref demonstrates medium-high resilience (0.67). The Central Region shows the highest resilience (0.93), reflecting irrigation infrastructure and higher adaptive capacity.

The results demonstrate that climate vulnerability in Sudan is not only environmental but also structural and systemic, embedded in production systems and amplified through spatial spillovers. The overall message is that Sudan's climate vulnerability is nonlinear, spatially differentiated, and system-wide. Modernization therefore needs to be integrated, regionally targeted, and climate-smart, linking crop science, grazing systems, feed infrastructure, veterinary systems, market access, and spatial resilience planning.

COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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DATA SHARING STATEMENT

No additional data are available.

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Efficacy of Entomopathogenic Fungi against Sapota Fruit Mite, *Tuckerella kumaonensis* Gupta (Tuckerellidae: Acari) under Laboratory Condition

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Abstract— A laboratory investigation was conducted during 2020 and 2021 at Biocontrol Laboratory, N. M. College of Agriculture, Navsari Agricultural University, Navsari, Gujarat, to test the efficacy of different entomopathogenic fungi against sapota fruit mite, *Tuckerella kumaonensis* Gupta infesting sapota. Among the various entomopathogenic fungi, the treatment of *Beauveria bassiana* (1×10^8 cfu/g) @ 4g/l found significantly superior (62.03% mortality) over the rest of the treatments. However, the treatment of *Lecanicillium lecanii* (1×10^8 cfu/g) @ 4g/l registered 45.41 per cent mortality and found the next best treatment against sapota fruit mite and was statistically at par with the treatment of *Metarhizium anisopliae* (1×10^8 cfu/g) @ 4g/l (42.39% mortality). The treatments of *Hirsutella thompsonii* (1×10^8 cfu/g) @ 4g/l found to be least effective against sapota fruit mite (31.04% mortality).

Keywords— Sapota, fruit mite, *Tuckerella kumaonensis*, entomopathogenic fungi, bio-efficacy.

I. INTRODUCTION

Sapota [*Manilkara achras* (Mill.) Fosberg] belongs to family Sapotaceae is an important tropical fruit crop having $2n=26$ chromosome number. It is a native of Mexico and Tropical America. It is commonly known as chiku. The sapota is a climacteric fruit. Fully ripen fruits of sapota are delicious and sweet in taste used as dessert fruits. It is a commercial orchard crop where the fruits are used for preparation of many value-added products viz. squash, jam, slices, butter, cheese, candy, milk shake, powder, biscuit, ice-cream, shrikhand, pulp, juice, dehydrated sapota slices, nectar, lassie, chocolate and bar. The latex obtained from stems and immature fruits is used in the preparation of chewing gum. Besides food values, the sapota fruits are also used in some ayurvedic preparations. Sapota is supposed to be medicinal also seeds as diuretic, bark as tonic, antipyretic, febrifuge and in curing biliousness and febrile attacks. The fruit is a good source of digestible sugar (12 to 18%) and appreciable source of protein, fat, fibre and minerals like calcium, phosphorous and iron (Chadha, 2001). In Gujarat state, it is cultivated in districts viz. Valsad, Navsari, Surat, Mehsana, Junagadh, Bhavnagar, Gir Somnath and Kachchh.

Among the various factors affecting the yield and quality of fruit, the damage caused by insect pests is considered as a major constraint. The yield and economic value of sapota fruits have been affected by number of insect pests as well as non-insect pests. More than 25 insect pests have been reported to attack on sapota tree at different crop stages during both on season and off seasons (Butani, 1979). Among them, about 16 insect pests and mites were identified in last two decades from sapota orchards in Gujarat (Patel et al., 2002) and their numbers reached to 33 insect pests and non-insect pests in sapota orchard with increase in the acreage (Bisane et al., 2018).

Sapota fruit mite, *Tuckerella kumaonensis* (Gupta) is responsible for qualitative losses to sapota fruits. The immature and adults of red coloured mite suck the cell sap from the fruit surface starting from marble size fruit stage thereby fruit surface become corky rough and black or dark colour with encrustation on fruits, which leads to qualitative loss of harvested products. This mite remains active throughout the year on sapota cv. Kalipatti under south Gujarat agro-climatic conditions. It is well known

fact that in South Gujarat, the sapota crop has played a significant role in socio-economic upliftment of both marginal and big farmers.

To mitigate these losses, chemical control remains the most practical option under field conditions, although overuse of conventional insecticides has led to concerns such as insecticide resistance, environmental hazards, and effects on natural enemies. In this context, evaluation of various entomopathogenic fungus is necessary to achieve effective mite management, enhance crop productivity and ensure economic viability. Therefore, the present investigation was undertaken to test the efficacy various entomopathogenic fungus against sapota fruit mite, *T. kumaonensis* under the laboratory condition.

II. MATERIALS AND METHODS

The laboratory trial was conducted to test the efficacy of various entomopathogenic fungi against sapota fruit mite during the year 2020 and 2021 at Biocontrol Laboratory, N. M. College of Agriculture, Navsari Agricultural University, Navsari, Gujarat, India. The experiment was laid out in Completely Randomized Design with four repetitions and six treatments. The treatments are as follow: *Hirsutella thompsonii* (1×10^8 cfu/g), *Beauveria bassiana* (1×10^8 cfu/g), *Lecanicillium (Verticillium) lecanii* (1×10^8 cfu/g), *Metarhizium anisopliae* (1×10^8 cfu/g), water spray and control. The dose of each treatment was 4g/l of water under the laboratory. The fungal cultures were obtained from the Biocontrol Laboratory culture collection; however, the specific strain designations and original sources are not recorded and should be considered a limitation of this study.

2.1 Maintenance of Laboratory Culture

The laboratory culture was maintained on healthy unripe sapota fruit. Healthy unripe ten sapota fruits as well as fruit mites affected fruits with peduncle per twig were collected from the Organic Farm, ASPEE College of Horticulture and Forestry, Navsari Agricultural University, Navsari from the unsprayed sapota orchard. Moist cotton swab was covered on peduncle per twig to avoid desiccation of fruit. On each fruit, 2 x 2 square cm arena was marked and the boarder of the arena was demarked with vaseline jelly to avoid the escape of fruit mite. For egg laying, fifteen adult mites were released with the help of "0" number camel hair brush in the evening on the marked surface of each fruit. The adults were removed when sufficient number of eggs were laid. Mass rearing of fruit mite was initiated with these eggs and same were utilized for further efficacy trial. Sapota fruits were changed at an interval of two to three days with new fresh unripe fruits to avoid the secondary growth of fungus as well as rotting of the fruits.

2.2 Method of Observations

The laboratory experiment was conducted at temperature $31.5 \pm 4.0^\circ\text{C}$ and relative humidity ranging between 72.0 ± 5.0 per cent during March, 2020 and March, 2021. Healthy unripe thirty sapota fruits along with peduncle per twig were brought to the laboratory from unsprayed orchard from Organic Farm, ASPEE College of Horticulture and Forestry, Navsari Agricultural University, Navsari, Gujarat, India. The fruit mites were released with the help of "0" number camel hair brush on 5mm thick pieces of unripe sapota fruits of the size 2.5 x 1.5 square cm arena with outer surface intact. Above mentioned treatments of entomopathogenic fungi were imposed by dipping the pieces of sapota fruits for five minutes in previously prepared conidial solution of respective entomopathogenic fungi treatments. For the water spray treatment, fruit pieces were dipped in distilled water for five minutes, while the control treatment received no dipping or treatment. After taking out from the solution the pieces were allowed to dry under ceiling fan. Five dried pieces for each repetition per treatment were placed on a wad of wet cotton to maintain turgidity of pieces of sapota fruits in petri dish (15cm x 2cm). In each treatment, hundred adult mites were released with the help of "0" number camel hair brush during evening hour on the outer surface of each treated piece. Thus, twenty-five adult mites were equally released on five treated pieces of unripe sapota fruits placed in each repetition of respective treatments (Photograph A). After 30 minutes of exposure, the fruit mites on treated pieces were transferred to fresh untreated pieces of sapota fruit. The per cent mortality were recorded at 3, 5, 7, 10 and 14 days after the treatments. Each treated pieces of sapota fruit were changed with new fresh untreated pieces of sapota fruit in same petri dish at alternate day. The data obtained on cumulative dead mite counts were summed up and utilized for calculation of per cent corrected mortality. Thus, the data on per cent mortality of the sapota fruit mites were corrected as per formula given by Henderson and Tilton (1955) by employing completely randomized design with four repetitions.

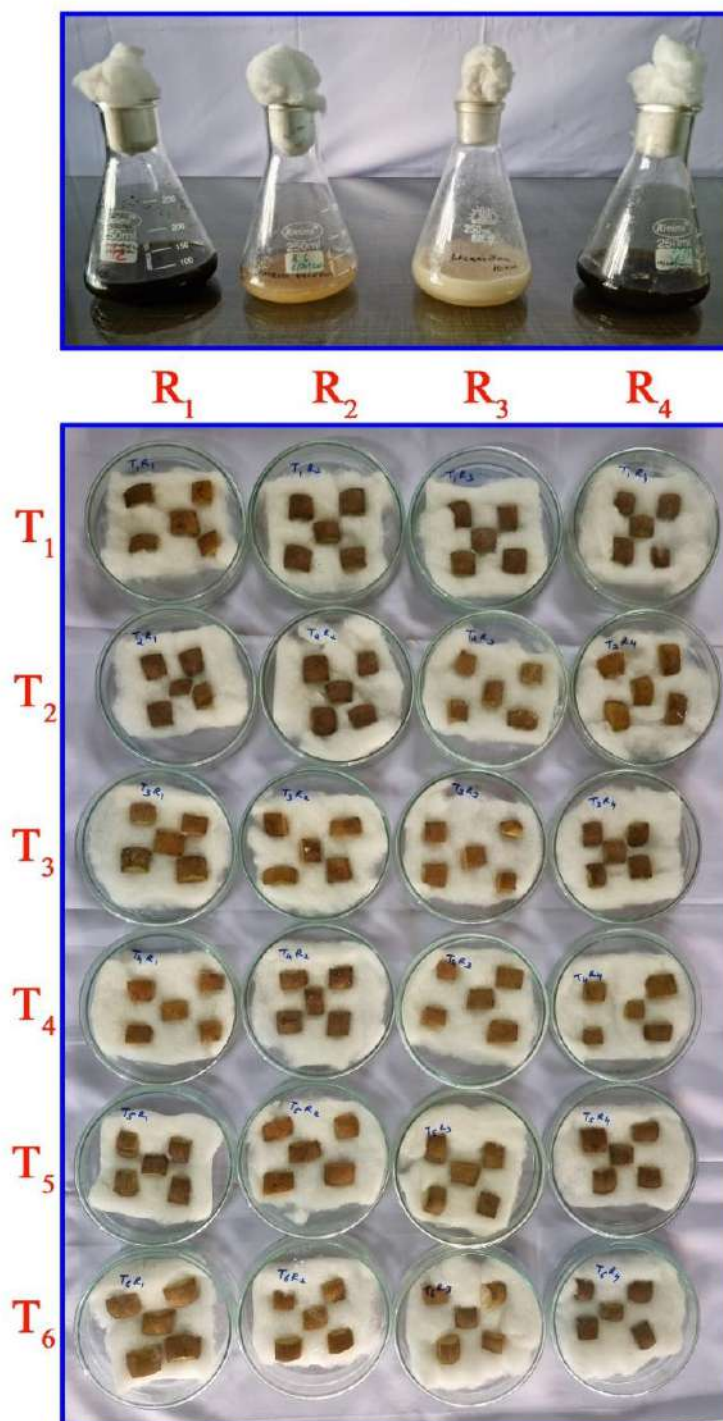
$$\text{Corrected per cent mortality} = \left(1 - \frac{T_a \times C_b}{T_b \times C_a}\right) \times 100 \quad (1)$$

Where,

- T_b = Number of mites observed before treatment

- T_a = Number of mites observed after treatment
- C_b = Number of mites observed from untreated control before treatment
- C_a = Number of mites observed from untreated control after treatment

All statistical analyses were performed using analysis of variance (ANOVA) appropriate for CRD. Treatment means were compared using the Least Significant Difference (LSD) test at 5% level of significance. The statistical software used for analysis was WASP-2.



PHOTOGRAPH A: Laboratory experiment on efficacy of various entomopathogenic fungi against sapota fruit mite, *T. kumaonensis*

III. RESULTS AND DISCUSSION

The overall pooled data was calculated on the basis of pooled value of mean corrected per cent mortality of sapota fruit mite, *T. kumaonensis* during the year 2020 and 2021 are presented in Table 1 and depicted in Fig. 1 indicated that all the entomopathogenic fungi treatments were found significantly effective over the water spray and control.

TABLE 1
EFFICACY OF ENTOMOPATHOGENIC FUNGI AGAINST SAPOTA FRUIT MITE, *TUCKERELLA KUMAONENSIS*
UNDER LABORATORY CONDITION

Sr. No.	Treatments	Conc.	Corrected per cent mortality					
			3 DAT	5 DAT	7 DAT	10 DAT	14 DAT	Overall Pooled
1.	<i>H. thompsonii</i>	4g/l	28.47 (22.76)*	30.71 (26.11)	34.35 (31.88)	36.14 (34.82)	38.99 (39.62)	33.85 (31.04)
2.	<i>B. bassiana</i>	4g/l	38.81 (39.32)	41.93 (44.65)	54.14 (65.62)	61.52 (77.08)	66.09 (83.47)	51.97 (62.03)
3.	<i>L. lecanii</i>	4g/l	33.61 (30.66)	37.86 (37.69)	43.60 (47.57)	47.64 (54.57)	48.80 (56.54)	42.36 (45.41)
4.	<i>M. anisopliae</i>	4g/l	32.24 (28.50)	36.17 (34.87)	41.72 (44.30)	45.57 (50.99)	46.91 (53.31)	40.61 (42.39)
5.	Water spray	-	10.89 (3.69)	12.01 (4.51)	13.43 (5.49)	14.15 (6.09)	14.56 (6.50)	13.14 (5.26)
6.	Control	-	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
S.Em. ±								
Treatment (T)			0.52	0.65	1.10	1.89	1.84	1.16
(Y×T)			0.73	0.92	0.89	0.98	1.00	0.60
C.D. at 5 %								
Treatment (T)			1.49	1.86	4.00	6.86	6.70	4.23
(Y×T)			NS	NS	NS	NS	NS	NS
C.V. %			6.12	6.95	5.71	5.71	5.59	3.97

***Figures in parentheses are retransformed values; those outside are arcsine transformed values, DAT: Days After Treatment**

Among the various treatments, the treatment *B. bassiana* (1×10^8 cfu/g) @ 4g/l was found significantly superior than rest of the entomopathogenic fungi treatments as it recorded 62.03 per cent mortality, which was significantly highest all over the tested entomopathogenic fungi as well as treatment of water spray and control. However, the treatment of *L. lecanii* (1×10^8 cfu/g) @ 4g/l registered 45.41 per cent mortality and found best next in order for their effectiveness against sapota fruit mite and was statistically at par with the treatment of *M. anisopliae* (1×10^8 cfu/g) @ 4g/l exhibited 42.39 per cent mortality. The treatments of *H. thompsonii* (1×10^8 cfu/g) @ 4g/l found least effective against sapota fruit mite, which indicated 31.04 per cent mortality. The lowest per cent mortality (5.26%) was found in treatment of water spray. Further, in case of untreated control no mortality of sapota fruit mite was recorded.

The descending order of effectiveness of treatments based on corrected per cent mortality of sapota fruit mite, *T. kumaonensis* was:

B. bassiana (1×10^8 cfu/g) @ 4g/l > *L. lecanii* (1×10^8 cfu/g) @ 4g/l > *M. anisopliae* (1×10^8 cfu/g) @ 4g/l > *H. thompsonii* (1×10^8 cfu/g) @ 4g/l > water spray > control.

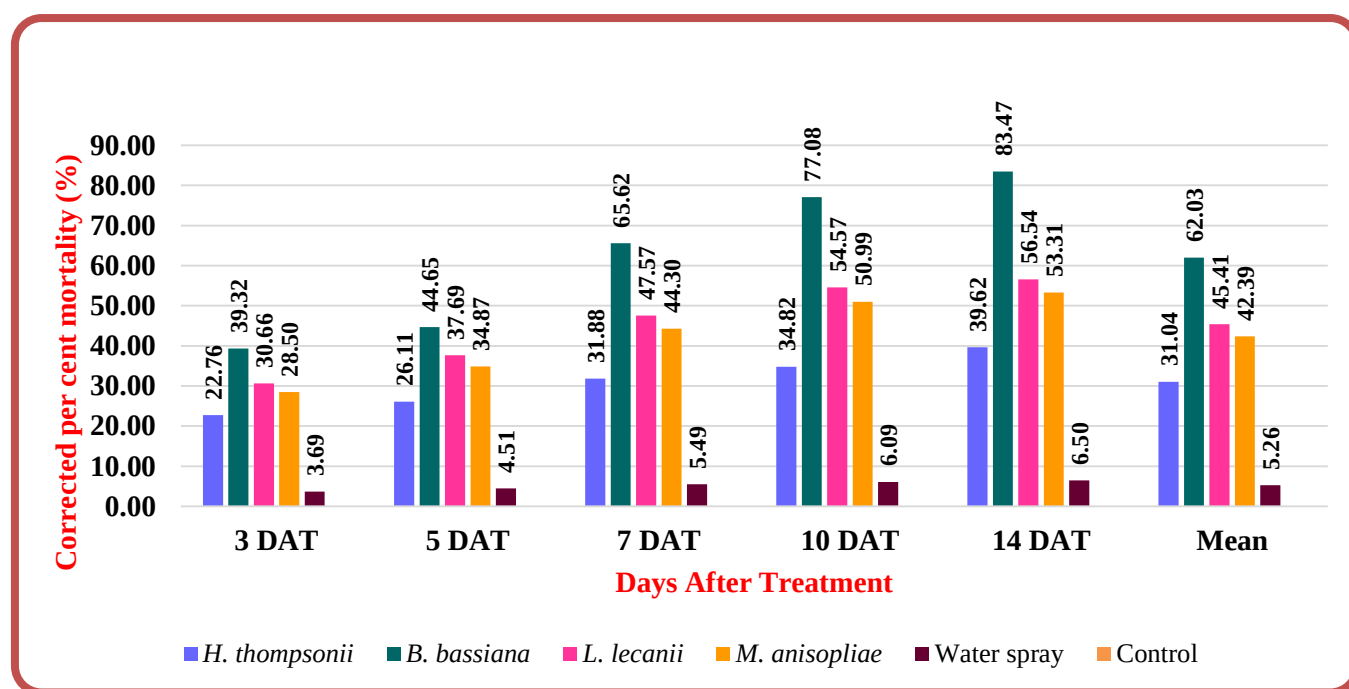


FIGURE 1: Efficacy of entomopathogenic fungi against fruit mite, *T. kumaonensis* under laboratory condition (Pooled)

The higher efficacy of *B. bassiana* against sapota fruit mite, *T. kumaonensis* was supported by various workers. In a study, Ghosh et al. (2007) exhibited *B. bassiana* more virulent against adults of *T. urticae*. Negash et al. (2014) found highest mortality of *T. urticae* by applying *B. bassiana* 9614 ($82.38 \pm 3.44\%$) and *B. bassiana* 9609 ($65.39 \pm 0.77\%$). Further, *B. bassiana* @ 5g/l registered 32.68 per cent mortality of coconut eriophyid mite, *A. guerreronis* (Sathish et al., 2019). The entomopathogenic fungi, *B. bassiana* @ 4g/l exhibited highest per cent mortality of sorghum mite, *O. indicus* (58.03%) by Prajapati et al. (2022).

The efficacy of *L. lecanii*, *M. anisopliae* and *H. thompsonii* against sapota fruit mite, *T. kumaonensis* was reported by different workers. *H. thompsonii* registered 78.70 per cent mortality against *A. guerreronis* (Wijesinghe and Rubasinghe, 2003), *V. lecanii* and *H. thompsonii* were found second best treatments (Ghosh et al., 2007), 90.00 per cent reduction in the coconut eriophyid mite population (Kumar, 2009). Negash et al. (2014) revealed maximum mortality of *T. urticae* by imposing *M. anisopliae* MM ($76.63 \pm 1.07\%$) and *M. anisopliae* PPRC 6 ($61.19 \pm 1.86\%$), *H. thompsonii* @ 5g/l registered maximum mortality (38.75%) of coconut eriophyid mite, *A. guerreronis* (Hegade et al., 2016); Hegade et al. (2016) reported maximum mortality of coconut eriophyid mite, *A. guerreronis* by *V. lecanii* @ 5g/l (12.75% mortality), *B. bassiana* @ 5g/l (12.25% mortality) and *M. anisopliae* @ 5g/l (7.0% mortality). *H. thompsonii* @ 5g/l and *V. lecanii* 5g/l found effective (58.89% and 32.55% mortality, respectively) against *A. guerreronis* (Sathish et al., 2019), *V. lecanii*, *M. anisopliae* and *H. thompsonii* @ 4g/l recorded 40.78, 37.64 and 28.43 per cent mortality of *O. indicus*, respectively (Prajapati et al., 2022).

The present findings are in accordance with the findings of Ghosh et al. (2007), Negash et al. (2014), Sathish et al. (2019) and Prajapati et al. (2022). While, findings of Wijesinghe and Rubasinghe (2003), Ghosh et al. (2007), Kumar (2009), Negash et al. (2014), Hegade et al. (2016), Sathish et al. (2019) and Prajapati et al. (2022) are not in accordance with present investigation, it might be due to different ecological conditions as well as change in the mode of action of tested biopesticides used during the course of investigation on targeted pest.

The superior efficacy of *B. bassiana* over other entomopathogenic fungi may be attributed to its higher virulence, efficient sporulation, and ability to produce cuticle-degrading enzymes such as chitinases and proteases that facilitate penetration of the mite cuticle. Additionally, *B. bassiana* produces secondary metabolites (beauvericin and bassianolide) with insecticidal and acaricidal properties. The relatively lower efficacy of *H. thompsonii* observed in this study could be due to strain-specific differences, environmental conditions, or the particular susceptibility of *T. kumaonensis* to different fungal species. These differences highlight the importance of strain selection and screening for specific pest-pathogen combinations.

IV. CONCLUSION

Among the various treatments of entomopathogenic fungi, the treatment of *B. bassiana* (1×10^8 cfu/g) @ 4g/l found significantly superior than rest of the entomopathogenic fungi treatments as it recorded 62.03 per cent mortality, which was significantly highest all over the tested entomopathogenic fungi as well as treatment of water spray and control. However, the treatment of *L. lecanii* (1×10^8 cfu/g) @ 4g/l registered 45.41 per cent mortality and found best next in order for their effectiveness against sapota fruit mite which was statistically at par with the treatment of *M. anisopliae* (1×10^8 cfu/g) @ 4g/l exhibited 42.39 per cent mortality. The treatments of *H. thompsonii* (1×10^8 cfu/g) @ 4g/l found least effective against sapota fruit mite which indicated 31.04 per cent mortality. The lowest per cent mortality (5.26%) was recorded in treatment of water spray, while in case of control, mortality was not recorded.

The study demonstrates that *B. bassiana* has significant potential as a biological control agent against sapota fruit mite, *T. kumaonensis* under laboratory conditions. However, field validation studies are essential to confirm the efficacy of these entomopathogenic fungi under natural conditions, considering the challenges of temperature, humidity, UV radiation, and application technology. Future research should focus on developing appropriate formulations, optimizing application methods, and evaluating the compatibility of these fungi with other pest management strategies.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Remote Sensing and Machine Learning for Futuristic Horticulture: A Comprehensive Review

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Abstract— Horticultural crops—fruits, vegetables, plantation crops, flowers, spices and medicinal plants—form the nutritional and economic backbone of India's agricultural sector. However, they face persistent challenges of yield variability, water and nutrient inefficiency, pest and disease pressure and post-harvest losses. This review synthesises the transformative role of Remote Sensing (RS) and Machine Learning (ML) in enabling futuristic, sustainable and precision horticulture. The evolution of agricultural production systems from Agriculture 1.0 to Agriculture 5.0 is traced, followed by a comprehensive discussion of RS principles, elements, four fundamental resolutions (spatial, spectral, temporal, radiometric), and multi-platform architectures (satellite, aerial, UAV, ground-based). A parallel taxonomy of ML—supervised, semi-supervised, unsupervised, reinforcement and deep-learning frameworks—is presented, with emphasis on Random Forest, Support Vector Machine, XGBoost, and Convolutional Neural Network algorithms most widely applied to horticultural datasets. Five representative case studies are analysed in depth: (i) UAV multispectral + ensemble learning for leaf nitrogen monitoring in custard apple [1]; (ii) hyperspectral + ANN / RF / DT models for mango and strawberry fruit-quality parameters [2]; (iii) UAV-hyperspectral detection of citrus canker [3]; (iv) machine-learning-based crop recommendation under NPK, pH and climatic variables [4]; and (v) RS + GIS soil-site suitability for six major fruit crops in the Ganjigatti sub-watershed, Karnataka [5]. National platforms such as CHAMAN, Bhoonidhi, Bhuvan and PMFBY are reviewed as operational demonstrations of the RS + ML value chain. Finally, technical, economic and ethical challenges—ground-truth scarcity, sensor cost, model interpretability, digital divide and data privacy—are discussed, and a way forward for Indian horticulture in the Agriculture 5.0 era is proposed.

Keywords— Remote sensing, machine learning, precision horticulture, UAV, hyperspectral imaging, vegetation indices, XGBoost, convolutional neural network, Agriculture 5.0, decision support system.

I. INTRODUCTION

Horticulture constitutes a vital component of the world's agricultural systems, contributing significantly to food and nutritional security, rural livelihoods, export earnings and agro-industrial development. Fruits, vegetables, spices, plantation crops and ornamental plants deliver essential vitamins, minerals, antioxidants and dietary fibre indispensable to human health and well-being. In developing economies such as India, horticulture has emerged as a high-growth sector by virtue of higher productivity per unit area, greater income potential and expanding domestic and international markets [6].

Despite its importance, horticultural production faces numerous challenges, including declining soil fertility, water scarcity, climate variability, pest and disease outbreaks, labour shortages and rising input costs. Traditional horticultural practices, largely dependent on farmer experience and visual field observations, often result in inefficient input use, yield variability and environmental degradation. These limitations have accelerated the need for advanced technologies that can support precise, timely and site-specific decision-making [7], [8].

Remote Sensing (RS) and Machine Learning (ML) together offer transformative solutions by enabling non-destructive, rapid and large-scale monitoring of crops and orchards. RS technologies provide continuous observations of crop condition across spatial and temporal scales, while ML algorithms extract meaningful patterns and predictive insights from complex, high-dimensional datasets. Their integration supports informed decision-making related to irrigation scheduling, nutrient management, disease control, harvest planning and yield forecasting [1], [2], [7], [9].

While several reviews have addressed RS and ML in agriculture broadly, this review specifically focuses on horticultural crops—a sector with unique characteristics (perennial nature, high-value produce, complex canopy structures) that pose distinct challenges and opportunities for RS + ML applications. Furthermore, this review integrates the Indian national context, covering operational platforms such as CHAMAN, Bhoonidhi, Bhuvan and PMFBY that are rarely discussed together in the international literature. The review also explicitly connects the evolution from Agriculture 1.0 to Agriculture 5.0 with the technological readiness of RS + ML systems, providing a forward-looking perspective on intelligent horticulture.

This review synthesises the state of the art of RS and ML for horticulture as of 2026. Section 2 traces the evolution of agricultural systems from Agriculture 1.0 to Agriculture 5.0. Sections 3 and 4 present the technical foundations of RS and ML respectively. Section 5 discusses the synergistic integration of RS and ML, and Section 6 presents five case studies. Section 7 reviews Indian national operational platforms (CHAMAN, Bhoonidhi, Bhuvan, PMFBY). Section 8 discusses limitations, and Section 9 concludes with a way-forward road-map.

II. EVOLUTION OF AGRICULTURE TOWARDS SMART FARMING

Agricultural systems have progressed through five clearly distinguishable phases, each characterised by transformative technological, social and economic changes. Understanding this evolution is essential for appreciating the emergence of RS and ML as core technologies of futuristic horticulture (Fig. 1) [10], [11].

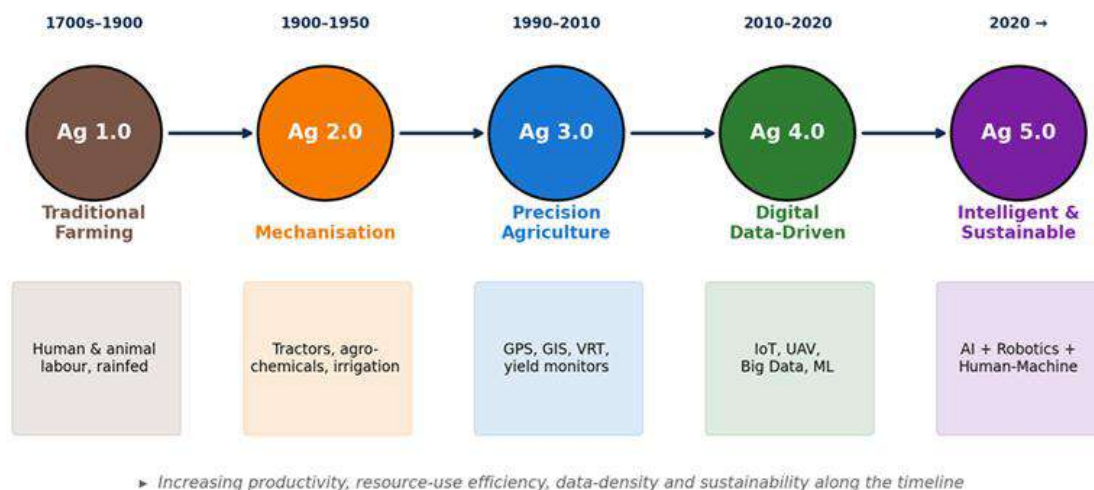


FIGURE 1: Evolution of agriculture from traditional farming (Agriculture 1.0) to intelligent, sustainable systems (Agriculture 5.0). Adapted from [10], [11].

2.1 Agriculture 1.0—Traditional Farming Systems

Agriculture 1.0 represents the era of subsistence and traditional farming (pre-1900), where crop production relied heavily on human and animal labour, indigenous knowledge and natural rainfall. Decision-making was based on farmer experience, visual crop assessment and inherited practices. In horticulture, traditional practices often resulted in non-uniform crop growth, inefficient water and nutrient use and delayed detection of pests and diseases [10].

2.2 Agriculture 2.0—Mechanisation and Input Intensification

The second agricultural revolution (1900–1950) introduced mechanisation, synthetic fertilisers, pesticides and improved irrigation infrastructure. Tractors, harvesters and chemical inputs significantly increased crop yields, but blanket application of inputs led to soil degradation, water pollution and biodiversity loss [10].

2.3 Agriculture 3.0—Precision Agriculture

Agriculture 3.0 (1990–2010) marked the transition to site-specific management using GPS, GIS, yield monitors and variable-rate applicators. RS emerged as a valuable tool, providing spatially-explicit information on crop condition and variability. In horticulture, precision approaches enabled improved irrigation scheduling, fertiliser management and yield estimation, particularly in orchards with heterogeneous soil and canopy conditions [7], [12].

2.4 Agriculture 4.0—Digital and Data-Driven Farming

Agriculture 4.0 (2010–2020) integrated the Internet of Things (IoT), cloud computing, big-data analytics and automation. Continuous data streams from sensors, weather stations, UAVs and satellites enable near-real-time monitoring of crops and environmental conditions. ML models play a central role in Agriculture 4.0 by analysing large multidimensional datasets to generate actionable insights. In horticulture, ML-driven systems support yield prediction, disease detection, fruit counting and quality assessment, significantly enhancing decision-making accuracy [13], [14].

2.5 Agriculture 5.0—Intelligent and Sustainable Systems

Agriculture 5.0 (2020 onwards) builds upon digital farming by emphasising Artificial Intelligence, robotics, human–machine collaboration and sustainability. In futuristic horticulture, Agriculture 5.0 envisions autonomous UAVs and robots integrated with RS, ML and decision-support systems to deliver precise inputs, monitor crop health continuously and adapt management strategies dynamically [10], [11], [15].

III. REMOTE SENSING—TECHNOLOGY AND PRINCIPLES

Remote Sensing is the science and technology of acquiring information about objects, areas or phenomena without direct physical contact, by measuring reflected or emitted electromagnetic radiation with instruments not physically connected to the subject. Pisharoth Rama Pisharoty is recognised as the Father of Remote Sensing in India [16].

3.1 History and Development

The term Remote Sensing was first coined in the United States in the 1950s by Ms Evelyn Pruitt of the U.S. Office of Naval Research. RS technologies in agriculture began with the launch of the Earth Resources Technology Satellite (ERTS-1, later renamed Landsat) in 1972, which carried the Return Beam Vidicon (RBV) and Multispectral Scanner (MSS) sensors. In India, the first documented use of RS was for coconut root-wilt disease detection in 1970, and the country's first RS satellite IRS-1A was launched on 17 March 1988. The most recent milestone is the NASA-ISRO Synthetic Aperture Radar (NISAR) launched on 30 July 2025 from Satish Dhawan Space Centre, Sriharikota, carrying dual-frequency L- and S-band SAR sensors with 3 m resolution for high-resolution tracking of surface moisture, biomass, crop areas, mangroves and wetlands [16], [17].

3.2 Principle of Remote Sensing and its Elements

The principle of RS rests on collecting information about a target without physical contact, using sensors to detect and record electromagnetic energy that is either reflected or emitted by the target. The seven fundamental elements of RS—Energy source, Interaction with the atmosphere, Interaction with the target, Sensor, Data transmission, Product generation and User application—form the operational chain illustrated in Fig. 2 [16].

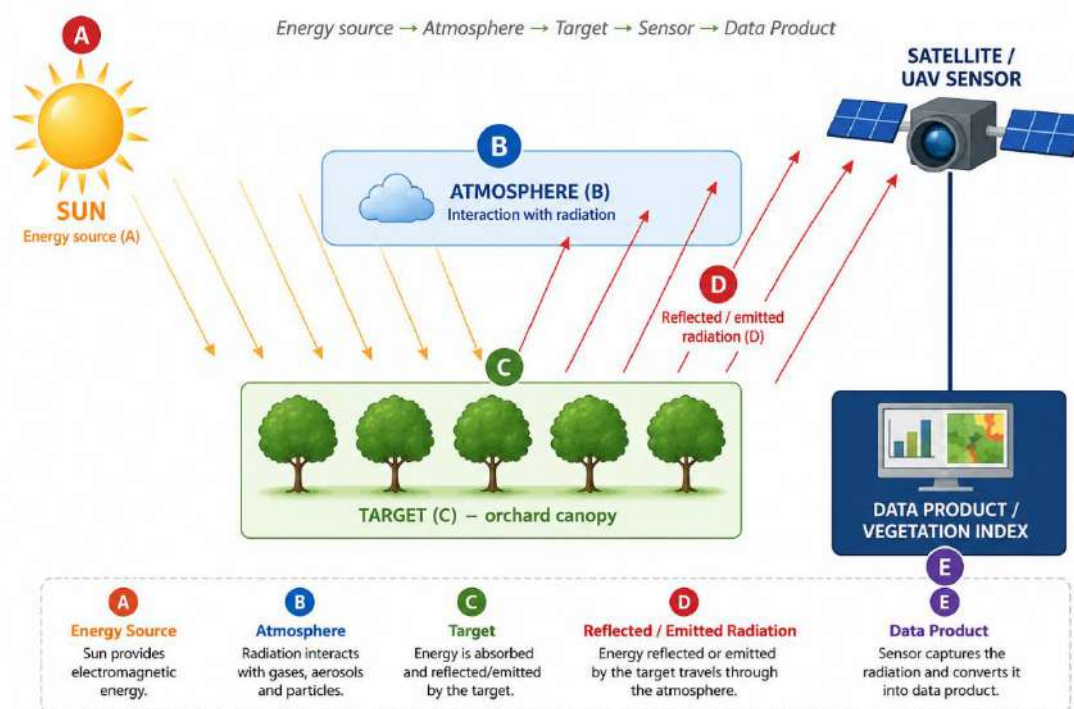


FIGURE 2: Elements and working principle of Remote Sensing—from solar energy source through atmospheric interaction, target reflectance and sensor acquisition to final data product.

3.3 Geographic Information Systems (GIS) and Global Navigation Satellite Systems (GNSS)

GIS, originating from Roger Tomlinson's 1963 work on Canada's national land-use programme, is a computer-based system designed to capture, store, manipulate, analyse and display geographically-referenced data (ESRI). Jack Dangermond and Laura Dangermond founded the Environmental Systems Research Institute (ESRI) in 1969 and developed ARC/INFO, the first commercial GIS product, in 1981. GIS-derived mapping products used in horticulture include soil classification, crop-distribution mapping, land-utilisation mapping, contour mapping and irrigation-system analysis [12].

Global Navigation Satellite Systems (GNSS) comprise localisation constellations that provide accurate location, navigation and timing information—the positioning backbone of precision agriculture. Major constellations include NAVSTAR-GPS (USA, 1972), GLONASS (Russia, 1982), BeiDou (China, 2000), Galileo (EU, 2011), QZSS (Japan, 2010) and IRNSS/NavIC (India, 2013). GNSS in horticulture supports yield monitoring, compaction profile sensing, tree-planting and site-specific fumigant application, RTK-GPS plant mapping, precise weed management and robotic operations [12].

3.4 Passive and Active Remote-Sensing Systems

RS systems are broadly classified into passive and active sensors based on the energy source. Passive sensors rely on natural energy—primarily solar radiation—and measure reflected or emitted energy from the Earth's surface. Most optical multispectral and hyperspectral sensors used in horticulture, such as Landsat, Sentinel-2 and UAV-mounted cameras, are passive systems.

Active RS systems, in contrast, emit their own energy and measure the returned signal after interaction with the target. Synthetic Aperture Radar (SAR) and Light Detection and Ranging (LiDAR) are common active systems. SAR operates in the microwave region and can acquire data under all-weather and day-night conditions, making it valuable for soil-moisture estimation and crop-structure analysis. LiDAR provides precise three-dimensional information on canopy height, volume and structure, particularly useful in orchard management and pruning assessment [18], [19].

3.5 Sensor Resolutions in Remote Sensing

The quality and applicability of RS data are determined by four fundamental resolutions—spatial, spectral, temporal and radiometric (Fig. 3) [20].

SPATIAL	Ground area / pixel Range: Sub-metre → 30 m UAV 0.02 m • WorldView 0.3 m • Sentinel-2 10 m • Landsat 30 m
SPECTRAL	Number & width of bands Range: 3 → 300+ bands RGB 3 • Multispectral 4-10 • Hyperspectral 100-300
TEMPORAL	Revisit frequency Range: Minutes → Weeks UAV on-demand • Sentinel-2 5 d • Landsat 16 d
RADIOMETRIC	Bit-depth sensitivity Range: 8 → 16 bit 8-bit legacy • 12-bit Sentinel • 14-bit WorldView

FIGURE 3: Four fundamental resolutions of Remote Sensing (spatial, spectral, temporal, radiometric) and their typical ranges across UAV, satellite and airborne platforms.

- **Spatial resolution**—the ground area represented by a single pixel. Sub-metre to a few metres (UAVs, commercial satellites) is essential for horticultural applications where individual trees, rows or fruit clusters must be resolved.
- **Spectral resolution**—the number and width of bands. Hyperspectral sensors with 100–300 narrow bands provide detailed spectral information enabling precise estimation of chlorophyll, nitrogen and water content [20].
- **Temporal resolution**—the revisit frequency. High temporal resolution is critical for monitoring crop growth dynamics, stress development and phenological changes in fast-growing horticultural crops.
- **Radiometric resolution**—the sensor's sensitivity to detect small energy differences, expressed in bits. Higher radiometric resolution improves the detection of subtle reflectance variations associated with early stress symptoms.

3.6 Remote-Sensing Platforms and Sensors for Horticulture

Modern horticulture increasingly relies on a multi-platform approach that integrates satellite, aerial, UAV and ground-based observations to capture crop variability across scales (Fig. 4).

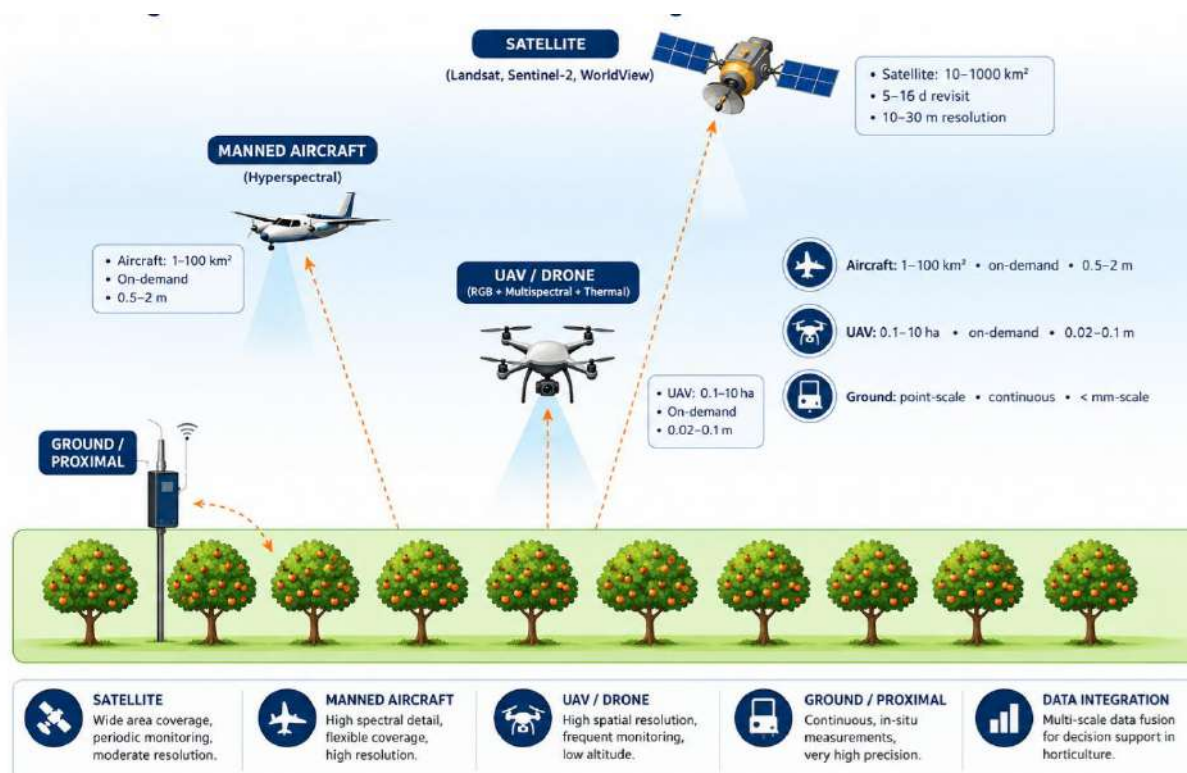


FIGURE 4: Multi-platform Remote-Sensing architecture for horticulture, spanning satellite, manned-aircraft, UAV and ground/proximal sensor levels.

3.6.1 Satellite Remote Sensing

Satellite RS remains the backbone of large-scale agricultural monitoring due to its consistent coverage, long-term data archives and standardised products. Medium-resolution satellites such as Landsat (30 m) and Sentinel-2 (10–20 m) are widely used for monitoring crop growth, phenology and stress dynamics over regional to national scales. Sentinel-2's red-edge bands offer enhanced sensitivity to canopy chlorophyll content and structure, particularly valuable for orchard and plantation-crop monitoring [7], [21], [22]. High- and very-high-resolution commercial satellites including WorldView-3/4, GeoEye-1, Pléiades and Planet Labs provide sub-metre resolution enabling detailed tree-level analysis and inventory of high-value orchards.

3.6.2 Airborne and UAV Remote Sensing

Aerial platforms include manned aircraft carrying hyperspectral or LiDAR sensors, providing high-resolution data over intermediate spatial scales. UAV platforms have revolutionised horticultural RS by delivering ultra-high spatial resolution (< 5 cm) on-demand at moderate cost. UAVs carrying RGB, multispectral, hyperspectral or thermal cameras support intensive orchard monitoring, individual-tree analysis and rapid stress detection [22], [23], [24].

IV. MACHINE LEARNING—TAXONOMY AND ALGORITHMS

Machine Learning is a subfield of Artificial Intelligence that enables computer systems to learn patterns from data and improve performance without being explicitly programmed. In horticulture, ML provides powerful tools for analysing high-dimensional RS data, integrating heterogeneous data sources and generating predictive insights that support decision-making across the crop cycle [15], [25].

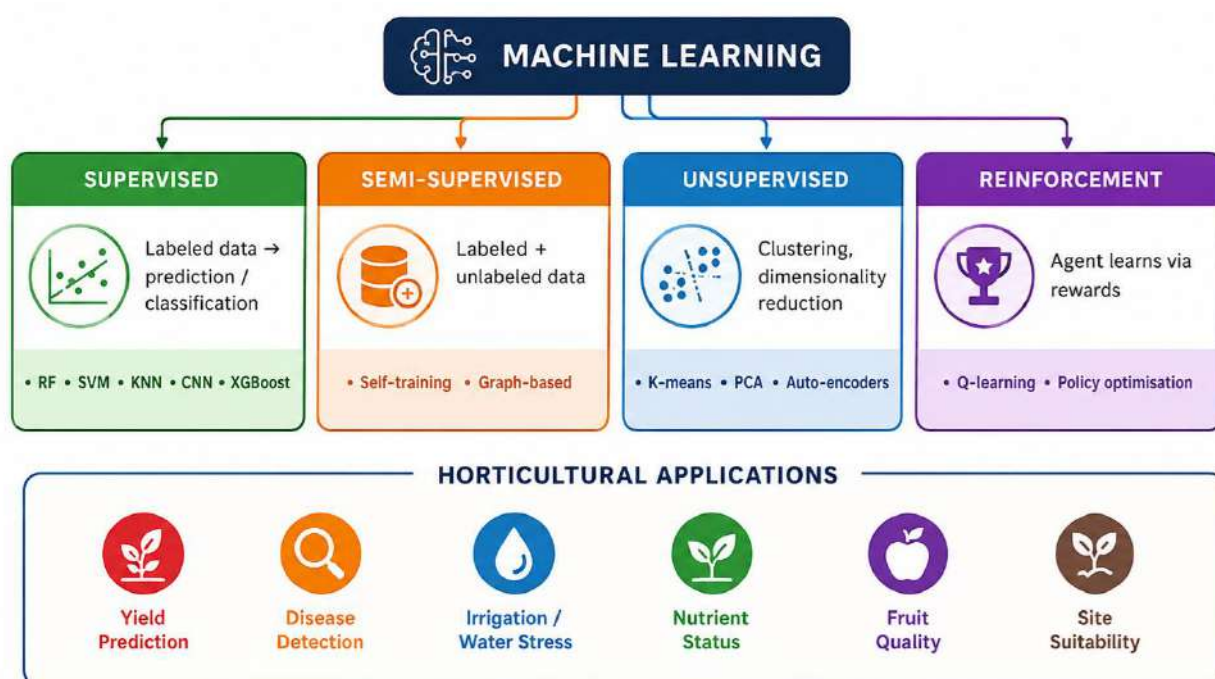


FIGURE 5: Machine-Learning taxonomy for precision horticulture—four principal learning paradigms and their key horticultural applications.

4.1 Classification of ML Models

Supervised Learning: Models learn from labelled training data to make predictions or classifications. Common families include tree-based (decision trees, random forest), Bayesian (naïve Bayes, hidden Markov models), instance-based (k-nearest neighbours, support vector machines), regularisation-based (ridge, logistic regression), neural-network based (MLP, CNN, RNN) and ensemble models (bagging, boosting, stacking).

Semi-Supervised Learning: These models use both labelled and unlabelled data—inductive (self-training, co-training, boosting) and transductive (graph-based generative, manifold, maximum-margin) methods.

Unsupervised Learning: Models analyse unlabelled data to uncover hidden patterns—cluster-based (K-means, hierarchical, DBSCAN), dimensionality-reduction (PCA, ICA) and neural-network based (autoencoders, GANs, Boltzmann networks).

Reinforcement Learning: An agent learns optimal actions in an interactive environment by maximising rewards, via model-based or model-free (policy optimisation, Q-learning) techniques.

4.2 Classical ML Algorithms Widely Applied to Horticulture

Decision Trees (DT) are intuitive models that partition data based on decision rules; easy to interpret but prone to over-fitting when used alone. Random Forests (RF), an ensemble of decision trees, improve predictive performance by reducing variance and handling non-linear relationships. RF models have been extensively used for yield prediction, disease classification and nutrient-status estimation in horticultural crops [1], [2], [25]. Support Vector Machines (SVM) are effective for high-dimensional data and have demonstrated strong performance in crop classification, disease detection and quality assessment using spectral features. K-Nearest Neighbours (KNN) is a simple, instance-based method that classifies samples based on similarity, though its performance depends on appropriate distance metrics and data normalisation.

4.3 Ensemble Learning and XGBoost

Ensemble learning combines multiple base learners to achieve better generalisation and robustness. Random Forest, Gradient Boosting Decision Trees (GBDT) and Extreme Gradient Boosting (XGBoost) are widely used in precision agriculture. XGBoost has gained particular popularity due to its high accuracy, computational efficiency and ability to handle complex non-linear interactions among variables. In horticulture, ensemble models have been applied to crop-recommendation systems using soil NPK, pH, temperature, rainfall and humidity data, as well as to yield prediction and stress assessment using RS-derived features [1], [4].

4.4 Deep Learning and Convolutional Neural Networks

Deep Learning, a subset of ML based on artificial neural networks with multiple hidden layers, has revolutionised image-based analysis in horticulture. Convolutional Neural Networks (CNNs) are particularly effective for processing RGB, multispectral and hyperspectral images. CNN-based models have been successfully applied to fruit detection, counting and sizing in orchards, enabling automated yield estimation and harvest planning. Deep-learning approaches also support disease detection by identifying subtle visual and spectral patterns associated with early infection stages [3], [14], [26].

4.5 Model Training, Validation and Performance Metrics

Robust ML model development requires careful partitioning of data into training, validation and testing sets—typically 70/15/15 or 80/20 splits. Cross-validation (5- or 10-fold) is commonly used to assess generalisation. Classification tasks are evaluated using accuracy, precision, recall and F1-score, while regression problems use coefficient of determination (R^2), root-mean-square error (RMSE) and mean absolute error (MAE). Interpretability techniques such as feature-importance analysis and SHAP (Shapley Additive Explanations) values help elucidate model behaviour and build user trust [15].

V. INTEGRATION OF REMOTE SENSING AND MACHINE LEARNING

The combination of RS and ML brings new possibilities for Precision Horticulture (PH). RS data exhibit significant complementarities in meeting PH needs, with hyperspectral RS being the most widely used and UAV RS offering the greatest per-hectare potential. Among ML algorithms, SVM is the most widely applied in horticultural literature, closely followed by Random Forest [22], [25]. The integrated workflow—from data acquisition through decision support—is illustrated in Fig. 6.

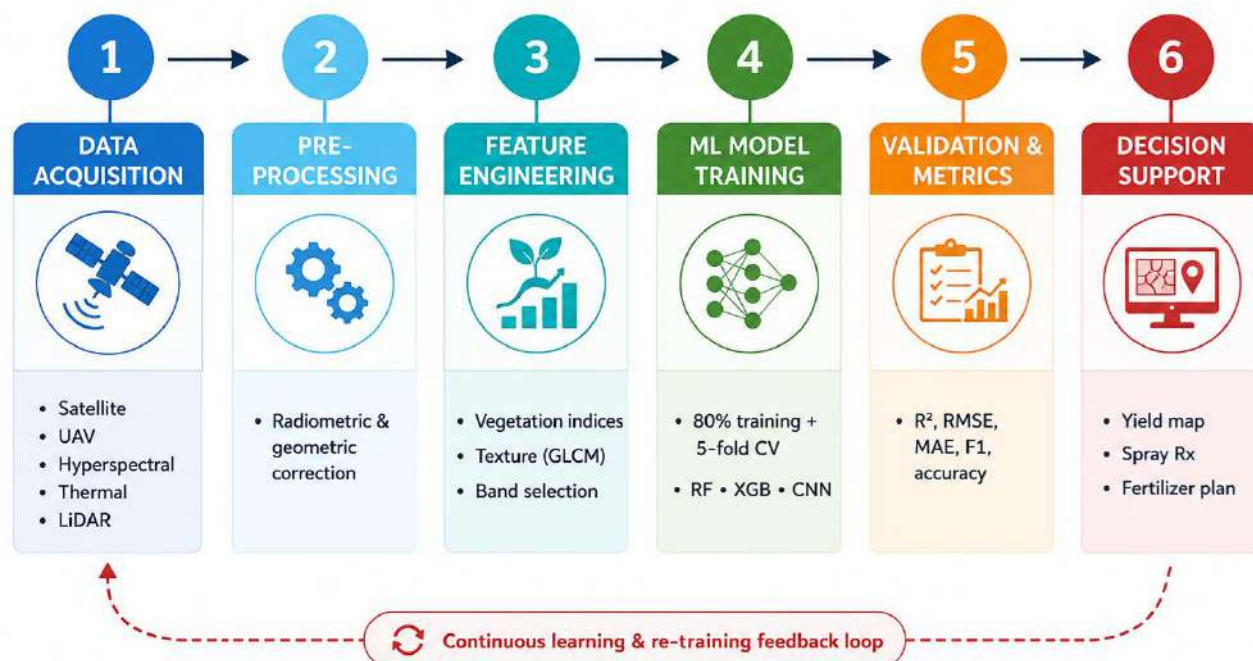


FIGURE 6: Integrated Remote-Sensing + Machine-Learning workflow for precision horticulture, showing six sequential steps and the feedback loop for continuous model improvement.

5.1 Key Application Areas of the RS + ML Combination

- **Crop-disease observation:** UAV RGB, multispectral and hyperspectral cameras coupled with CNN or SVM enable early detection of viral, fungal and bacterial diseases before visual symptoms appear [3].
- **Soil-water content estimation:** Random-Forest regression and SVR applied to UAV thermal, multispectral and hyperspectral data predict soil moisture with RMSE < 4%.
- **Weed detection:** Deep-learning models (MobileNetV2-UNet, FFB-BiseNetV2) applied to UAV imagery deliver real-time weed detection and classification.
- **Crop monitoring:** UAV multispectral and RGB cameras track crop height, phenology, chlorophyll content, flowering stages and yield potential.
- **Fruit-quality assessment:** Hyperspectral proximal sensing coupled with ANN, RF or DT accurately estimates total soluble solids, firmness, chlorophyll and colour of ripening fruits [2].

VI. RESEARCH FINDINGS AND CASE STUDIES IN PRECISION HORTICULTURE

This section synthesises five representative case studies published between 2019 and 2025 that collectively demonstrate the operational maturity of RS + ML in horticulture.

6.1 UAV Ensemble Learning for Leaf-Nitrogen Content in Custard Apple [1]

Jiang et al. (2025) [1] combined UAV multispectral imagery from a DJI Mavic 3M platform with a two-layer stacking ensemble learning framework to monitor leaf nitrogen content (LNC) in custard apple (*Annona squamosa* L.) orchards in Yuanmou County, China. Eleven vegetation indices (NDVI, MNDRE, NRI, RESR, TNDVI, WDRVI, NGI, MSR, NREI_R, RVI, NREI) were derived from green, red, red-edge and NIR bands. Eight Gray-Level Co-occurrence Matrix (GLCM) texture features were extracted per band. Five base learners—Random Forest, Gradient Boosting Decision Trees, Adaptive Boosting, Linear Regression and Extremely Randomised Trees—were stacked with Lasso regression as the meta-model. The optimised model achieved $R^2 = 0.661$, RMSE = 0.059 and MAE = 0.193 for LNC prediction across three growth stages, confirming the operational feasibility of UAV-based ensemble learning for site-specific nitrogen management in orchards.

Critical Evaluation: While the study demonstrates the feasibility of UAV-based ensemble learning, the R^2 value of 0.661 indicates that approximately 34% of the variance in leaf nitrogen content remains unexplained. This suggests that additional predictors (e.g., soil properties, microclimate, crop variety) may be needed for more accurate predictions. The study's reliance on a single orchard location also limits generalizability.

6.2 Hyperspectral + ML for Fruit Quality of Mango and Strawberry [2]

Elsayed et al. (2025) [2] evaluated the biochemical quality of mango cv. 'Succarri' and strawberry cv. 'Florida' at three ripening stages (unripe, ripe, overripe) using proximal hyperspectral reflectance (302–1148 nm, 2 nm spectral resolution) coupled with Artificial Neural Networks (ANN), Random Forest (RF) and Decision Trees (DT). Sixteen Spectral Reflectance Indices (SRIs)—four existing and twelve newly developed two-band indices—were used as inputs. The ANN model outperformed RF and DT for TSS, firmness and chlorophyll estimation, with R^2 values ranging 0.71–0.94 across ripening stages. This study established hyperspectral + ML as a robust non-destructive alternative to conventional laboratory-based fruit-quality analysis.

Critical Evaluation: The study's strength lies in its high R^2 values (0.71–0.94), indicating strong predictive performance. However, the laboratory-based hyperspectral measurements (handheld sensor) may not translate directly to field-based remote sensing applications. The limited sample size and single cultivar per crop also limit generalizability.

6.3 UAV Hyperspectral + ML for Citrus Canker Detection [3]

Abdulridha, Batuman and Ampatzidis (2019) [3] employed a UAV-mounted hyperspectral camera and machine-learning classifiers to detect citrus canker disease in Florida orchards. The workflow combined spectral reflectance analysis with SVM and neural-network classifiers, achieving disease-detection accuracy > 90% at symptomatic and 82% at asymptomatic stages, thereby confirming UAV-hyperspectral systems as viable precision-management tools for perennial fruit orchards.

Critical Evaluation: The high accuracy (>90% for symptomatic detection) is impressive. However, the study was conducted in a single region (Florida) with a specific citrus variety. The asymptomatic detection accuracy (82%) suggests that early detection capability, while promising, still has room for improvement.

6.4 ML-Based Crop and Fertiliser Recommendation under NPK, pH and Climate [4]

Dey, Ferdous and Ahmed (2024) [4] developed an ML-based recommendation system for agricultural and horticultural crop farming in India, integrating soil NPK, pH, temperature, rainfall and humidity variables. XGBoost achieved the highest accuracy—99.09% for agricultural crops and 99.3% for horticultural crops—outperforming previous studies that reported 95.62% accuracy for XGBoost in mixed-crop models. The output supports user-friendly precision-agriculture tools to optimise crop selection and nutrient application.

Critical Evaluation: While the high accuracy (99.3%) is notable, the recommendation system relies on static soil and climate inputs rather than dynamic, real-time data. The model's performance may vary under different soil types and climatic conditions not represented in the training data.

6.5 RS + GIS Soil-Site Suitability for Six Major Fruit Crops [5]

Narasimha Yadav et al. (2023) [5] evaluated 21 soil series of the Ganjigatti sub-watershed (5B1A4F), Dharwad district, Karnataka (15° 10'–15° 17' N, 75° 0'–75° 4' E, elevation 610 m MSL, annual rainfall 917 mm) using RS + GIS on ArcGIS v10.8. Suitability was assessed following FAO (1976) and Naidu et al. (2006) frameworks across three phases—landscape and soil characteristics, crop-specific requirements, and rainfed limitations (no, slight, moderate, severe, very severe). Ten soil series (BGD, BNK, KDK, KMD, KRL, MLP, MRK, SDK, SSK, YSJ) were classified as N (currently not suitable) due to severe limitations of soil depth and slope. AKT, BGH and MVD were moderately to marginally suitable for mango, guava, pomegranate, sapota, citrus and grape. This case study underscores the operational value of RS + GIS for landscape-scale horticultural land-use planning.

Critical Evaluation: The study's strength is its systematic approach to land suitability assessment. However, the classification is based on static soil and terrain parameters rather than dynamic climatic and market conditions that may affect the viability of fruit cultivation.

6.6 Comparative Summary of Case Studies

TABLE 1
COMPARATIVE SUMMARY OF CASE STUDIES

Case	Crop	Sensor / Platform	ML Model	Key Performance	Limitations
Jiang et al., 2025 [1]	Custard apple	UAV multispectral	Stacking ensemble	$R^2 = 0.661$, RMSE = 0.059	Single location; unexplained variance
Elsayed et al., 2025 [2]	Mango, Strawberry	Handheld hyperspectral	ANN, RF, DT	R^2 0.71–0.94	Lab-based; limited sample size
Abdulridha et al., 2019 [3]	Citrus	UAV hyperspectral	SVM, ANN	Accuracy > 90%	Single region; asymptomatic accuracy 82%
Dey et al., 2024 [4]	Multi-crop	Soil + climate variables	XGBoost	Accuracy 99.3%	Static inputs; limited soil diversity
Narasimha et al., 2023 [5]	6 fruit crops	Satellite + GIS	Rule-based suitability	21 series → S1-N	Static parameters; no economic assessment

VII. INDIAN NATIONAL PLATFORMS AND OPERATIONAL APPLICATIONS



FIGURE 7: Application wheel of RS + ML in futuristic horticulture—ten operationally-validated domains with representative performance metrics.

7.1 CHAMAN—Coordinated Horticulture Assessment and Management

Coordinated Horticulture Assessment and Management using Geo-informatics (CHAMAN) is a national mission project under the Mission for Integrated Development of Horticulture (MIDH), Ministry of Agriculture and Farmers Welfare, Government of India. It has extensively used satellite data for inventory of major horticultural crops (mango, banana, citrus) across 40 selected districts of the country, establishing the largest RS-based horticultural inventory in India [16].

7.2 Pradhan Mantri Fasal Bima Yojana (PMFBY)—Crop Insurance

PMFBY is the national flagship crop-insurance programme. The National Remote Sensing Centre (NRSC) conducts geomatics-based studies to improve area-yield estimates for insurance mechanisms. A Crop Insurance Decision Support System (CIDSS) is being developed as a web-enabled integrated package for States, improving efficiency, transparency and objective decision-making in sampling design and yield estimation [16].

7.3 Bhoonidhi and Bhuvan—Open RS Data Portals

Bhoonidhi (ISRO Open Data Access) is a single-window portal disseminating IRS and non-IRS satellite data products online. Under the Indian Space Policy 2023, satellite data of 5 m and coarser resolution are free and open to all users; finer data (except DEM, merged, mosaicked and customised products) are free for government entities and priced for non-government users. Available resolutions span very-high (0.1–1 m), high (1–5 m), medium (5–25 m), low (25–100 m) and coarse (100 m–1 km). Sensor types include AIS, AVHRR, AWiFS, LISS-1/2/3/4, MODIS, OCM, OLI+TIRS, PAN, SAR, SCAT, VIIRS and WiFS. Bhuvan, ISRO's Indian Geo-portal, complements Bhoonidhi by providing thematic visualisation and value-added services [16], [17].

Critical Evaluation: While these platforms provide valuable data access, challenges remain in data discovery, processing and integration for horticultural applications. The fine-resolution data (0.1–1 m) required for tree-level analysis is not freely available, limiting their use for smallholder orchard monitoring.

VIII. CHALLENGES, LIMITATIONS AND WAY FORWARD

Despite substantial advances, the widespread adoption of RS, GIS and ML in precision horticulture faces several technical, operational, economic and ethical challenges. A SWOT synthesis is presented in Fig. 8.



FIGURE 8: SWOT analysis of RS + ML in horticulture—strengths, weaknesses, opportunities and threats for Indian precision-horticulture ecosystems.

8.1 Data Quality, Availability and Ground-Truth Constraints

The accuracy of RS + ML systems depends heavily on the quality and representativeness of input data. Variability in sensor calibration, atmospheric conditions, illumination geometry and acquisition timing introduces noise and uncertainty into spectral

measurements. Complex orchard canopies and background effects further complicate interpretation. Ground-truth data collection remains a major bottleneck for perennial orchards, and insufficient ground truth leads to model over-fitting and reduced generalisability across seasons and locations.

8.2 Sensor, Platform and Resolution Limitations

Each platform involves inherent trade-offs. Satellite data offer broad coverage but often lack the resolution required for tree-level analysis. UAVs provide high-resolution data but are constrained by limited coverage, flight regulations and weather. Hyperspectral and LiDAR sensors, though information-rich, are expensive and generate large data volumes demanding substantial computational resources [22].

8.3 Model Generalisability and Interpretability

ML models trained on one crop, region or season may not generalise well to different conditions. Deep-learning models in particular are often treated as black boxes, complicating adoption by farmers and policymakers. Explainable-AI techniques such as SHAP values are increasingly essential to build trust and regulatory acceptance [15].

8.4 Economic and Digital-Divide Barriers

High initial investment in sensors, computing infrastructure and skilled personnel limits adoption by small and marginal horticulturists. Bridging this divide requires public-private partnerships, custom-hiring service models, subsidised UAV services and integration with existing extension networks. The digital divide—access to technology, internet connectivity and digital literacy—remains a significant barrier for smallholder farmers in rural India.

8.5 Policy and Institutional Constraints

The lack of clear policies on data ownership, privacy and sharing, particularly for UAV and farmer-level data, hinders the development of scalable RS + ML solutions. Regulatory restrictions on drone operations and the absence of standardised data formats further complicate deployment.

8.6 Way Forward

- 1) **Establish national ground-truth data repositories** for major horticultural crops and orchard systems, with standardised protocols for data collection and sharing.
- 2) **Promote low-cost, MSME-fabricable UAV and sensor platforms** for last-mile deployment, reducing the cost barrier for smallholder adoption.
- 3) **Expand Bhoonidhi and Bhuvan** to include pre-computed vegetation-index products and ML-ready analysis-ready-data (ARD) cubes.
- 4) **Integrate 5G, edge computing and IoT** to enable in-field ML inference and real-time decision support.
- 5) **Strengthen farmer capacity** through cooperative Custom Hiring Centres (CHC) and Farmer Producer Organisations (FPOs) offering RS + ML as a service.
- 6) **Develop crop-specific benchmark datasets** and open-source ML libraries tailored to Indian horticulture (mango, banana, citrus, grape, guava, tomato, chilli, potato).
- 7) **Establish public-private partnerships** to fund infrastructure development, technology transfer and capacity building.
- 8) **Develop clear data policies** on ownership, privacy and sharing to facilitate collaborative research and deployment.
- 9) **Create regulatory frameworks** that enable safe and scalable UAV operations for agricultural monitoring.

IX. CONCLUSION

Remote Sensing and Machine Learning constitute two mutually reinforcing pillars of futuristic horticulture. RS provides multi-scale, multi-temporal, multi-spectral windows into the orchard environment, while ML converts the resulting high-dimensional data into actionable knowledge. Together, they are reshaping horticulture across every operational domain—yield forecasting, disease detection, nutrient monitoring, irrigation, fruit-quality assessment, weed detection, site-suitability planning and crop

insurance. Case-study evidence from India, China, USA and Egypt demonstrates R^2 values of 0.66–0.94, accuracy > 90% and RMSE reductions of one order of magnitude against classical statistical methods.

For India, the confluence of Agriculture 5.0 principles, open-data platforms like Bhoonidhi and Bhuvan, national missions like MIDH-CHAMAN and PMFBY, and a growing agri-tech start-up ecosystem creates an unprecedented opportunity to leap-frog into intelligent, sustainable horticultural production. Addressing the current limitations of ground-truth scarcity, sensor cost, model interpretability and digital divide through coordinated policy, technology transfer and capacity building will determine how quickly this promise is realised. The next decade of Indian horticulture will be defined not merely by hectares under cultivation, but by the depth of digital intelligence guiding every hectare.

Limitations of the Review: This review is based on a narrative synthesis of published literature rather than a formal systematic review. The case studies were selected to represent diversity in crops, sensors and ML approaches, but may not be exhaustive of all relevant research. The review focuses primarily on Indian and international studies published in English, potentially overlooking research in other languages or regional contexts.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Detection and Histopathological Characterization of *Megalocytivirus pagrus 1* (ISKNV) in Nile Tilapia (*Oreochromis niloticus*) under Experimental Infection and Density Stress

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Abstract— The project encompasses the investigation of the presence of *Megalocytivirus pagrus 1* (subtype ISKNV) in fish (*Oreochromis niloticus*), which has serious implications for animal health, public health and agribusiness. We aimed at the prospection and detection of ISKNV with molecular and histological techniques. Viral fish diseases caused by viruses of the family Iridoviridae, to which ISKNV belongs, are distributed worldwide and represent a real threat to the expansion of the global aquaculture system, due to their pathogenicity, which causes significant economic losses. Thus, the improvement and application of existing diagnostic techniques become necessary to control or prevent the advance of this virosis among countries and in Brazil. In addition, studies in our field that aim to detect and characterize them in a more comprehensive way are scarce. We were able to evidence the presence of the virus through clinical signs during the experiment, detection of genetic material by conventional PCR and by the presence of inclusion bodies, identified by histopathological analysis. We observed a higher infection rate in the period of 14 days after infection by intraperitoneal viral inoculation, as well as greater viral proliferation in the treatment submitted to stress, however without resulting in mortality.

Keywords— *Megalocytivirus pagrus 1* (ISKNV), *Oreochromis niloticus*, Diagnostic techniques.

I. INTRODUCTION

The expansion of aquaculture in recent decades, driven by the increase in global demand for fish, has promoted significant changes in production systems, especially with the increase in stocking density and the intensification of management. In Brazil, tilapia (*Oreochromis niloticus*) stands out as the main cultivated species, representing approximately 42% of national production, which exceeded 700 thousand tons in 2024 (Associação Brasileira de Aquicultura, 2024). On a global scale, aquaculture production intended for human consumption reached around 94 million tons in 2022, evidencing the economic relevance of the sector (FAO, 2024).

However, the intensification of production systems favors the occurrence and dissemination of infectious diseases, since high population densities and controlled environmental conditions may act as predisposing factors for epizootic outbreaks. In this context, viral agents assume a prominent role, especially due to their high transmission capacity and potential to cause expressive economic losses (Wang et al., 2011).

Among the viruses of sanitary importance in aquaculture, members of the family Iridoviridae stand out, especially the genus *Megalocytivirus*, responsible for systemic infections in several species of freshwater and marine fish (Koda et al., 2018). *Megalocytivirus pagrus 1* (subtype ISKNV) is considered an emerging pathogen, with wide geographical distribution

and capacity to infect more than 50 fish species. The infection may result in significant mortality, especially in initial stages of development, such as fingerlings and juveniles.

Clinically, ISKNV infection presents nonspecific signs, including lethargy, anorexia, swimming alterations, hyperpigmentation and cutaneous lesions. From the histopathological point of view, it is characterized by the presence of cytomegalic cells and intracytoplasmic inclusions in multiple organs, such as kidney, spleen, liver and intestine, these alterations being considered important markers for the diagnosis of the disease (Yanong & Waltzek, 2010; Wang et al., 2011).

The detection of ISKNV can be performed by means of different diagnostic approaches, including molecular techniques, such as polymerase chain reaction (PCR), and histopathological analyses.

Given this scenario, the present study aimed to investigate the presence of *Megalocytivirus pagrus 1* (subtype ISKNV) in Nile tilapia submitted to experimental infection, associated with high-density stress, through the integrated application of molecular and histological techniques (Guo et al., 2025).

General Objective: Improvement and application of molecular and histological diagnostic techniques for the detection and characterization of *Megalocytivirus pagrus 1* (subtype ISKNV).

Specific Objectives: (1) to perform experimental infection by intraperitoneal inoculation of viral extract in Nile tilapia, (2) to evaluate the presence of viral genetic material after experimental infection by means of the conventional PCR technique, and (3) to perform histopathological analyses by means of the hematoxylin-eosin staining technique (H&E) for the evaluation of post-infection tissue alterations.

II. MATERIAL AND METHODS

The experiment was conducted at the Fisheries and Biological Institutes of São Paulo, in the Multiuser Laboratory for Experimentation and Interinstitutional Aquaculture Health (LISA).

2.1 Ethical Approval

The study was conducted in accordance with the ethical principles of animal experimentation. All procedures were approved by the Institutional Animal Care and Use Committee (Protocol No. [to be specified by the authors]).

2.2 Transport and Acclimatization

The animals were acquired from a fish farm in Vale do Paraíba, in Pindamonhangaba/SP, and transported in 60 L bags containing water and oxygen. Subsequently, they were acclimatized in two 100 L tanks for 30 days.

2.3 Physical and Feeding Management

During the experimental period, the tanks were siphoned daily for the removal of dirt and mortality recording. The fish were fed with feed corresponding to 3% of the biomass, divided into two daily portions.

2.4 Experimental Design

The experiment lasted 14 days. The viral inoculum was prepared from tissue samples (25 mg) previously positive for *Megalocytivirus pagrus 1* (subtype ISKNV), presenting Ct 24. The material was macerated in 500 µL of sterile PBS under laminar flow and subsequently centrifuged at $16,000 \times g$, for 10 min, at 4 °C, with the supernatant being used as inoculum.

Before the experimental infection, the fish were anesthetized using a eugenol solution prepared with 8 mL of eugenol diluted in 50 mL of alcohol. Then, the animals were inoculated intraperitoneally and transferred to their respective experimental aquariums.

The experimental design was completely randomized, composed of four treatments with two simultaneous replicates:

- **T1** — negative control (without inoculation);
- **T2** — control inoculated with PBS;

- **T3** — fish infected with ISKNV;
- **T4** — fish infected with ISKNV (high density).

All groups were subjected to the condition of high-density stress. Aquariums of 12 L were used, with random distribution of the fingerlings. In treatments T1, T2 and T3, 12 fish per aquarium were housed, while in T4, 28 fish per aquarium were maintained. Additionally, treatment T3 had an extra replicate intended for histological sampling, totaling 104 fish in the experiment (Figure 1).

All sampled and surviving animals were anesthetized with eugenol (75 mg L⁻¹), euthanized by spinal cord section, autoclaved and properly discarded. The materials used and the aquarium water were disinfected with chlorine at 10 ppm for 24 h.

In the first collection, 12 fish were sampled, six from T3 and six from T4 (three from each replicate) to confirm the experimental infection. In the second collection, 42 fish were sampled for PCR analysis, six from T1, four from T2, eight from T3 and 24 from T4, in addition to 24 fish intended for histopathological analysis. The organs collected were kidney and spleen, subsequently fixed in 10% buffered formalin for seven days for histopathology or stored frozen in 1.5 mL microtubes for subsequent molecular analysis by PCR.

2.5 Conventional PCR

DNA extraction was performed using the commercial Wizard® Genomic DNA Purification kit (Promega®, 2023), following the manufacturer's instructions.

Viral detection was conducted by conventional PCR using the GoTaq® G2 Master Mix (Promega®) and the primers MCP-uni332-F3 (5'-AGGTGTCGGGCGCAAAG-3') and MCP-uni1108-R8 (5'-TCTCAGGCATGCTGGGCGCAAAG-3'), described by Kurita and Nakajima (2012), which amplify a 777 bp fragment of the MCP gene. The amplification conditions consisted of initial denaturation at 95 °C for 5 min, followed by 30 cycles of 94 °C for 30 s, 58 °C for 30 s and 72 °C for 1 min, with final extension at 72 °C for 5 min.

The amplified products were submitted to electrophoresis in 2.4% agarose gel, using Nucleic Acid Stain (Cellco®) for staining, and visualized in a Gel Doc™ XR+ system (Bio-Rad®) through the Image Lab software. The analyses were performed using spleen and kidney samples collected at 7 and 14 days post-infection, with pooled extraction being performed when necessary.

2.6 Histological Technique (Hematoxylin-Eosin – H&E)

The samples were processed at the Laboratory for Investigation in Aquaculture Health (LISA) according to the protocol described by Michalany (1980), including the steps of dehydration in increasing series of alcohols, clearing, paraffin embedding, microtomy and staining by the hematoxylin-eosin technique (H&E).

2.7 Histopathological Scoring

For semi-quantitative analysis, histopathological lesions were scored using a standardized system: 0 = absent, 1 = mild, 2 = moderate, 3 = severe. Lesions evaluated included inclusion bodies, inflammatory infiltrate, glomerulotubulonephrosis, tubular vacuolization, melanomacrophage centers, and hemorrhage. Scores were compared between treatments and sampling periods.

2.8 Biometry and Acclimatization

The animals had a mean body weight of 9.28 ± 3.2 g, and the mean water temperature during the experimental period was 24.93 ± 1.52 °C.

2.9 Clinical Signs

Infected fish showed clinical signs characterized by erratic swimming, melanosis, anorexia, lethargy, continuous stress, ascites, cutaneous hemorrhagic lesions, and friable kidneys (Figure 1). In the groups subjected to high-density stress, the formation of more cohesive schools was observed, indicating a behavioral change associated with the stress condition. In contrast, the control groups (T1 and T2) showed no relevant clinical changes throughout the experimental period.

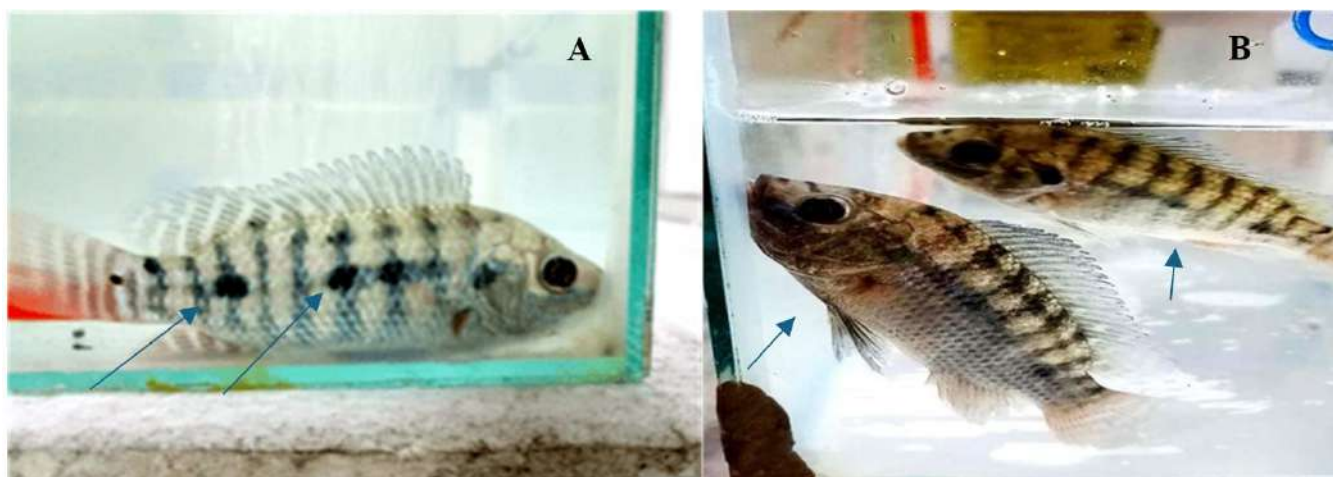


FIGURE 1: A. Melanosis near the lateral line (long arrow). B. Erratic swimming and cutaneous lesions (short arrow).

2.10 Statistical Analysis

All statistical analyses were performed using [specify software, e.g., GraphPad Prism or SPSS]. Differences in PCR positivity rates between treatments and sampling periods were analyzed using Fisher's exact test. Histopathological scores were compared using the Mann-Whitney U test (for two groups) or Kruskal-Wallis test followed by Dunn's post-hoc test (for multiple groups). Significance was set at $p < 0.05$. Data are presented as mean $\pm$ standard deviation where applicable.

III. RESULTS

3.1 PCR

Of the 32 samples analyzed, 43.75% (14/32) tested positive in groups T3 and T4, whereas all six samples from the control groups (T1 and T2) were negative.

A higher number of positive samples was observed on day 14 compared with day 7 post-infection. On day 7, 2 out of 12 samples (16.7%) were positive, while on day 14, 12 out of 20 samples (60.0%) were positive (Fisher's exact test, $p < 0.05$). Additionally, the high-density stress group (T4) showed a higher positivity rate (11/18, 61.1%) compared to the infected group without stress (T3) (3/14, 21.4%) on day 14 (Fisher's exact test, $p = 0.04$).

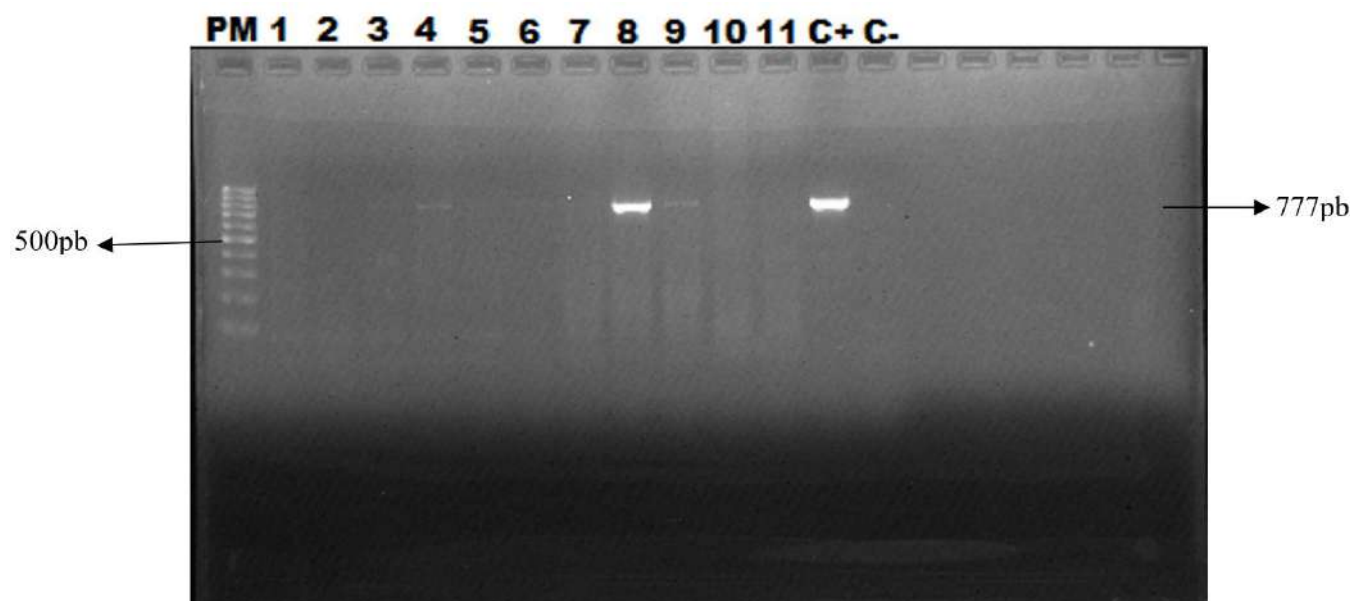


FIGURE 2: Electrophoresis of PCR-amplified DNA products for the amplification of a fragment of the MCP region of *Megalocytivirus pagrus* 1 (subtype ISKNV) on days 7 and 14. PM:

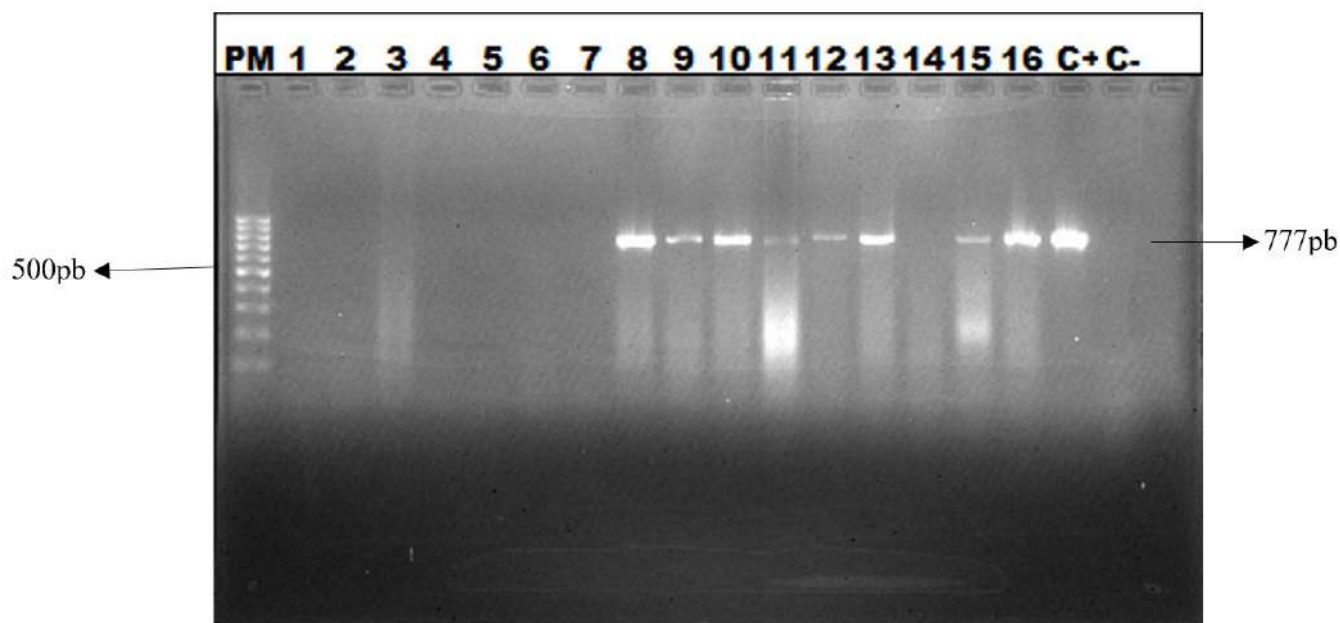


FIGURE 3: Electrophoresis result of PCR-amplified DNA products for the amplification of a fragment of the MCP region of *Megalocytivirus pagrus 1* (subtype ISKNV) on day 14. PM: molecular weight marker (100 bp DNA Ladder, Celco®); lanes 1 to 6: control samples (T1 and T2); lanes 7 to 16: infected DNA samples (T3 and T4); C+: positive control; C-: negative control.

TABLE 1
CONVENTIONAL PCR RESULTS BY TREATMENT ON DAY 7

Sample	Treatment	Aquarium	PCR
1	T3	Infected	Negative
2	T3	Infected	Negative
3	T3	Infected	Positive
4	T3	Infected	Positive
5	T3	Infected	Negative
6	T3	Infected	Negative
7	T4	Infected	Negative
8	T4	Infected	Negative
9	T4	Infected	Negative
10	T4	Infected	Negative
11	T4	Infected	Negative
12	T4	Infected	Negative

TABLE 2
CONVENTIONAL PCR RESULTS BY TREATMENT ON DAY 14

Sample	Treatment	Aquarium	PCR
1	T1	Control	Negative
2	T1	Control	Negative
3	T1	Control	Negative
4	T1	Control	Negative
5	T1	Control	Negative
6	T1	Control	Negative
7	T2	Control	Negative
8	T2	Control	Negative
9	T2	Control	Negative
10	T2	Control	Negative
11	T3	Infected	Positive
12	T3	Infected	Negative
13	T3	Infected	Negative
14	T3	Infected	Negative
15	T3	Infected	Positive
16	T3	Infected	Negative
17	T3	Infected	Positive
18	T3	Infected	Positive
19	T4	Infected	Positive
20	T4	Infected	Positive
21	T4	Infected	Positive
22	T4	Infected	Positive
23	T4	Infected	Positive
24	T4	Infected	Positive
25	T4	Infected	Positive
26	T4	Infected	Positive
27	T4	Infected	Positive
28	T4	Infected	Positive
29	T4	Infected	Positive
30	T4	Infected	Positive
31	T4	Infected	Negative
32	T4	Infected	Positive
33	T4	Infected	Positive
34	T4	Infected	Positive
35	T4	Infected	Positive
36	T4	Infected	Negative
37	T4	Infected	Negative
38	T4	Infected	Negative
39	T4	Infected	Negative
40	T4	Infected	Negative
41	T4	Infected	Negative
42	T4	Infected	Negative

3.2 Histopathology

Histopathological analysis revealed significant alterations in the kidney and spleen of the infected groups. In the kidney, lesions were characterized by glomerulotubulonephrosis, tubular vacuolization and hyalinization, subcortical hemorrhage, enlargement of Bowman's space, inflammatory infiltrate, and the presence of scattered melanomacrophages, as well as an increase in melanomacrophage centers.

Inclusion bodies were identified in medullary and cortical regions in treatments T3 and T4. In treatment T3, these structures were observed in both sampling periods, at 7 and 14 days post-infection (Figures 4 and 5). Histopathological scores were significantly higher in infected groups compared to controls ($p < 0.05$), with higher scores observed on day 14 compared to day 7 (Mann-Whitney U test, $p < 0.05$).

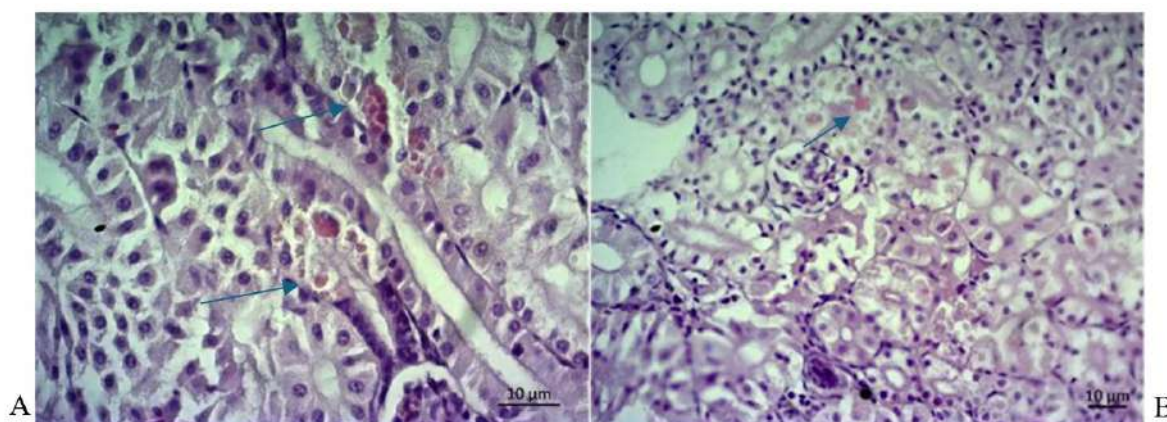


FIGURE 4: Photomicrograph of kidney tissue from Nile tilapia (*Oreochromis niloticus*) experimentally infected with *Megalocytivirus pagrus* 1, subtype ISKNV, at 7 days of experimentation. T3: infected animals without stress. A – Arrows indicate inclusion bodies in the medullary region of the histological section, monolymphocytic glomerulotubulonephritis, and tubular vacuolization in the cortical regions. HE staining; 630× magnification. B – Arrows indicate inclusion bodies near the cortical regions of the histological section and monolymphocytic glomerulotubulonephritis in the central region. HE staining; 400× magnification.

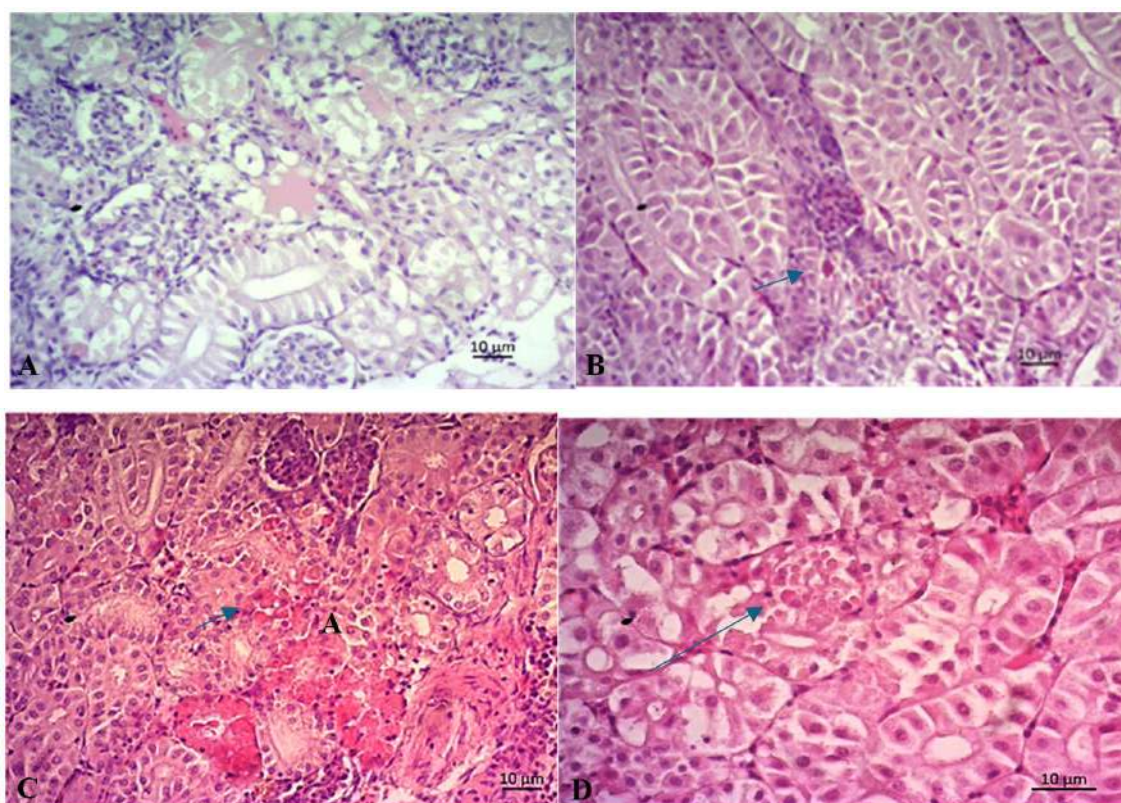


FIGURE 5: Photomicrograph of kidney tissue from Nile tilapia (*Oreochromis niloticus*) experimentally infected with *Megalocytivirus pagrus* 1, subtype ISKNV, at 14 days of experimentation. T4: infected animals subjected to stress; and T3: infected animals without stress. A – Hyalinized and/or vacuolated glomeruli and tubules. HE staining; 400× magnification. B – Arrows indicate inclusion bodies in the medullary and cortical regions of the section. HE staining; 400× magnification. C – Tubular hyalinization with the presence of melanomacrophages and structures suggestive of inclusion bodies. HE staining; 400× magnification. D – Arrow indicates structures suggestive of inclusion bodies in the central region of the section. HE staining; 630× magnification.

In the spleen, the alterations observed in treatments T3 and T4 included subcapsular hemorrhage, vascular congestion, hemosiderin deposition, increased numbers of melanomacrophages, and lymphoid hypoplasia. Additionally, inclusion bodies were identified in splenic parenchyma (Figure 6).

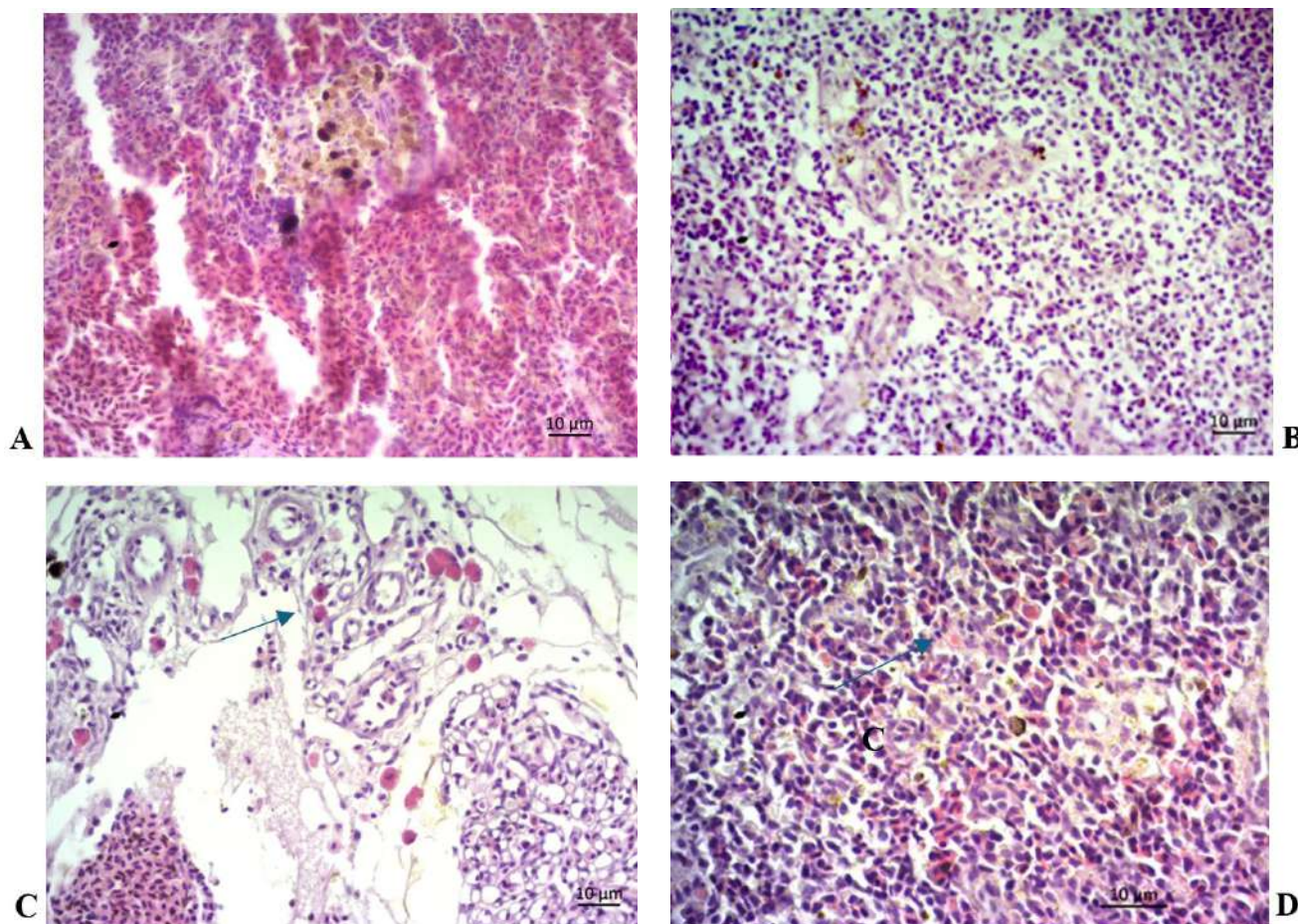


FIGURE 6: Photomicrograph of splenic tissue from Nile tilapia (*Oreochromis niloticus*) experimentally infected with *Megalocytivirus pagrus* 1, subtype ISKNV, at 7 and 14 days of experimentation. T4: infected animals subjected to stress; and T3: infected animals without stress. A – Melanomacrophage center in the medullary region, congested erythrocytes in the cortical regions, and lymphoid follicle hypoplasia near the white pulp. H&E staining; 630× magnification. B – Splenic hypoplasia throughout the section parenchyma and focal melanomacrophages in the medullary region of the histological section. H&E staining; 400× magnification. C – Red arrows indicate multiple eosinophils and a congested area in the pulp with hemosiderin deposition. H&E staining; 400× magnification. D – Arrows indicate an inclusion body in the splenic parenchyma. H&E staining; 630× magnification.

Inclusion bodies were identified at 7 and 14 days post-infection. On day 14, a greater extent of lesions was observed, associated with an increase in inflammatory infiltrate (Figures 5 and 6). Additionally, all infected samples showed renal lesions, indicating kidney involvement during the experimental infection (Figures 4 and 5).

**TABLE 3
SUMMARY OF HISTOPATHOLOGICAL FINDINGS**

Lesion Type	T1 (Control)	T2 (PBS)	T3 (ISKNV)	T4 (ISKNV + Stress)
Inclusion Bodies	Absent	Absent	Present (Day 7 & 14)	Present (Day 7 & 14)
Glomerulotubulonephrosis	Absent	Absent	Moderate (Day 7) / Severe (Day 14)	Moderate (Day 7) / Severe (Day 14)
Tubular Vacuolization	Absent	Absent	Mild-Moderate	Moderate-Severe
Inflammatory Infiltrate	Absent	Absent	Mild (Day 7) / Moderate (Day 14)	Moderate (Day 7) / Severe (Day 14)
Melanomacrophage Centers	Minimal	Minimal	Increased	Markedly Increased
Splenic Lesions	Absent	Absent	Present	Present

IV. DISCUSSION

The results obtained in this study confirm the occurrence of infection by *Megalocytivirus pagrus* 1 (ISKNV) in tilapia subjected to experimental infection, as evidenced by molecular detection using PCR and corroborated by the histopathological findings. The identification of cytomegalic cells and intracytoplasmic inclusions in organs such as the kidney and spleen is consistent with the classical pattern described for megalocytivirus infections in different fish species (Dong et al., 2008; He et al., 2001; Wang et al., 2011; Subramaniam et al., 2016; Liu et al., 2019), reinforcing the biological consistency of the experimental model employed.

The higher frequency of viral detection on day 14 (60.0%) compared with day 7 (16.7%) indicates progression of the infection throughout the experimental period, suggesting an increase in viral load in the analyzed tissues ($p < 0.05$, Fisher's exact test). This temporal pattern is compatible with the viral replication dynamics previously described for ISKNV (Maganha et al., 2018) and indicates that the experimental period was sufficient to establish a detectable systemic infection.

Despite confirmation of infection and the presence of clinical signs and evident histopathological alterations, no mortality was observed in the infected group subjected to high-density stress. This finding contrasts with studies reporting high mortality rates associated with ISKNV, particularly in early developmental stages (Subramaniam et al., 2016; Wang et al., 2011). This discrepancy suggests that factors such as the viral dose used, strain virulence, observation period (14 days), or physiological characteristics of the animals may have influenced the course of infection in the present study. It is possible that a longer observation period or higher viral dose would have resulted in mortality. The absence of mortality may also reflect the use of a less virulent strain or the age of the fish (juveniles may be more resistant than fingerlings).

Although high-density stress did not result in increased mortality up to day 14, a higher frequency of viral detection was observed in the groups subjected to this condition (T4: 61.1% vs. T3: 21.4% on day 14; $p = 0.04$, Fisher's exact test). This pattern suggests a possible increase in viral dissemination, potentially associated with greater contact among individuals and continuous exposure to contaminated water. Behavioral changes, such as the formation of more cohesive schools in the stressed groups, may have contributed to this scenario, since they increase proximity among individuals and favor horizontal transmission of pathogens (Rodrigues et al., 2021). In addition, high-density stress may impair the immune response of fish, favoring infection progression (Molico, 2013). In this context, the absence of mortality does not indicate absence of biological impact, but rather a possible modulation of infection severity under the experimental conditions evaluated.

The presence of clinical signs, such as lethargy, melanosis, and swimming abnormalities, associated with consistent histopathological alterations, indicates that the infection was biologically relevant. These findings agree with previous descriptions of megalocytivirus infection (Maganha et al., 2018; Silva, 2022) and reinforce the importance of an integrated assessment combining clinical signs, histopathology, and molecular methods.

The histopathological alterations observed in this study are compatible with infection by *Megalocytivirus*, as described by Zhu et al. (2021) and Martins et al. (2015, 2022). However, they differ from experimental models using *Danio rerio*, in which more extensive tissue necrosis has been described (Xu et al., 2008). This difference may reflect variations in susceptibility among species, viral strain virulence, or the experimental conditions employed. The detection of inclusion bodies in the analyzed tissues, especially more evident on day 14, suggests intensification of viral replication over time, corroborating the molecular findings. The semi-quantitative histopathological scoring confirmed that lesion severity increased from day 7 to day 14 ($p < 0.05$), with higher scores observed in the high-density stress group (T4) compared to the infected group without stress (T3).

Detection of viral DNA by PCR demonstrated high sensitivity, confirming its applicability as a diagnostic tool for ISKNV, as widely documented (Kurita & Nakajima, 2012; WOA, 2025; Joahan et al., 2023; Saksmerprom et al., 2025). The use of conventional PCR with primers targeting the MCP gene proved effective for detecting the virus in both kidney and spleen tissues.

Limitations of the Study: The study did not perform quantitative PCR (qPCR), which would have allowed quantification of viral load and more precise assessment of viral replication dynamics. The observation period was limited to 14 days, which may have been insufficient to observe mortality. Stress indicators (e.g., cortisol, glucose) were not measured to confirm the physiological impact of high-density stress. The viral dose was not quantified (only tissue homogenate volume was specified). Future studies should address these limitations by incorporating qPCR, longer observation periods, stress biomarker measurements, and viral dose quantification.

Taken together, the results demonstrate that the integrated approach using PCR and histopathology was effective in detecting ISKNV infection. The study contributes to the understanding of ISKNV infection dynamics in tilapia and highlights the potential role of density stress in modulating viral dissemination.

V. CONCLUSION

The results of this study confirm that experimental infection with *Megalocytivirus pagrus 1* (ISKNV) was successfully established in Nile tilapia, as detected by PCR and corroborated by characteristic histopathological alterations, especially in the kidney and spleen. The integrated diagnostic approach combining PCR and histopathology proved effective for detecting viral infection.

The absence of mortality, even in the groups subjected to high-density stress, indicates that, under the experimental conditions evaluated, the infection did not progress to lethal outcomes during the analyzed period, despite the presence of clinical signs and evident tissue lesions. This finding suggests that factors such as exposure time, viral load, and environmental conditions may influence the expression of ISKNV pathogenicity. A longer observation period or higher viral dose may be necessary to induce mortality.

A trend toward greater viral dissemination was observed in the groups subjected to density stress (T4: 61.1% positivity vs. T3: 21.4% on day 14; $p = 0.04$), indicating that intensive farming conditions may act as modulators of infection dynamics, favoring viral transmission even in the absence of increased mortality. High-density stress may impair the immune response and increase contact among individuals, facilitating viral spread.

Thus, the results obtained contribute to the understanding of ISKNV infection dynamics in tilapia and reinforce the importance of combined diagnostic strategies, especially in intensive production systems, where stress factors may influence the dissemination of pathogenic agents.

Limitations: The study did not perform qPCR to quantify viral load, did not measure stress biomarkers, and the observation period was limited to 14 days. Future research should address these limitations by incorporating qPCR, stress biomarker measurement, longer observation periods, and viral dose quantification.

Future Research Directions: Future studies should investigate the effects of different viral doses, longer observation periods, and other stress factors on ISKNV infection dynamics. The development of qPCR assays for viral load quantification and the measurement of stress biomarkers (cortisol, glucose) would provide more comprehensive data on the mechanisms underlying stress-induced susceptibility to ISKNV.

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DECLARATIONS

Conflict of Interest: The authors declare no conflicts of interest regarding the publication of this manuscript.

Data Availability: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Outbreak of Cutaneous Papillomatosis in Buffaloes (*Bubalus bubalis*): Diagnosis by Transmission Electron Microscopy

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Abstract— Papillomatosis is an emerging infectious disease that causes significant economic losses in intensive and semi-intensive buffalo production systems. In dairy herds, the disease impairs milking, causes cutaneous lesions and bleeding, and predisposes animals to mastitis. In beef production systems, the main impacts include reduced weight gain, hide damage, and increased veterinary care costs. The disease may occur in cutaneous and mucosal forms. The cutaneous form is characterized by the presence of warts or fibropapillomas distributed throughout different regions of the body, whereas the mucosal form is associated with bovine enzootic hematuria and urinary bladder carcinogenesis. The lesions observed include papillomas, fibropapillomas, and fibromas, as well as verrucous lesions affecting the mucosa of the rumen, oral cavity, esophagus, and amniotic membrane. Transmission occurs mainly from animal to animal and is facilitated by injuries to the skin and mucous membranes caused by fences, water troughs, feeding troughs, or instruments used for animal restraint. Bovine papillomaviruses are double-stranded DNA viruses belonging to the family Papillomaviridae. In 1993, fibropapilloma samples from five buffaloes (*Bubalus bubalis*) originating from a farm located in the municipality of Registro, São Paulo State, Brazil, were submitted to the Electron Microscopy Laboratory of the Biological Institute, São Paulo, Brazil. The samples were processed using transmission electron microscopy, negative staining, and resin embedding techniques. In all samples, a large number of non-enveloped papillomavirus particles with icosahedral symmetry were observed. These particles were characterized as "full" and "empty" virions, measuring approximately 60 nm in diameter. In ultrathin sections of papilloma fragments, intracytoplasmic viral particles measuring approximately 30 nm in diameter were observed, associated with thickening of the plasma membrane, which exhibited a serrated appearance. In addition, intranuclear viral particles and membrane-bound intracytoplasmic vacuoles were identified. In the reticular layer, a nucleus with an irregular contour, marginalized chromatin, and the presence of viral particles was observed. The results confirm the occurrence of papillomatosis in buffaloes and demonstrate the importance of electron microscopy for the rapid diagnosis and morphological characterization of the viral agent.

Keywords— Papillomatosis, Buffaloes, Transmission electron microscopy.

I. INTRODUCTION

Bovine papillomatosis is an infectious disease of viral origin caused by bovine papillomavirus (BPV). Although it is more frequently described in cattle, it also affects buffaloes, in which it may occur in both cutaneous and mucosal forms. The cutaneous form is characterized by the presence of warts or fibropapillomas distributed across various regions of the body, including the head, neck, back, ears, abdomen, gluteal region, teats, udder, vulva, and perivulvar area (Silvestre et al., 2009). These tumors, which may occur as single or multiple lesions of varying sizes, tend to develop more frequently in previously

traumatized areas, possibly due to the release of inflammatory cytokines, reactivation of latent viral infections, and stimulation of cellular proliferation (Silvestre et al., 2009; Al-Redah et al., 2021).

The mucosal form of the disease, mainly associated with BPV-2, is related to bovine enzootic hematuria and urinary bladder carcinogenesis in adult animals grazing on pastures containing bracken fern (*Pteridium aquilinum*). This condition results from a synergistic interaction between the virus and carcinogenic compounds present in the plant. In buffaloes, this form has been reported in both Brazil and Italy (Maiolino et al., 2013; Roperto et al., 2013; Rocha et al., 2022).

In Brazil, cutaneous papillomatosis was first described in buffaloes in 1993 in females raised in the municipality of Registro, São Paulo State, through transmission electron microscopy and histopathological analyses (Cappellaro et al., 1993; Cappellaro, 1994). Subsequently, cases have been reported in several countries, including Italy, Iraq, Turkey, India, Mexico, and Brazil, and have been more commonly observed in adult animals, although occasional cases have been described in young individuals (Singh et al., 2010). Transmission occurs mainly from buffalo to buffalo, without the need for an intermediate bovine host, and is facilitated by injuries to the skin and mucous membranes caused by fences, water troughs, feeding troughs, or instruments used for animal restraint (Somvanshi, 2011). In addition to horizontal transmission, vertical transmission has also been reported (Russo et al., 2017). Different types of lesions may be observed, including papillomas, fibropapillomas, and fibromas (Jangir et al., 2017), as well as verrucous lesions affecting the mucosa of the rumen, oral cavity, and esophagus (Kumar et al., 2012), and even the amniotic membrane (Russo et al., 2020).

In general, papillomatosis is considered a self-limiting disease, with spontaneous regression of lesions occurring within approximately 12 months, depending on the host's cellular immune response. However, in some cases, malignant transformation may occur as a consequence of prolonged viral persistence within the host (Nasir & Campo, 2008).

Bovine papillomaviruses belong to the family *Papillomaviridae* and are non-enveloped, double-stranded DNA viruses with icosahedral symmetry and a diameter ranging from 45 to 55 nm (Freitas et al., 2011). Their capsid consists of 72 capsomeres, and the genome, approximately 8 kb in length, is organized into early (E1–E7) and late (L1 and L2) genes (Borzacchiello, 2008; Doorbar et al., 2012). To date, approximately 40 BPV types have been described infecting the skin, mucosal surfaces, and associated tissues (Elghmry et al., 2025). BPV types 1, 2, 5, and 6 are most frequently associated with fibropapilloma formation, whereas BPV-2 has been linked to urinary bladder tumors and amniotic lesions (Jangir et al., 2017; Maiolino et al., 2013; Rocha et al., 2022; Silva et al., 2026). The early genes E1 and E2 are involved in viral replication control and transcriptional regulation, while E5, E6, and E7 play key roles in cellular transformation and modulation of the host immune response (Borzacchiello et al., 2008; DiMaio & Petti, 2013). Among these proteins, E5 is considered the major BPV oncogene because of its ability to activate cellular proliferation pathways, particularly through interaction with growth factor receptors such as PDGFβR (Bocaneti et al., 2016). The late genes L1 and L2 encode the structural proteins of the viral capsid, with L1 being highly conserved among members of the *Papillomaviridae* family (Doorbar et al., 2012).

Papillomatosis is considered an emerging disease and causes substantial economic losses in intensive and semi-intensive dairy buffalo production systems. These losses are mainly associated with difficulties during milking, the presence of cutaneous lesions and bleeding, and an increased predisposition to mastitis. In meat production systems, the disease results in reduced weight gain, hide damage, and increased clinical complications, leading to higher veterinary care costs (Somvanshi, 2011; Rojas-Anaya et al., 2016). Furthermore, enzootic hematuria represents an important cause of economic losses in Brazil due to mortality and reduced productivity in affected animals (Rocha et al., 2022).

Given this scenario, the rapid diagnosis of papillomavirus infection in buffaloes is essential for disease control and for minimizing economic losses in production systems. The present study aimed to detect the presence of papillomavirus particles in cutaneous lesions of buffaloes using transmission electron microscopy techniques, providing ultrastructural characterization of the viral agent and contributing to the understanding of this disease in buffalo populations.

II. MATERIALS AND METHODS

2.1 Clinical Case

In 1993, samples of fibropapillomas located in the auricular region of five adult female Murrah buffaloes (*Bubalus bubalis*), aged between 18 and 20 months, from a farm located in the municipality of Registro, São Paulo State, Brazil, were sent to the Electron Microscopy Laboratory of the Biological Institute of São Paulo, São Paulo State, Brazil. The macroscopic appearance of all papillomas was that of spherical, grayish tumor masses measuring 0.5 to 2 cm, hairless, with a rough surface, elevations, and indentations.

2.2 Transmission Electron Microscopy

The samples were processed for transmission electron microscopy using negative staining, also known as rapid preparation, and resin embedding techniques.

2.2.1 Negative Staining Technique (Rapid Preparation)

During the negative staining procedure, fibropapilloma samples collected from the auricular region of buffaloes were first macerated and then suspended in 0.1 M phosphate buffer at pH 7.0, followed by transfer to sterile microtubes. Aliquots from the surface of these suspensions were deposited onto copper grids previously prepared with 0.5% collodion film in amyl acetate and reinforced with a delicate layer of carbon and were then allowed to adsorb briefly. Excess fluid was carefully removed with filter paper, and the grids were subsequently negatively stained with 2% ammonium molybdate at pH 5.0 (Brenner & Horne, 1959). At least three grids were prepared per sample, and multiple fields were examined to ensure representative sampling.

2.2.2 Resin Embedding Technique

The five fibropapilloma tissue fragments were initially fixed in 2.5% glutaraldehyde prepared in 0.1 M phosphate buffer at pH 7.0, followed by post-fixation in 1% osmium tetroxide using the same buffer. Subsequently, the samples were dehydrated through a graded acetone series and embedded in Spurr resin (González-Santander, 1969; Luft, 1961). Ultrathin sections were produced with an LKB ultramicrotome and placed onto copper grids. Finally, the sections were stained with uranyl acetate and lead citrate (Watson, 1958; Reynolds, 1963). Multiple sections were examined per sample to ensure representative sampling of the tissue.

2.2.3 Electron Microscopy Examination

All grids were examined using a Philips EM208 transmission electron microscope at an accelerating voltage of 80 kV. Viral particles were identified based on morphological criteria including size, shape, capsomere arrangement, and presence of typical papillomavirus features. Particle diameters were measured using calibrated scale bars and image analysis software. A minimum of 50 particles per sample were measured to calculate mean particle sizes. Negative controls consisted of grids processed without sample material to monitor for contamination.

III. RESULTS

3.1 Clinical Case

Fibropapilloma samples obtained from buffaloes (Fig. 1, arrow) were prepared using the negative staining technique and subsequently analyzed by transmission electron microscopy with a Philips EM208 instrument. Papillomavirus particles were detected in all five samples examined (100% detection rate).

3.2 Transmission Electron Microscopy

3.2.1 Negative Staining (Rapid Preparation) Technique

In all five fibropapilloma samples examined by transmission electron microscopy using the negative staining technique (rapid preparation), papillomavirus particles, either isolated or grouped, were observed (Figs. 2-4). Their surfaces were composed of distinct subunits in symmetrical arrangements, with 15 to 17 capsomeres at the periphery, in which case they were interpreted

as intact or complete particles (Figs. 3, 4, large arrow). Often, however, the central portion was stained, and they were then considered empty particles (Figs. 3, 4, small arrow). The virions were non-enveloped and isometric, with an average diameter of 50.2 ± 3.8 nm (range 45–55 nm), consistent with previously reported measurements for bovine papillomaviruses (Freitas et al., 2011). No tubular particles were visualized.



FIGURE 1: Photograph of a cauliflower-like papilloma (arrow), located at the base of a buffalo's ear.

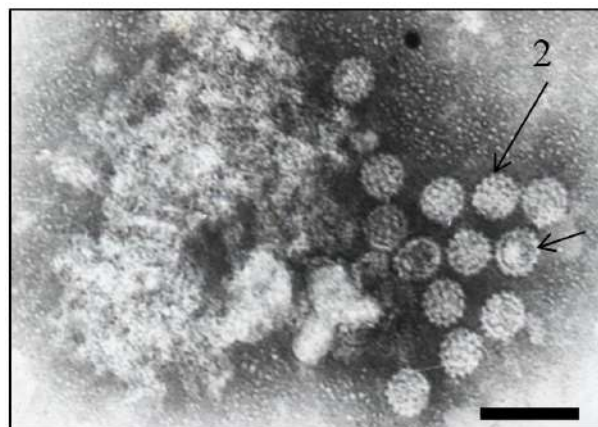


FIGURE 2: Negatively stained, non-enveloped, isometric papillomavirus particles, measuring an average of 50 nm in diameter (large arrow), showing individual capsomers (small arrow). Scale bar: 140 nm.

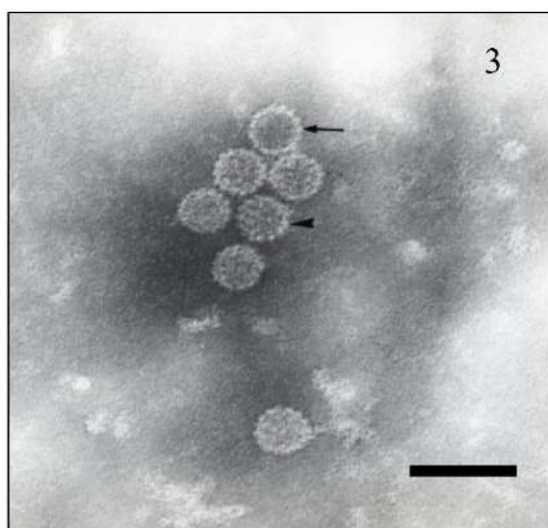


FIGURE 3: Negative staining of papillomavirus particles, showing "complete" particles (arrowhead) and "empty" particles (arrow). Scale bar: 120 nm.

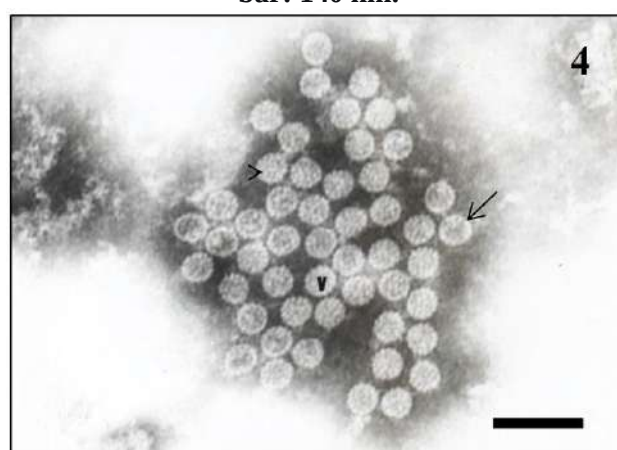


FIGURE 4: Negatively stained papillomavirus particles (v), non-enveloped and isometric, including "complete" (arrowhead) and "empty" (arrow) particles, measuring approximately 50 nm in diameter. Scale bar: 180 nm.

3.2.2 Resin Embedding Technique

In ultrathin sections of papilloma fragments, intracytoplasmic viral particles measuring approximately 30 nm in diameter (Fig. 5, large arrow) were observed in cells of the granular layer, associated with thickening of the plasma membrane, which exhibited a serrated appearance (Fig. 5, small arrow). In addition, intranuclear viral particles (Fig. 6, large arrow) and membrane-bound intracytoplasmic vacuoles (Fig. 5, arrowhead) were identified. In the reticular layer, a nucleus with an irregular contour, marginalized chromatin (Fig. 6, large arrow), and the presence of viral particles were observed (Fig. 6, small arrow).

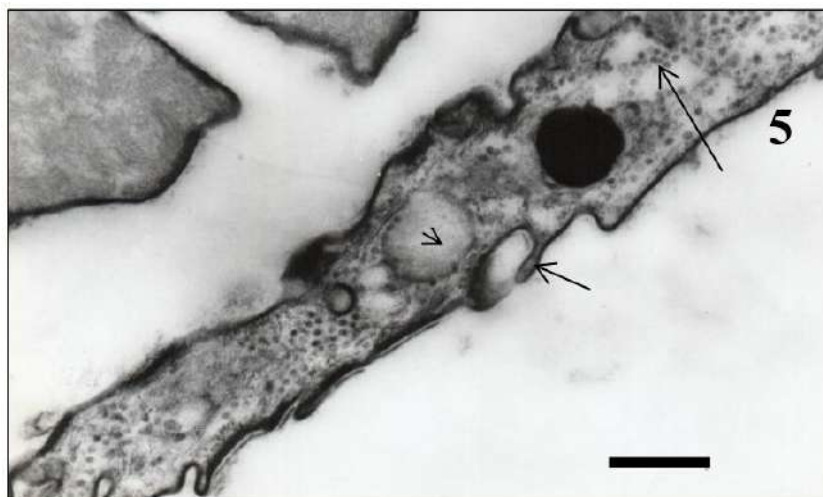


FIGURE 5: Ultrathin section of a papilloma showing a portion of a cell from the granular layer, with intracytoplasmic viral particles (large arrow) and thickening of the plasma membrane, which exhibits a serrated appearance (small arrow). Scale bar: 500 nm.

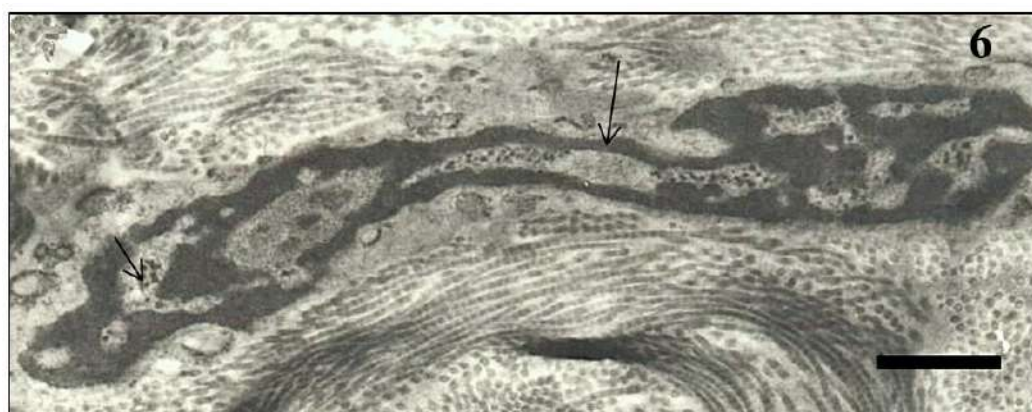


FIGURE 6: Ultrathin section of a papilloma showing, in the reticular layer, a nucleus with an irregular contour and marginalized chromatin (large arrow), as well as the presence of viral particles (small arrow). Scale bar: 620 nm.]

IV. DISCUSSION

In the present study, an ultrastructural investigation of cutaneous papillomatosis observed in buffaloes was conducted during an outbreak on a farm located in Registro, São Paulo State, Brazil.

The animals evaluated belonged to the Murrah breed, a finding that corroborates previous reports of papillomatosis in buffaloes described by Nooruddin et al. (1989), Prasad et al. (2009), and Singh et al. (2010). Furthermore, Raval et al. (2015) reported the occurrence of mammary fibroadenoma in a Mehsana buffalo raised in India, while Williams et al. (2011) described papillomatous lesions in African buffaloes (*Syncerus caffer*) in South Africa.

In this research, cutaneous papillomatosis was diagnosed in female buffaloes, a finding that is consistent with most previous reports involving this species (Singh et al., 2010; Williams et al., 2011; Raval et al., 2015; Russo et al., 2020; Rocha et al., 2022). Pangty et al. (2010) reported the occurrence of papillomas in 18 heifers, three adult female buffaloes, and two buffalo calves, whereas Maiolino et al. (2013) and Dileepkumar and Ansari (2012) described the disease in males. In an epidemiological study conducted by Nooruddin et al. (1989), involving 4,166 females and 284 males, the prevalence of papillomatosis was 0.36% in females and 0.7% in males. These findings indicate that the disease can affect animals of both sexes, with no apparent sex predisposition.

Regarding age, the buffaloes evaluated in the present study were between 18 and 20 months old. In previous investigations, the age of affected animals ranged from 6 to 18 months (Pangty et al., 2010), 1.5 years (Dileepkumar and Ansari, 2012),

approximately 2 years (Williams et al., 2011), between 3 and 5 years (Maiolino et al., 2013), 10 years (Raval et al., 2015), and 12 years (Prasad et al., 2009). Nooruddin et al. (1989) reported prevalences of 0.4% in animals up to 1 year of age, 0.35% in those between 1 and 3 years, and 0.38% in animals older than 3 years, indicating that both young and adult animals are susceptible to infection. Similarly, Singh et al. (2010) observed a higher frequency of the disease in adult animals, whereas younger individuals were less frequently affected.

It is noteworthy that, in the present study, papillomas were observed exclusively in the periauricular region. In contrast, several anatomical locations have been reported in buffaloes by different authors, highlighting the wide distribution of papillomatous lesions. These include the vulvar and perivulvar regions, back, and gluteal areas (Silvestre et al., 2009); teats, head, face, neck, legs, back, and urinary bladder (Roperto et al., 2013); legs and abdomen (Singh et al., 2010); the right eye (Singh & Mouli, 1990); the udder (Singh et al., 1991; Joshi et al., 1994; Raval et al., 2015); the face, eyelids, ears, neck, body, and trunk (Leishangthem et al., 2008; Dileepkumar & Ansari, 2012); the inguinal region, udder, groin, and thigh (Williams et al., 2011); the amniotic membrane (Russo et al., 2020); the rumen, reticulum, oral cavity, and esophagus (Kumar et al., 2012); the forehead (Prasad et al., 2009); the back, ears, knees, legs, limbs, and tail (Jangir et al., 2017); the head, neck, and udder (Al-Redah et al., 2021); and the urinary bladder (Roperto et al., 2013; Maiolino et al., 2013; Rocha et al., 2022). These reports demonstrate that papillomatosis may affect not only cutaneous surfaces but also mucosal tissues and internal organs.

Regarding their gross appearance, the papillomas presented as circumscribed, pedunculated tumor masses with a cauliflower-like appearance, a grayish, rough, fleshy surface, and absence of hair, features similar to those described by other authors (Singh et al., 2010; Pangty et al., 2010; Williams et al., 2011; Al-Redah et al., 2021). In previous studies, these lesions have also been described as small or large spherical nodules (Kumar et al., 2010), dome-shaped verrucous lesions, small growths or protuberances (Jangir et al., 2017), papillomatous nodules (Russo et al., 2020), fibropapillomas (Singh & Mouli, 1990; Joshi et al., 1994), warts (Leishangthem et al., 2008), and fibroadenomas or neoplastic masses (Singh et al., 1991; Prasad et al., 2009; Raval et al., 2015).

The tumor masses observed in the buffaloes examined in the present study ranged from 0.5 to 2 cm in diameter. In contrast, lesion sizes reported in previous studies have varied from 2.5 mm to 6 cm (Kumar et al., 2010; Pangty et al., 2010; Williams et al., 2011; Al-Redah et al., 2021).

Negative staining, also known as rapid preparation, was the method employed in the present study for the morphological characterization of viral particles, as it provides the most detailed visualization of these structures (Hazelton & Gelderblom, 2003; Goldsmith & Miller, 2009). Using this technique, isometric viral particles with an average diameter of 50.2 ± 3.8 nm were observed and classified as "complete" and "empty" particles. Similar findings have been reported in buffalo papillomas (Leishangthem et al., 2008; Silvestre et al., 2009; Singh et al., 2010), cattle (Catroxo et al., 2013; Módolo et al., 2017; Vrablikova et al., 2023), giraffes, and sable antelopes (Van Dyk et al., 2011). In contrast, Savini et al. (2020) were unable to visualize papillomavirus particles in ovine papilloma samples examined in their study. It is important to emphasize that successful application of the negative staining technique depends on the use of mechanically and thermally stable support films, reinforced with a thin carbon layer and applied to the metal grids prior to sample adsorption. This procedure provides greater stability to the specimen and facilitates the adequate visualization of viral particles (Gentile & Gelderblom, 2014).

In ultrathin sections of papilloma fragments, intracytoplasmic and intranuclear viral particles measuring approximately 30 nm in diameter were observed beginning in the stratum spinosum. These findings are consistent with those reported in buffaloes (Leishangthem et al., 2008; Singh et al., 2010; Williams et al., 2011; Roperto et al., 2013), cattle (Catroxo et al., 2013; Ozmen & Kale, 2023), dogs (Buff Jr. et al., 1988), and giraffes (Van Dyk et al., 2011). Pleomorphic nuclei with irregular contours and thickened, marginalized chromatin were also observed, similar to the ultrastructural alterations described by other authors (Leishangthem et al., 2008; Silvestre et al., 2009; Singh et al., 2010). The presence of membrane-bound intracytoplasmic vacuoles identified in the present study was likewise reported by Singh et al. (2010). However, unlike the findings of Singh et al. (2010) in buffaloes, we did not observe crystalline arrays of intranuclear viral particles. Such inclusions have been described in keratinocytes of papillomas in mice (Ingle et al., 2011).

The absence of molecular characterization (PCR, sequencing) to identify the specific BPV type represents a limitation of this study. The samples were collected in 1993, before molecular techniques were routinely available for viral typing in diagnostic laboratories. Based on the lesion morphology (fibropapillomas) and location (cutaneous), it is likely that the virus belongs to the genus *Deltapapillomavirus*, particularly BPV types 1 or 2, which are most commonly associated with fibropapillomas in cattle and buffaloes (Silvestre et al., 2009; Singh et al., 2010; Jangir et al., 2017). However, without molecular confirmation,

the specific BPV type cannot be definitively determined. This limitation should be addressed in future studies by applying PCR and sequencing to archived or new samples.

Buffalo papillomatosis is a highly contagious disease with a marked capacity for dissemination within herds and is considered endemic in buffaloes as well as in other livestock species. In addition to its sanitary and economic impacts, the disease has been regarded as a potential risk factor for both animals and humans (Jelinek & Tachezy, 2005). Several therapeutic approaches have been described for the treatment of papillomatosis, including autoimmunotherapy, surgical excision, cryotherapy, the use of antimony lithium thiomalate, and oral administration of *Thuja* extract in combination with the topical application of ointments containing this plant (Ghim et al., 2000; Dileepkumar & Ansari, 2012; Kavithaa et al., 2014; Lalrinkima et al., 2022).

The implementation of preventive sanitary measures is essential to minimize the spread of disease within production systems. The main control strategies include careful inspection of animals before their introduction into the herd, isolation of affected animals, periodic vaccination, proper cleaning and disinfection of milking equipment, and the use of disposable materials. Additionally, ectoparasite control, combined with the maintenance of high standards of hygiene and biosecurity, contributes significantly to herd health and the quality of animal production (Maeda et al., 2007).

Buffalo papillomatosis can result in significant economic losses, including reduced weight gain, decreased milk production, and alterations in meat and hide quality, thereby directly affecting the commercial value of the animals (Módolo et al., 2017). Therefore, early diagnosis is essential for the prompt implementation of control and preventive measures. In this context, the diagnostic techniques employed proved to be valuable tools for the rapid confirmation of papillomavirus infection, enabling high-resolution visualization of viral particles and characterization of the etiological agent during the outbreak affecting buffaloes.

V. CONCLUSION

This study confirms the occurrence of cutaneous papillomatosis in buffaloes in Brazil and demonstrates the utility of transmission electron microscopy for the rapid diagnosis and morphological characterization of bovine papillomavirus. The ultrastructural findings, including the visualization of non-enveloped, icosahedral viral particles with "full" and "empty" virions (45–55 nm), as well as intracytoplasmic and intranuclear viral particles (30 nm) and associated cellular alterations (serrated membranes, irregular nuclei with marginalized chromatin), provide detailed morphological evidence of papillomavirus infection in buffalo cutaneous fibropapillomas.

The results highlight the importance of electron microscopy as a diagnostic tool for emerging viral diseases in livestock. The high detection rate (100%) and the characteristic ultrastructural features confirm the presence of papillomavirus in the examined samples and contribute to the understanding of the pathogenesis of cutaneous papillomatosis in buffaloes.

Overall, this study provides valuable baseline information on the ultrastructural features of papillomavirus in buffaloes and emphasizes the need for integrated diagnostic approaches combining electron microscopy, histopathology, and molecular techniques for effective disease surveillance and control.

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DECLARATIONS

- **Ethics Approval:** Not applicable. This study was conducted on diagnostic samples submitted for analysis; no animal experimentation was performed.
- **Conflict of Interest:** The authors declare no conflicts of interest regarding the publication of this manuscript.
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- **Author Contributions:** [To be specified by the authors]
- **Data Availability:** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request

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Application of Nanotechnology for Integrated and Precision Weed Management in Agriculture: Nano-herbicides, Nanocarrier-Mediated Delivery, Herbicidal Efficiency, Resistance Management, and Environmental Considerations – A Review

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Abstract— The science of manipulating materials at the nano-scale is known as nanotechnology. Nanotechnology is a key component of the most recent advancements in technology. Precision farming will come from the use of minimal pesticides and herbicides as well as increased efficiency, controlled release, and application to a specific target. Crop improvement is a constant process in agriculture. The management of perennial weeds and the degradation of the weed seed bank are issues that are being tackled through the development of nano-herbicides. This technology also emphasizes the development of nano-herbicides to deal with weed control and details of potential applications and strategies for weed management using nanotechnology.

Keywords— Nanotechnology, nano-herbicides, nanoparticles, Weed management, Agriculture.

I. INTRODUCTION

Changes in agricultural technology have been a major factor shaping modern agriculture. Among the latest line of technological innovations, nanotechnology occupies a prominent position in transforming agriculture and food production. The development of nano-devices and nano-materials could open up novel applications in plant biotechnology and agriculture (Scrini & Lyons, 2007). Nanotechnology permits broad advances in agricultural research, such as reproductive science and technology, conversion of agricultural and food wastes to energy and other useful by-products through enzymatic nano-bioprocessing, disease prevention and treatment in plants using various nano-cides (Moraru et al., 2003). Nanotechnology is the science of working with the smallest particles, increases hope to improve the productivity of agricultural ecosystems, through encounter with problems that have remained unanswered by customary practices and has opened a new way in farming.

The use of chemical herbicides is a common method to control weeds, which in addition to the beneficial effects on weed control can have harmful effects such as environmental pollution, residue in soil and damage to next crop, resistance in weeds and they also have difficult control. In recent years, scientists using nanotechnology and production of nano-herbicide attempted to solve this problem. Nano-herbicides with features such as effective concentration, time-controlled release in response to specific stimuli, increased activity at the target site and less toxicity for ecosystem can be a good alternative to chemicals, and prevent the occurrence of problems and challenges arising from the use of herbicides in weed management.

The powerful technology of nanotechnology allows us to study atomic and molecular level structures at the nano-level. Research and development in nanotechnology is predicted to increase the agricultural sector's use of genetically modified crops, precision farming, chemical pesticides, and inputs for animal production (Abd-Elrahman & Mostafa, 2015). Nanotechnology is an interdisciplinary field with applications in chemistry, physics, biology, medicine, and engineering, among other applied sciences. The study of materials with atomic, molecular, and supramolecular dimensions in order to understand, control, and measure them is known as nanotechnology. Or, to put it another way, nanotechnology is the manipulation or self-assembly of individual atoms, molecules, or molecular clusters into structures to produce materials and technologies with brand-new or vastly different characteristics. For example, photonics applications in nano-electronics and nano-engineering, which require shrinking the size of the smallest structures to the nano-scale, are examples of how nanotechnology can operate from the top down or the bottom up (which involves manipulating individual atoms and molecules into nanostructures and more closely resembles chemistry or biology).

One billionth of a metre is known as a nanometre. Generally speaking, the term "nano" refers to a scale of size between 1 nanometre (nm) and 100 nm in at least one dimension, and relates to the development or modification of materials or electronics within that range. Technically speaking, "nano" refers to 10^{-9} , or one billionth of something. For comparison, the wavelength of visible light is between 400 nm and 700 nm. A leukocyte has the size of 10,000 nm, a bacteria 1000-10,000 nm, virus 75-100 nm, protein 5-50 nm, glucose 1 nm, deoxyribonucleic acid (DNA) ~2 nm (width), and an atom ~0.1 nm. In this scale, physical, biological and chemical characteristics of materials are fundamentally different from each other and often unexpected actions are seen from them. Nanotechnology considers the topics with viruses and other pathogens scale, so it has high potential to identify and eliminate pathogens (Prasanna, 2007 & Predicala, 2009).

Recent advances in nanotechnology have made it possible to create nano-scale structures that can be controlled, regulated, and used to accelerate chemical reactions. Nanomaterials are made up of very smaller components, and the properties of materials at the macro level are affected by these parts. Nanoparticles can act as "magic bullets," releasing herbicides, drugs, or genes that are targeted at specific plant tissues. Herbicides can be effectively absorbed by nano-capsules through tissues and cuticles, allowing for a steady release of the active ingredients. Nanobiotechnology refers to the nano-scale fusion of technology and biology (Perea-de-Luque & Rubiales, 2009). The current era's sixth revolutionary technology is emerging as nanotechnology. It is believed to be an emerging branch of science that is extensively embraced in many scientific domains and is anticipated to play a major role in the fields of agriculture and food science in the future; however, there are currently few scientific studies about its use in agriculture globally (Mousavi & Rezaei, 2011).

The use of materials and equipment that can utilize a substance's physical and chemical characteristics at the molecular level to explore the biological and material worlds in nano-scale size is known as nanotechnology. It can be applied in a variety of fields, such as medicine and agriculture (Fakruddin et al., 2012). Nanotechnology is the study and application of small things, specifically of materials with a size of less than 100 nm. Nanotechnology integrates solid state physics, chemistry, chemical engineering, biochemistry, biophysics, and materials science; one nanometre is equal to 10^{-9} metres.

According to recent studies, nanotechnology has the potential to enhance farming techniques by improving the effectiveness of farm inputs and offering solutions to agricultural and natural resource concerns. Based on current ecological conditions, agricultural disease detection and control, and improving crops' ability to absorb minerals from the soil, nanotechnology will increase crop productivity (Alfadul et al., 2017). Nanotechnology will substitute all agricultural endeavours (Mukhopadhyay, 2014).

The characteristics of nanoparticles comprise extremely small size (1-100 nm), high activity, and chemical and optical attributes unique to this size range (Khan & Rizvi, 2014). Hydrophilicity, miscibility, unevenness, structure, adsorption during synthesis, ability to produce superoxide radicals, stoichiometry, competitive receptor binding ability, dispersion, and agglomeration are some of the attributes of nanoparticles (Somasundaran et al., 2010). Nanoparticles are useful in a wide range of disciplines and have brought up a lot of opportunities for scientific research in agriculture (Kanjana, 2015). Nano-aluminum has been widely

used in various industries and hence there is greater chance for the interaction of such nanomaterials with higher plants that constitute a major portion of the ecosystem. Pure alumina nanoparticles (13 nm) without any modifications reduced root elongation in studied plants (corn (*Zea mays*), cucumber (*Cucumis sativus*), soybean (*Glycine max*), carrot (*Daucus carota*) and cabbage (*Brassica oleracea*) thus potentially retarding the growth of plants (Yang & Watts, 2005). Seed germination of rye grass and corn was inhibited by nanoscale zinc (nano-Zn (35 nm)) and zinc oxide (nano-ZnO (15–25 nm)) respectively (Lin & Xing, 2007).

II. REVIEW METHODOLOGY

This narrative review was prepared to: (i) explain the fundamentals of nanotechnology relevant to weed management; (ii) identify the challenges of conventional herbicide use; (iii) summarize the development and application of nano-herbicides; (iv) discuss smart delivery mechanisms and detoxification of herbicide residues; and (v) evaluate environmental and safety aspects of nano-herbicides.

Literature was identified through targeted searches of journal databases including Web of Science, Scopus, PubMed Central, and Google Scholar using search terms including "nanotechnology," "nano-herbicides," "weed management," "nanoparticles," "smart delivery systems," "herbicide resistance," and "environmental safety." Foundational papers necessary to define the field were included alongside more recent studies. Species or application examples are reported as documented examples only when supported by the cited source.

III. NANOTECHNOLOGY FUNDAMENTALS AND AGRICULTURAL APPLICATIONS

3.1 Definition and Scope

Nanotechnology is the science of manipulating materials at the nano-scale (1-100 nm). It is a key component of the most recent advancements in technology and is an interdisciplinary field with applications in chemistry, physics, biology, medicine, and engineering. The study of materials with atomic, molecular, and supramolecular dimensions in order to understand, control, and measure them is known as nanotechnology. It can be applied in a variety of fields, such as medicine and agriculture (Fakruddin et al., 2012).

3.2 Nanoparticle Characteristics

The characteristics of nanoparticles comprise extremely small size (1-100 nm), high activity, and chemical and optical attributes unique to this size range (Khan & Rizvi, 2014). Hydrophilicity, miscibility, unevenness, structure, adsorption during synthesis, ability to produce superoxide radicals, stoichiometry, competitive receptor binding ability, dispersion, and agglomeration are some of the attributes of nanoparticles (Somasundaran et al., 2010). Nanoparticles are useful in a wide range of disciplines and have brought up a lot of opportunities for scientific research in agriculture (Kanjana, 2015).

3.3 Nanotechnology in Agriculture

According to recent studies, nanotechnology has the potential to enhance farming techniques by improving the effectiveness of farm inputs and offering solutions to agricultural and natural resource concerns. Based on current ecological conditions, agricultural disease detection and control, and improving crops' ability to absorb minerals from the soil, nanotechnology will increase crop productivity (Alfadul et al., 2017). Nanotechnology will substitute all agricultural endeavours (Mukhopadhyay, 2014). The development of nano-devices and nanomaterials could open up novel applications in plant biotechnology and agriculture (Scrinis & Lyons, 2007). Nanotechnology permits broad advances in agricultural research, such as reproductive science and technology, conversion of agricultural and food wastes to energy and other useful by-products through enzymatic nano-bioprocessing, disease prevention and treatment in plants using various nano-cides (Moraru et al., 2003).

IV. NANOTECHNOLOGY AND WEED MANAGEMENT

4.1 Challenges in Conventional Weed Management

Weeds may threaten the complete harvest in sensitive agro-ecosystems because 2/3 of Indian agriculture is rainfed cultivation, which uses relatively little herbicide. Market-available herbicides are made to kill or control the weed plants' above-ground growth. None of the herbicides prevent the growth of rhizomes or tubers, which are active belowground plant portions that serve as a seed for new weeds the following season. Lower yields than soils where weeds are controlled are likely to result from weed infestations and weed seeds (Chinnamuthu & Kokiladevi, 2007).

The most significant pests in terms of economic impact and environmental harm are weeds, and most insecticides used globally are directed at them. For instance, insecticides account for 29% of global agrochemical sales, while herbicides account for 47% (McFadyen, 1998). Herbicide resistance and poor control were the consequences of a multi-species approach with a single herbicide in a cropped environment. When a plant community is repeatedly exposed to one herbicide in one season and another herbicide in another season, resistance eventually develops and the plant community can no longer be controlled by chemicals (Chinnamuthu & Kokiladevi, 2007).

4.2 Nano-Herbicides for Effective Weed Control

In agriculture, weeds are a major threat since they significantly lower the yield. Therefore, the only choice is to completely eradicate them. Without leaving any hazardous residues in the soil or environment, nanotechnology has the ability to eradicate weeds through the use of nano-herbicides in an environmentally friendly manner (Pérez-de-Luque & Rubiales, 2009). Improvements in the efficacy of herbicides through the use of nanotechnology could result in greater production of crops. There are now inert ingredients for herbicide application that say they contain nanomaterials. When glyphosate is treated with a "nanotechnology-derived surfactant," it has been observed that glyphosate-resistant crops become sensitive to the herbicide. Crops that are resistant to glyphosate are potentially susceptible to it thanks to a soybean-based nanosurfactant (Chinnamuthu & Kokiladevi, 2007).

Nano-encapsulated agrochemicals should be designed in such a way that they possess all necessary properties such as effective concentration (with high solubility, stability and effectiveness), time controlled release in response to certain stimuli, enhanced targeted activity and less ecotoxicity with safe and easy mode of delivery thus avoiding repeated application (Green & Beestman, 2007; Wang et al., 2007; Boehm et al., 2003; Tsuji, 2001). The control of parasitic weeds with nano-capsulated herbicides thereby reducing the phytotoxicity of herbicides on crops is a best example (Pérez-de-Luque & Rubiales, 2009). Properly functionalized nano-capsules provide better penetration through cuticle and allow slow and controlled release of active ingredients on reaching the target weed. Nano-encapsulation of chemicals with biodegradable materials also makes the concentrated active ingredients safe and easy to handle by the growers.

Nano-herbicides are different forms of herbicides developed in collaboration with nanomaterials, and they are herbicides encapsulated in synthetic polymer core shell nanoparticles (Kumar et al., 2015). To eliminate individual weeds by acting on specified root receptors, nanoparticles incorporating target-specific herbicides are used (Jampilek & Kráľová, 2015). The design of a target-specific herbicide chemical encapsulated in a nanoparticle is directed at a specific binder of target weed roots that encompasses the root system and is translocated to the areas that obstruct roots' glycolysis. The outcome is that the weed plant will starve to death (Chinnamuthu & Kokiladevi, 2007).

4.3 Smart Delivery Mechanisms

"Smart Delivery Systems" in agriculture should possess combinations of time controlled, specifically targeted, highly controlled, remotely regulated/pre-programmed/self-regulated and multifunctional characteristics to avoid biological barriers for successful targeting. Agriculture and food system security, novel delivery systems for disease treatment, new tools for molecular and cellular biology and new materials for plant pathogen detection are some of the nano-technological links to agriculture and food science. Besides these, plants and/or their extracts provide a biological synthesis route of several metallic nanoparticles which is more eco-friendly and allows a controlled synthesis with well-defined size and shape (Kumar & Yadav, 2009; Sharma et al., 2009).

The introduction of a target-specific herbicide compound enclosed in a nanoparticle is directed to a specific receptor in the roots of the target weeds, where it enters the system and travels to regions that hinder the hydrolysis of food reserves in the root system. This will cause the particular weed plant to run out of nourishment and die (Chinnamuthu & Kokiladevi, 2007). Herbicide treatment with insufficient soil moisture may result in loss as vapour in rain-fed locations. Still, it is difficult for us to accurately forecast when it will rain; pesticides cannot be used in advance to prepare for it. The competing weeds with crops should be eliminated via the controlled release of encapsulated pesticides.

Herbicide usage can be prevented by using nanotechnology, which also provides safe and effective delivery methods (González et al., 2014). When nanoparticles are sprayed to leaf surfaces, they move to different tissues after entering through stomatal holes or the bases of trichomes (Uzu et al., 2010; Fernández & Eichert, 2009; Eichert et al., 2008). The valuable feature of utilizing magnetic nanoparticles is that they enable highly precise localisation of the particles to release their load, which is of considerable interest in the research of nano-particulate delivery for plants. A few experiments on the uptake, translocation, and precise localisation of magnetic nanoparticles (less than 50 nm) in pumpkin plants have been published (González-Melendi et al., 2008; Zhu et al., 2008; Corredor et al., 2009).

4.4 Carbon Nanotubes and Weed Seed Germination

Carbon nanotubes also breach the dormancy of weed seeds, speed up germination, and cut germination time in half by forming tubes that cause breaches in the seed coat that allow water and chemicals to enter (Khodakovskaya et al., 2009). Molecular characterisation of underground plant parts for a novel target domain (Zimdahl, 2018) may lead to receptor-based herbicide molecules with specific binding properties using nano-herbicide molecules like carbon nanotubes capable of killing the viable and dormant underground propagules of weed seeds.

V. DETOXIFICATION OF HERBICIDE RESIDUES

Herbicides that are used in excess leave residue in the soil and harm succeeding crops. Herbicide-resistant weed species evolve as a consequence of repeated exposure and the weed flora changes. Atrazine, an s-triazine ring herbicide, is used globally for the control of pre and post-emergence of broadleaf and grassy weeds. Herbicide use is at risk of becoming frequently used due to residual issues caused by the use of atrazine, which also restricts the types of crops that can be rotated.

Recent research from Tamil Nadu Agricultural University gives hope that atrazine residue in soil can be removed quickly. Under controlled conditions, application of silver modified with magnetite nanoparticles stabilised with Carboxy Methyl Cellulose (CMC) nanoparticles resulted in 88% breakdown of herbicide atrazine residue (Susha et al., 2008). Atrazine is a commercially used herbicide with a long half-life (125 days) and increased mobility in some soils for the control of weeds with broad leaves and grassy characteristics that emerge before and after planting. Atrazine residues were broken down by 88 percent when silver was combined with magnetite nanoparticles and stabilised with Carboxy Methyl Cellulose (CMC) nanomaterial under controlled conditions (Susha et al., 2008).

VI. MECHANISMS OF HERBICIDE ACTION AND NANOTECHNOLOGY

Herbicides administered topically to perennial weeds like *Cynodon dactylon*, *Cyperus* spp., and *Solanum elaeagnifolium* do not totally eradicate them. Inhibiting lipid biosynthesis, interfering with cell division by disrupting the mitotic sequence or preventing the mitotic entry, destroying the structure and function of the plant-specific chloroplast, destroying cellulose biosynthesis, and deregulating auxin-induced cell growth are among the target areas of today's herbicides in a plant cell (Boger & Sandmann, 1989; Wakabayashi, 1989; Wakabayashi, 1993; Wakabayashi & Sato, 1992; Wakabayashi & Böger, 2004).

Root absorption is less complicated than foliar absorption. Although mature roots are coated by a suberized layer, mature roots do not have cuticles like leaves do. This indicates that plant roots have few obstacles to absorbing herbicides. Herbicides that are lipophilic will be easily absorbed because roots are fundamentally lipophilic. About 60% of conventional herbicides interfere with the photo-electron transport system of the chloroplast, despite the fact that molecular mechanisms of action for even some commercially available herbicides are still not fully understood. There are currently no commercial herbicides that prevent the formation of sugar and the fixation of CO₂. Creating a receptor-based herbicide molecule with particular binding properties using nano-herbicide molecules like carbon nanotubes capable of killing the viable and dormant underground propagules of weed seeds offers a promising approach (Zimdahl, 2018).

VII. ENVIRONMENTAL AND SAFETY ASPECTS OF NANO-HERBICIDES

7.1 Benefits of Nano-Herbicides

The integration of nanotechnology in agriculture, particularly through nano-herbicides, offers significant promise in enhancing efficacy and environmental safety in weed management (Susha et al., 2022). Nano-enabled agricultural technologies address the growing need for increased crop yields while reducing environmental impact (Yin et al., 2018). Nano-herbicides represent one application in this field, where nanoscale formulations deliver active ingredients with higher precision and controlled release, resulting in improved bioavailability and reduced chemical usage (Zargar et al., 2023). These properties allow for efficient weed control at lower doses and with less frequent applications, leading to more sustainable agricultural practices (Bajwa, 2014).

A distinct advantage of nano-herbicides lies in their increased surface area, which enhances interactions with target weed species and allows for more efficient absorption and bioavailability of active components (Paul et al., 2024). These properties enable deeper penetration of active ingredients into pest tissues, prevent premature degradation, and reduce losses to the environment, thus extending their effectiveness (Shang et al., 2019). By minimizing environmental runoff and reducing the total volume of chemicals needed, nano-herbicides help limit off-target effects, protecting non-target plants, soil, and water ecosystems while contributing to increased crop productivity. Additionally, nanomaterials as carriers can achieve site-specific targeting of herbicides, allowing controlled delivery to specific areas where they are most needed (Narware et al., 2019).

In addition to direct weed control, nanotechnology advancements have facilitated the development of nanobiosensors for environmental monitoring and detection of plant stressors, including weed infestations. These technologies support precision agriculture by enabling real-time monitoring, which optimizes weed management through timely, targeted applications (Shang et al., 2019). Such smart technology aids in reducing the overall chemical load by ensuring that herbicides are applied only where and when necessary, further enhancing environmental sustainability.

7.2 Risks and Side Effects of Nano-Herbicides

However, despite the benefits, the environmental and safety implications of nano-herbicides require careful consideration. Although these formulations reduce the overall chemical input, nanoparticles may persist in soil and water, raising concerns about their long-term ecological impact (Narware et al., 2019). Persistent nanoparticles could potentially disrupt soil microflora and aquatic ecosystems, which necessitates the development of biodegradable nanoparticles that can naturally decompose, such as those based on chitosan (Chugh et al., 2021). Regulatory frameworks and ongoing environmental risk assessments are critical to ensuring that nano-enabled weed management solutions remain effective while safeguarding ecological integrity, thus supporting a balanced approach to sustainable agriculture.

The potential for nanoparticles to bioaccumulate in food products and penetrate intact human skin are just two of the many threats that come with the misuse of nanotechnology. The health of humans and animals is especially at risk from airborne nanoparticles. Unintended effects on non-target plants and related creatures are another source of worry. Nano-herbicides, for instance, have the potential to disrupt pollination by blocking plant vascular bundles. Potential problems include phytotoxicity, cytotoxicity, and genotoxicity, which may result in DNA alterations or cellular damage. Additionally, certain algal and soil microbial populations may be negatively impacted by nanomaterials (Sakarvadia, 2022; Alama et al., 2023; Pradhan et al., 2024; Chikowo et al., 2009).

7.3 Regulatory and Risk Assessment Considerations

Safety evaluation should include nanoparticle characterization, screening for toxicity, environmental persistence, non-target effects, and bioaccumulation potential. Regulatory systems may differ for a single nanoparticle formulation, a mixed formulation, or a nano-enabled delivery system. Claims should distinguish a research formulation from a registered commercial product. A traceable chain of identity, formulation, quality control, and field performance is required for responsible translation.

VIII. CONCLUSIONS AND FUTURE OUTLOOK

Nanotechnology is transforming agriculture, especially in sustainable weed management with the use of nano-herbicides. These nanoscale formulations improve the effectiveness of herbicides, decrease the amount of chemicals used, and lessen off-target effects, thereby supporting sustainable farming practices. However, for widespread adoption, comprehensive environmental and health risk assessments are necessary.

Current research is fostering innovation in advanced delivery systems that allow for precise herbicide application, which helps to minimize environmental exposure. The integration of smart nano-sensors for real-time monitoring of plant health, soil quality, and weed detection is enhancing precision agriculture. Biodegradable nanomaterials provide eco-friendly alternatives, and their combined use with biological control methods and integrated pest management is bolstering weed management strategies. Creating a regulatory framework is crucial for the responsible use of nanotechnology, ensuring a sustainable, resilient, and productive future for agriculture.

Limitations of this Review: This review is based on a narrative synthesis of published literature rather than a formal systematic review. The examples are selected to illustrate the diversity of approaches and should not be considered exhaustive. The focus is primarily on nano-herbicides and delivery systems, with less attention to other nanotechnology applications in weed management such as nanosensors and nanobiosensors.

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CONFLICT OF INTEREST

The authors declare no conflict of interest regarding the publication of this manuscript

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Microbiome-Assisted Breeding: Engineering the Holobiont in Horticultural Crops

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Abstract— Horticultural crop improvement is moving from a plant-centred model toward a soil-plant-microbiome framework in which host genotype, root-zone biology and the production environment are considered together. Microbiome-assisted breeding (MAB) aims to select plant genotypes that recruit, accommodate or respond to microbial communities capable of improving nutrient acquisition, soil fertility, disease suppression, abiotic-stress resilience, fruit quality and post-harvest performance. This review synthesizes the current basis of holobiont engineering with a primary focus on soil and plant-associated microbes of horticultural crops. The rhizosphere, rhizoplane, root endosphere, seed, flower and fruit compartments are considered as connected but functionally distinct microbial habitats. Important microbial groups include arbuscular mycorrhizal fungi, plant-growth-promoting rhizobacteria, diazotrophs, phosphate-solubilizing bacteria and fungi, actinobacteria, *Trichoderma*, endophytes, yeasts and defined synthetic communities. Recent literature highlights three developments: regulation of rhizosphere microbiomes by host traits and management, microbiome-interactive traits as potential breeding targets, and rhizosphere hybridization or microbiome engineering to build climate-smart and disease-suppressive soils. However, microbial abundance alone is not evidence of function, and inoculants frequently perform inconsistently when they cannot establish within a compatible native community. A practical MAB pipeline should combine host genotyping, soil physicochemical analysis, 16S/ITS or shotgun sequencing, culturomics, metabolomics, causal inoculation, synthetic-community testing and multi-environment validation. The review proposes priority research pathways for fruit, vegetable, spice, ornamental and underutilized crops and emphasizes that plant genotype × microbiome × soil management interactions must be measured explicitly. MAB should therefore complement—not replace—conventional breeding, crop management, conservation and farmer knowledge.

Keywords— holobiont; horticultural crops; soil microbiome; rhizosphere; plant-growth-promoting rhizobacteria; arbuscular mycorrhizal fungi; microbiome-assisted breeding; synthetic communities; climate-resilient horticulture.

I. INTRODUCTION

Horticultural crops are expected to produce high yield, nutritional quality, flavour, appearance and shelf life while facing heat, drought, salinity, soil degradation, emerging pathogens, declining biodiversity and restrictions on agrochemical use. Conventional breeding has delivered major gains, but it generally evaluates the plant phenotype while treating the microbial environment as background. That assumption is increasingly difficult to defend. Roots release carbon compounds, organic acids, amino acids, sugars and signalling molecules that structure the rhizosphere, while soil microorganisms transform nutrients, modify root development, antagonize pathogens and influence plant immunity. The plant is therefore not an isolated genetic entity but a host embedded in a dynamic soil-plant-microbe system [1], [2].

The term holobiont is useful as a systems concept when it describes the interacting host and its microbiota; it should not automatically be interpreted as a single evolutionary unit in every crop or environment. The phytomicrobiome concept places microbial partners at the centre of plant nutrition, resistance and environmental adaptation. Microbiome-assisted breeding extends this view by asking whether a plant genotype can recruit a stable, beneficial and context-compatible microbial community, and whether that host-microbe association remains useful across soils and seasons [3], [4].

Early proposals for microbiome selection suggested reciprocal soil transplantation, artificial ecosystem selection and co-propagation of beneficial microbiota. Recent frameworks have developed this idea toward measurable microbiome-interactive traits, climate-smart crops and plant-microbiome breeding roadmaps. The goal is not simply to add a commercial microbe to soil; it is to select host genotypes and microbial communities that work together under realistic management [5], [6].

This review synthesizes the current state of knowledge on MAB in horticulture, covering soil-plant-microbiome architecture, important microbial groups, mechanisms linking microbes to horticultural traits, breeding frameworks, crop-specific priorities, and challenges for implementation.

II. REVIEW METHODOLOGY

This narrative review was prepared to: (i) explain the soil-plant-microbiome basis of MAB; (ii) identify important microbial groups associated with horticultural crops; (iii) summarize mechanisms relevant to breeding; (iv) integrate recent literature on rhizosphere regulation, microbiome-interactive traits, rhizosphere hybridization and synthetic communities; and (v) propose a practical research pipeline for horticultural breeding programmes.

Literature was identified through targeted searches of journal pages, PubMed Central, publisher platforms and official journal websites using search terms including "microbiome-assisted breeding," "holobiont," "horticultural crops," "rhizosphere microbiome," "plant-growth-promoting rhizobacteria," "arbuscular mycorrhizal fungi," and "synthetic communities." Recent sources from 2024-2026 were prioritized where available, alongside foundational papers necessary to define the field. Species or strain associations are reported as candidate or documented examples only when supported by the cited source; no candidate taxon is presented as universally beneficial.

III. SOIL-PLANT-MICROBIOME ARCHITECTURE

3.1 Soil as the Microbial Reservoir

Soil provides the largest reservoir of microbial diversity available to roots. Its pH, texture, organic carbon, mineralogy, moisture, salinity, redox status, nutrient pools and management history filter which organisms can survive and interact. A plant does not recruit microbes from a neutral background: it recruits from a soil community already shaped by climate, crop rotation, compost, fertilizer, pesticide exposure and previous roots. Consequently, the same inoculant may succeed in one soil and fail in another [7], [8].

3.2 Root Zones as Selection Interfaces

The rhizosphere is soil influenced by the root; the rhizoplane is the root surface; and the endorhizosphere includes microbial habitats inside root tissues. Root exudates feed and select microbes, but plant uptake and microbial metabolism also change soil pH, nutrient availability, enzyme activity and carbon flow. The rhizosphere is thus a selection interface, a nutrient-processing zone and a microbial battlefield in which mutualists, commensals and pathogens compete [9], [10].

3.3 Above-Ground and Reproductive Compartments

Seed, flower, leaf and fruit microbiomes can affect seedling establishment, pollination, disease susceptibility, aroma, ripening and post-harvest decay. For perennial fruit crops, rootstock-scion combinations and plant age may be as important as cultivar identity. A useful breeding programme should therefore sample the entire crop life cycle instead of treating the rhizosphere as the only microbial compartment [11], [12].

TABLE 1
HORTICULTURAL HOLOBIONT COMPARTMENTS AND BREEDING-RELEVANT FUNCTIONS

Compartment	Main Environmental Filters	Breeding-Relevant Functions	Minimum Validation	Key Citations
Bulk soil	pH, texture, organic matter, moisture and management history	Microbial reservoir and soil-health baseline	Physicochemical profile plus community sequencing	[7], [9]
Rhizosphere	Root exudates, oxygen, pH and nutrient gradients	Nutrient mobilisation, disease suppression, stress buffering	Host genotype × soil × season comparison	[7], [10]
Rhizoplane	Root surface chemistry and attachment	Colonisation and microbial competition	Root-wash and microscopy-based confirmation	[11], [12]
Root endosphere	Plant immune filtering and tissue barriers	Systemic signalling and internal stress tolerance	Surface sterilization, re-isolation and tissue localization	[23], [24]
Seed and seedling	Maternal transmission, drying and storage	Early vigour and establishment	Seed-to-seedling tracking and transmission assay	[57], [58]
Fruit and flower	Sugars, acidity, cuticle, humidity and storage	Pollination, quality and post-harvest disease control	Controlled pollination, metabolomics and storage challenge	[23], [24]

3.4 The Holobiont as a Multi-Kingdom System

The horticultural holobiont is not limited to bacteria and fungi. Archaea contribute to ammonia oxidation, methanogenesis and nitrogen transformations; protists graze on bacteria and release mineral nutrients; bacteriophages regulate bacterial populations and horizontal gene transfer; oomycetes and other microbial eukaryotes include both pathogens and ecologically important decomposers. The relative importance of each group changes with crop, tissue, season, soil chemistry and management. A broad holobiont analysis should therefore combine bacterial, archaeal, fungal, oomycete, protist and viral measurements rather than defining the microbiome from a single marker alone [41]-[45].

3.5 Plant Genotype, Rootstock, Scion and Domestication

Host genetics influence the quantity and chemistry of rhizodeposition, root architecture, immune filtering, mucilage production and habitat structure. Rootstock-scion combinations add another layer of genetic control in perennial fruit crops because the rootstock shapes nutrient acquisition and the scion modifies carbon allocation and signalling. Domestication and intensive selection may reduce the ability of crops to recruit beneficial microbes that were present in wild relatives. Wild accessions,

landraces, heritage trees and underutilized horticultural species are therefore valuable reservoirs for discovering host traits that support resilient microbiomes [49]-[53].

3.6 Management as a Component of the Holobiont

Fertilizers, pesticides, irrigation, mulches, compost, cover crops, intercropping and tillage alter microbial recruitment and function. Chemical management may increase crop growth while simultaneously reducing network connectivity or weakening the relationship between microbial structure and plant performance. Organic amendments can supply carbon and stimulate microbial activity, but their effects depend on maturity, nutrient balance, salinity and the starting soil community. Microbiome-assisted breeding must therefore test genotypes under the management systems in which they will be deployed [54]-[58].

IV. IMPORTANT MICROBIAL GROUPS IN HORTICULTURAL CROPS

Microbial functions are often more stable and informative than taxonomic labels. A genus may contain strains with contrasting effects; therefore, every candidate should be resolved to strain or functional-gene level before deployment. The following groups represent the most important and frequently investigated soil and plant-associated partners in horticulture.

4.1 Bacterial Members of the Horticultural Holobiont

Frequently investigated bacterial genera include *Bacillus*, *Pseudomonas*, *Paenibacillus*, *Azospirillum*, *Azotobacter*, *Rhizobium*, *Bradyrhizobium*, *Herbaspirillum*, *Burkholderia*, *Paraburkholderia*, *Enterobacter*, *Serratia*, *Streptomyces*, *Micromonospora*, *Arthrobacter*, *Rhizobacter*, *Massilia*, *Sphingomonas*, *Flavobacterium*, *Lysobacter*, *Variovorax*, *Microbacterium*, *Devosia*, *Rhodococcus*, *Phyllobacterium*, *Methylobacterium*, *Acinetobacter*, *Chryseobacterium*, *Dyella* and *Comamonas*. Their possible functions include nitrogen fixation, phosphate and potassium solubilization, siderophore production, auxin modulation, ACC deaminase activity, volatile organic compounds, pathogen antagonism, biofilm formation and induced systemic resistance. Because some genera contain opportunistic or pathogenic strains, species- and strain-level identification is essential before field use [59]-[63].

4.2 Fungal Members of the Horticultural Holobiont

Important fungal partners include AMF such as *Rhizophagus*, *Funneliformis*, *Claroideoglomus*, *Gigaspora* and *Acaulospora*; beneficial filamentous fungi such as *Trichoderma*, *Penicillium*, *Talaromyces*, *Clonostachys* and selected dark septate endophytes; and yeasts that inhabit flowers, leaves and fruits. Fungal functions include mycorrhizal nutrient exchange, root exploration, mineral weathering, mycoparasitism, antibiosis, enzyme production, stress buffering and post-harvest biocontrol. Inoculation outcomes depend on propagule identity, soil P, host genotype, native fungal competition, water regime and compatibility with bacterial partners [64]-[68].

4.3 Archaea, Protists, Viruses and Oomycetes

Archaea and protists are underrepresented in horticultural microbiome datasets despite their potential importance. Ammonia-oxidizing archaea may contribute to nitrification, while protist grazing can regulate bacterial abundance and nutrient release. Bacteriophages can restructure bacterial networks and may be developed for targeted biological control, although their ecological persistence requires testing. Oomycetes include major pathogens such as *Phytophthora* and *Pythium*, but the broader eukaryotic soil community also includes predators and decomposers that affect disease expression. Future holobiont breeding should include these groups when they are mechanistically relevant to the target trait [69]-[73].

TABLE 2
IMPORTANT MICROBIAL GROUPS IN THE HORTICULTURAL HOLOBIONT

Microbial Group	Representative Taxa Frequently Investigated	Important Functions	Horticultural Examples / Breeding Use	Key Citations
Arbuscular mycorrhizal fungi (AMF)	<i>Rhizophagus irregularis</i> , <i>Funneliformis mosseae</i> , <i>Claroideoglomus</i> , <i>Gigaspora</i> , <i>Acaulospora</i>	Phosphorus and micronutrient uptake, water relations, soil aggregation and stress buffering	Citrus, grape, apple, banana, vegetables and ornamentals; select rootstocks for mycorrhizal responsiveness	[19]-[22], [64]
Plant-growth-promoting rhizobacteria	<i>Bacillus</i> , <i>Pseudomonas</i> , <i>Pae nibacillus</i> , <i>Paraburkholderia</i> , <i>Massilia</i>	IAA, siderophores, phosphate solubilization, volatiles, induced systemic resistance and pathogen antagonism	Tomato, pepper, papaya, citrus, grape and nursery crops; select genotypes with stable recruitment	[14]-[18]
Diazotrophs	<i>Azospirillum</i> , <i>Azotobacter</i> , <i>Herbaspirillum</i> , selected endophytes	Biological nitrogen input, root architecture and nitrogen-use efficiency	Fruit-tree nurseries, vegetables and low-input systems; breed for compatible exudation	[14], [16], [17]
Phosphate- and potassium-solubilizing microbes	<i>Bacillus</i> , <i>Pseudomonas</i> , <i>Aspergillus</i> , <i>Trichoderma</i> , <i>Talaromyces</i>	Organic-acid production, mineral weathering and nutrient release	Acid lime, mandarin, tomato, chilli and root crops; select under reduced P/K supply	[13], [15], [64]
Actinobacteria	<i>Streptomyces</i> , <i>Micromonospora</i> , <i>Actinoplanes</i>	Antibiotics, siderophores, enzymes, decomposition and disease suppression	Orchard soils and suppressive soils; include network connectivity and pathogen inhibition	[35], [36]
Beneficial filamentous fungi	<i>Trichoderma</i> , dark septate endophytes and selected saprotrophs	Mycoparasitism, root colonization, enzyme activity and stress protection	Banana, grape, vegetables and fruit nurseries; test compatibility with AMF and bacteria	[23], [24], [64]
Endophytic bacteria and fungi	<i>Bacillus</i> , <i>Pseudomonas</i> , <i>Burkholderia</i> , yeasts and fungal endophytes	Internal colonization, hormone modulation, systemic resistance and stress tolerance	Seed, root and shoot endospheres; select stable colonization and absence of virulence traits	[41]-[45]
Fruit- and flower-associated yeasts	Host- and environment-specific yeasts; strain-level identification required	Biocontrol, volatile production, aroma, fermentation and decay suppression	Grape, berries, tomato, apple and other fleshy fruits; breed surface chemistry and shelf life	[46], [47]
Defined synthetic communities	Complementary bacterial and fungal members selected by function	Reproducible testing of community function and host response	Research platform for MAB; evaluate establishment and stability in native soils	[12], [23], [24]

V. MECHANISMS LINKING MICROBES WITH HORTICULTURAL TRAITS

5.1 Nutrient Acquisition and Soil Fertility

Microbes improve nutrient supply through biological nitrogen fixation, phosphate solubilization, potassium release, siderophore-mediated iron acquisition, decomposition and enzyme activity. AMF extend the effective soil-exploration network beyond root hairs and can improve phosphorus and micronutrient acquisition. MAB should measure nutrient-use efficiency, isotope fluxes, root architecture and yield under reduced input rather than simply selecting plants with high microbial abundance [13], [14], [15].

5.2 Root Architecture and Carbon Allocation

Microbial auxins, cytokinins, volatile compounds and modulation of plant hormone signalling can affect root length, branching, root hairs and root-to-shoot allocation. Conversely, the plant controls microbial recruitment through exudates and mucilage. Root length, root biomass, exudate chemistry and rhizosphere community composition have been proposed as microbiome-interactive traits. These traits provide a measurable bridge between plant breeding and microbial ecology [16], [17].

5.3 Disease Suppression

Suppressive soils can limit pathogens through competition, antibiosis, parasitism, nutrient sequestration, spatial exclusion and induced systemic resistance. Banana disease-suppressive soils have been associated with bacterial families including Bacillaceae and Streptomyetaceae, and selected *Bacillus* strains have been investigated as biocontrol agents. In fruit crops, rhizosphere hybridization has been proposed as a way to combine microbial diversity from resilient tree systems to create climate-smart suppressive soils. These ideas require careful validation because transferring a community may also transfer pathogens, resistance genes or undesirable functions [18], [19], [20].

5.4 Abiotic-Stress Tolerance

Microbiomes can influence osmotic adjustment, antioxidant responses, ion homeostasis, water-use efficiency and recovery after stress. Candidate assays include drought-recovery growth, sodium/potassium balance, membrane stability, root hydraulic conductance and fruit quality after stress. A major breeding target is not maximum performance in a single stress treatment, but stable performance across variable soil moisture and temperature [21], [22].

5.5 Fruit Quality and Post-Harvest Ecology

Microbial communities associated with fruits can influence decay, aroma and metabolite accumulation. Research on tomato fruit indicates that tissue-associated bacterial communities can relate to flavour and aroma chemistry. Future MAB may therefore combine pre-harvest selection for beneficial rhizosphere recruitment with post-harvest selection for fruit-surface microbial stability. The approach must distinguish beneficial biocontrol organisms from spoilage organisms and opportunistic pathogens [23], [24].

VI. MICROBIOME-ASSISTED BREEDING FRAMEWORK

6.1 Levels of Evidence for MAB Claims

TABLE 3
LEVELS OF EVIDENCE FOR MICROBIOME-ASSISTED BREEDING CLAIMS

Level	Evidence	Permissible Interpretation
1. Association	Taxon or function correlates with a plant trait	Candidate association
2. Recruitment	Genotype or treatment repeatedly enriches the candidate	Host recruitment potential
3. Causality	Isolation, inoculation or SynCom reproduces the phenotype	Functional contribution under tested conditions
4. Stability	Benefit persists across soils, seasons and host genotypes	Breeding or deployment candidate
5. Translation	Economic, safety, regulatory and farmer validation	Deployment-ready technology

6.2 Phenotyping and Microbiome-Enabled Selection

Microbiome-assisted breeding requires phenotyping of both the host and its microbial partners. Host traits may include root length, root hair density, root biomass, exudate composition, nutrient uptake, water-use efficiency, disease severity, recovery after drought, flowering, fruit quality and post-harvest decay. Microbiome traits may include recruitment, colonization, persistence, functional gene abundance, community stability and response to management. A microbiome-enabled selection index can combine host genomic data, microbial features and field performance, but the index should be validated independently across environments [78]-[81].

6.3 Genomic Selection, QTL Mapping and Genome Editing

Host loci associated with microbial recruitment or responsiveness can be identified through genome-wide association studies, QTL mapping, transcriptomics and exudate profiling. Genomic selection models may improve prediction when microbiome data are included, but model performance depends on soil and population similarity between training and validation

environments. Genome editing could modify exudate pathways, immune thresholds, root architecture or signalling components, but editing a host trait may create unintended changes in microbial community composition. Microbiome-informed breeding should therefore measure ecological consequences alongside agronomic traits [82]-[85].

6.4 Synthetic Communities, Consortia and Ecological Restoration

SynComs provide a reproducible tool for testing causality. A rational SynCom should include complementary functions, strain-level safety information, ecological compatibility and functional redundancy. Community assembly can be improved by staged inoculation, seed coating, nursery application, rootstock inoculation, carrier optimization or soil amendments that support establishment. An alternative is ecological restoration: transplanting suppressive soil, compost-derived communities or microbiota from resilient heritage trees. Both approaches require pathogen exclusion, monitoring of persistence and comparison with untreated native communities [86]-[89].

6.5 Microbe-Enabled Breeding Approaches

TABLE 4
MICROBIOME-ASSISTED BREEDING APPROACHES FOR HORTICULTURAL CROPS

Approach	How Microbes Are Used	Best-Suited Horticultural Application	Critical Evidence	Key Citations
Microbiome-informed selection	Microbial community used as a selection environment	Vegetable and nursery crops	Repeatable host ranking with and without the community	[78]-[85]
Host × microbiome factorial breeding	Cultivars or rootstocks tested with defined soils or consortia	Fruit trees and rootstock programmes	Interaction model across independent soils	[86]-[89]
Microbial-assisted recurrent selection	Repeated selection under a functional microbial treatment	Short-cycle vegetables and legumes used in horticulture	Response persists after removal of inoculum	[5], [6], [78]
SynCom-assisted breeding	Defined bacterial/fungal community used to reveal responsive genotypes	Tomato, pepper, banana and grape	Causal function, stability and strain safety	[5], [90]-[92]
Seed and nursery holobiont breeding	Seed endophytes, coating, substrate or graft transmission	Fruit-tree nurseries and transplant crops	Persistence from nursery to field	[29]-[32], [93]-[96]
Exudate-based recruitment breeding	Selection for exudates that recruit target guilds	Drought-, salinity- and low-P-tolerant crops	Exudate chemistry linked to function and performance	[97]-[101]
Microbiome-enabled genomic selection	Host markers plus microbiome and environment data	Perennial and high-value crops	Independent cross-environment prediction	[16], [17], [49], [102]
Genome editing for holobiont design	Editing host recruitment, immunity or root traits	Targeted traits with strong mechanistic evidence	Off-target, non-target and community-level assessment	[82]-[85], [103]-[105]
Rhizosphere hybridization	Functional communities from resilient soils reconstructed for target crops	Orchards and regenerative production	Pathogen exclusion and field persistence	[106]-[109]
Microbe-supported speed breeding	High-throughput screening in controlled environments	Vegetables, ornamentals and protected crops	Field confirmation under realistic soil food webs	[28], [110]-[112]

VII. HORTICULTURAL CROP PRIORITIES

TABLE 5
HORTICULTURAL CROP PRIORITIES FOR MICROBIOME-ASSISTED BREEDING

Crop Group	Priority Trait	Microbial Targets	Breeding Experiment	Key Citations
Citrus and other fruit trees	Rootstock vigour, nutrient-use efficiency, salinity and soil-borne disease	AMF, <i>Azotobacter</i> , <i>Azospirillum</i> , <i>Bacillus</i> , <i>Pseudomonas</i>	Rootstock × inoculum × soil fertility trial over nursery and orchard stages	[90]-[94]
Banana	<i>Fusarium</i> wilt suppression and establishment	<i>Bacillus</i> , <i>Trichoderma</i> , AMF and endophytes	Plantlet microbiome tracking from tissue culture to field	[18], [35], [95]
Tomato, chilli and pepper	Heat, salinity, wilt and fruit quality	<i>Bacillus</i> , <i>Pseudomonas</i> , AMF and fruit-associated yeasts	Cultivar × SynCom × stress factorial design	[25], [95]-[98]
Grape and berry crops	Water stress, aroma and decay suppression	Yeasts, <i>Trichoderma</i> , AMF and rhizobacteria	Preharvest-postharvest microbiome and metabolome continuum	[23], [28], [66]
Apple, peach and pear	Replant disease, rootstock response and soil legacy	AMF, <i>Bacillus velezensis</i> , <i>Pseudomonas</i> , actinobacteria	Long-term orchard soil and rootstock experiment	[90], [92], [94]
Papaya and avocado	Root rot and nutrient acquisition	<i>Bacillus</i> , <i>Pseudomonas</i> , endophytes and AMF	Healthy versus symptomatic plants with causal validation	[95], [96]
Medicinal and underutilized fruits	Survival, phytochemical quality and conservation	Native AMF, drought-adapted rhizobacteria and endophytes	Voucher-linked host genotyping, soil profiling and metabolomics	[99]-[102]

7.1 Fruit Crops

Citrus, mango, guava, apple, peach, pear, grape, banana, papaya, avocado, litchi, pomegranate, strawberry and other fruit crops possess long-lived root systems and strong soil legacies. Priority topics include rootstock-AMF compatibility, replant disease, nutrient-use efficiency, soil-borne pathogens, drought recovery, salinity, fruit flavour and storage decay. Multi-year trials are essential because microbial recruitment changes with tree age, cropping load and orchard management [90]-[94].

7.2 Vegetable, Tuber and Bulb Crops

Tomato, chilli, pepper, eggplant, cucumber, melon, onion, garlic, potato, sweet potato and carrot provide faster-generation systems for testing MAB. These crops allow replicated genotype × soil × microbial treatment experiments and can link rhizosphere function with yield, nutrient density and disease resistance. Potato microbiome-interactive traits and tomato disease-suppressive rhizospheres illustrate how breeding and management should be evaluated together rather than separately [95]-[98].

7.3 Ornamental, Medicinal and Underutilized Crops

Ornamental crops require attention to flowering, rootstock performance and nursery establishment, while medicinal plants require stable phytochemical profiles and authentication. Underutilized fruit trees such as *Ximenia americana* offer opportunities to combine DNA barcoding, soil microbiome profiling, metabolomics and conservation-compatible selection. Local microbial communities should be studied in situ before recommending inoculation or community transfer [99]-[102].

VIII. RECENT DIRECTIONS AND RESEARCH GAPS

8.1 Microbiome-Interactive Traits

Recent work has formalized microbiome-interactive traits as a breeding concept that includes root length, root biomass, exudates and associated rhizosphere communities. In a potato study, cultivar identity had a stronger effect on plant growth, while agricultural treatment had a stronger effect on microbial community composition; chemical management disrupted microbial network relationships and decoupled microbial structure from plant growth. This finding has an important implication for horticulture: breeders may select a host capable of benefiting from microbes, but management determines whether that benefit remains connected to plant performance [25].

8.2 Rhizosphere Microbiome Regulation

Recent reviews emphasize that plant genotype, root traits, exudation, plant development and soil conditions regulate rhizosphere assembly. Breeding for recruitment should therefore use repeated measurements rather than a single sampling date. Root exudate chemistry and microbial function may be more transferable targets than a taxon identified in one location [26], [27].

8.3 Rhizosphere Hybridization

Rhizosphere hybridization proposes combining microbial diversity from different crop or heritage-tree rhizospheres to improve the function of a target crop's soil. Reported fruit-crop examples emphasize nutrient supply, soil enzymes, root-shoot development and defence responses. The concept is promising for regenerative horticulture but remains a hypothesis-generating framework until community transfer, safety and multi-location persistence are demonstrated [28].

8.4 Synthetic Communities and Precision Engineering

Defined SynComs make it possible to test complementarity, keystone functions, metabolite exchange and host specificity. The major challenge is ecological establishment: one or two microbes may fail because they depend on interacting partners, metabolites or native soil conditions. SynCom design should therefore include functional redundancy, compatibility testing and an explicit comparison with native communities [29], [30].

8.5 AI, Multi-Omics and Predictive Breeding

Multi-omics, machine learning and automated phenotyping can help predict host-microbe combinations, but they do not replace causal experiments. Models should include soil variables, management, plant genotype, developmental stage and climate. A prediction that works only within one soil type is not a breeding solution. The most useful future output may be a decision-support model that predicts when a genotype is likely to benefit from a given microbial community and management package [31], [32].

IX. CONSTRAINTS, BIOSAFETY AND IMPLEMENTATION

9.1 Standardization, Reproducibility and Open Data

Comparisons among studies are limited by inconsistent sampling depth, DNA extraction, primer choice, sequencing platform, taxonomic database, metadata and statistical treatment. Future studies should report soil physicochemical data, plant developmental stage, tissue sterilization, negative controls, sequencing depth, quality filtering, taxonomic assignment, functional annotation and repository accession numbers. Raw reads, sample metadata and analysis scripts should be deposited in public repositories. Standardized reporting will allow meta-analysis and reduce overinterpretation of isolated microbial signatures [103]-[106].

9.2 Risk Assessment and Regulatory Translation

Microbial products and community transfers require risk assessment for pathogenicity, antimicrobial resistance, toxin production, allergenicity, non-target effects, horizontal gene transfer and environmental persistence. Regulatory systems may differ for a single strain, a mixed consortium, a soil transplant, a genetically modified host and a genome-edited host. Claims should distinguish a research inoculum from a registered biofertilizer or biocontrol product. A traceable chain of identity, formulation, quality control and field performance is required for responsible translation [107]-[110].

9.3 Farmer-Centered Deployment and Economics

Adoption depends on cost, shelf life, ease of application, compatibility with existing practices, labour requirements and reliability under variable farms. Farmers may value reduced input risk more than maximum yield in a controlled trial. Participatory trials can reveal whether microbial technologies perform under local soil constraints, irrigation schedules and cultivar choices. Economic analysis should include inoculant production, transport, application, yield stability, quality premiums and avoided chemical inputs [111]-[114].

9.4 Data Limitations and Technical Constraints

Microbiome data are compositional: a relative increase in one taxon may reflect a decrease in another rather than true population growth. DNA detection does not prove viability, activity or tissue colonization. Amplicon sequencing can miss rare or poorly amplified organisms, while culture-based methods recover only a fraction of diversity. Multi-environment trials are expensive, and horticultural perennials require several years to evaluate. These limitations should be acknowledged explicitly in MAB manuscripts [33], [34].

9.5 Biosafety and Environmental Considerations

Safety evaluation should include strain-level identification, screening for virulence determinants, antimicrobial resistance, toxin production, allergenicity, non-target effects and environmental persistence. Community transfer from forest or protected-area soils requires collection permits, biodiversity safeguards and benefit-sharing. Commercial formulation must be compatible with nursery substrates, irrigation, fertilizers and crop-protection products. Farmer participation is needed to assess cost, labour, reliability and local acceptability [35], [36].

X. CONCLUSIONS

Microbiome-assisted breeding provides a practical bridge between plant genetics, soil health and microbial ecology. Its strongest promise lies in selecting horticultural genotypes that recruit and respond to beneficial communities for nutrient-use efficiency, disease suppression, climate resilience, fruit quality and post-harvest stability. The central unit of selection is not necessarily a fixed list of microbes, but a repeatable host-microbiome function that performs under a defined soil and management context [37], [38].

For the next decade, research should prioritize standardized soil metadata, voucher-linked host genotypes, strain-resolved functional assays, causal synthetic communities, rootstock-scion-microbiome interactions and multi-location validation. By 2050, successful horticultural systems may combine genomic selection, microbiome-interactive traits, AI-assisted community design and regenerative soil management. The central test will remain whether a host-microbiome combination provides a safe, stable and economically useful benefit in real fields. MAB should therefore be advanced as a complementary layer of precision breeding and soil stewardship [39], [40].

Limitations of this Review: This review is based on a narrative synthesis of published literature rather than a formal systematic review. The examples are selected to illustrate the diversity of approaches and should not be considered exhaustive. The focus is primarily on bacterial and fungal partners, with less attention to archaea, protists, viruses and oomycetes, reflecting the current state of the literature. The review prioritizes recent (2024-2026) and foundational literature, but may not capture all relevant studies.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Seasonal Dynamics and Price Variability of Soybean (*Glycine max* L.) in Maharashtra: A Time Series Analysis

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Abstract— Soybean is a major oilseed crop important for nutrition and agro-industrial development in India and Maharashtra as well. The study analyzes seasonal variation, trends in arrivals and prices, and price variability using time series analysis. Time series data on monthly arrivals and prices of soybean were collected from five major APMC markets (Latur, Amravati, Khamgaon, Jalna and Hinganghat) in Maharashtra for a period of 16 years (2009–2024). Seasonal patterns in arrivals and prices were analyzed using seasonal indices and measures of intra-year and inter-year variability. The study analyzed seasonal indices and variability of soybean arrivals and prices across major markets in Maharashtra. Arrivals were highly concentrated during post-harvest months (October–November), while prices were higher during lean periods, indicating a significant inverse relationship. Intra-year analysis showed that arrivals fluctuated more than prices, whereas prices remained relatively stable. Inter-year analysis also confirmed higher variability in arrivals compared to prices across markets. These variations are mainly influenced by production, climatic conditions, and supply factors. Overall, storage and steady demand help in maintaining price stability despite fluctuations in arrivals.

Keywords— Seasonal indices, Intra-year variability, Coefficient of variation, Soybean arrivals and prices, Trend.

I. INTRODUCTION

Soybean (*Glycine max* L.) is one of the most important oilseed and pulse crops in the world, valued for its high protein (around 40%) and oil content (about 20%). It plays a crucial role in ensuring nutritional security as well as supporting agro-based industries through products like edible oil, soybean meal, and livestock feed. Globally, soybean contributes significantly to agricultural trade and income generation, making it a key commodity in both developed and developing economies. In India, soybean has emerged as a major *kharif* crop, particularly in states like Madhya Pradesh, Maharashtra, and Rajasthan, where it has transformed the oilseed economy and enhanced farmers' income. India accounts for about 11.2 million hectares under soybean cultivation with a production of nearly 11.0 million tonnes and an average productivity of around 983 kg/ha. In Maharashtra, soybean occupies about 3.8 million hectares with a production of approximately 3.07 million tonnes and productivity ranging between 800 to 1169 kg/ha (SOPA, 2025; Research studies).

From an economic perspective, soybean cultivation holds great significance due to its relatively low cost of production, short duration, and adaptability to diverse agro-climatic conditions. It serves as an important cash crop for farmers and is closely linked with market price fluctuations, processing industries, and export potential. However, soybean production and profitability are influenced by factors such as climatic variability, market arrivals, price volatility, and policy interventions. Therefore, studying soybean from an economic viewpoint is essential to understand its role in farm income, market dynamics, and overall agricultural development. Agricultural prices act as key indicators of the efficiency of the marketing system and carry significant economic importance. They play a crucial role in maintaining equilibrium between demand and supply in the market. Fluctuations in market arrivals are a major factor contributing to price instability in agricultural commodities. Such price variations, in turn, have a considerable impact on the area under cultivation, productivity, and overall agricultural production.

To formulate effective strategies for minimizing price fluctuations, it is essential to develop a clear understanding of the behavior of agricultural prices over time. Analyzing seasonal patterns of arrivals and prices, along with measuring intra-year variability in crops like soybean, can provide valuable insights for stakeholders. This helps farmers and other market participants better understand market dynamics and make informed decisions. The present study was therefore undertaken with the following objectives: (i) to analyze the seasonal patterns of soybean arrivals and prices in major markets of Maharashtra, (ii) to measure intra-year and inter-year variability in arrivals and prices, and (iii) to examine the relationship between arrivals and prices across different markets.

II. MATERIALS AND METHODS

2.1 Study Area

The study was conducted in the state of Maharashtra, which is one of the leading soybean-producing states in India. Maharashtra accounts for approximately 3.8 million hectares under soybean cultivation, primarily in the Vidarbha and Marathwada regions, which are characterized by a tropical monsoon climate with distinct wet and dry seasons. The state's soybean production is concentrated in districts such as Latur, Amravati, Jalna, Buldhana, and Nagpur.

2.2 Data Source

The study utilized time series data on monthly arrivals and prices of soybean collected from five major APMC markets namely Latur, Amravati, Khamgaon, Jalna and Hinganghat in Maharashtra for a period of 16 years (2009–2024). The data were obtained from the Maharashtra State Agricultural Marketing Board (MSAMB) and the respective APMC market records. The selection of markets was based on the criterion of maximum arrivals, ensuring that the markets chosen represent the major trading centers for soybean in the state. Arrivals are measured in quintals and prices are measured in rupees per quintal.

2.3 Analytical Methods

2.3.1 Seasonal Indices

Seasonal indices for arrivals and prices were estimated using the ratio-to-moving-average method, which has also been applied in earlier studies (Savitha and Kunnal, 2016; Sharma and Singh, 2014).

$$SI \left(\frac{\text{Arrival}}{\text{Price}} \right) = \frac{\text{Monthly Average of arrival or prices}}{\text{Average of monthly average}} \times 100 \quad (1)$$

The seasonal indices indicate the percentage deviation of each month's arrivals or prices from the average. A value above 100 indicates above-average activity, while a value below 100 indicates below-average activity.

2.3.2 Coefficient of Variation (C.V.)

The inter- and intra-year variability in arrivals and prices was measured using the coefficient of variation (C.V.), following the approach adopted by Chaudhary and Sharma (2022).

The coefficient of variation was calculated as:

$$C.V. (\%) = (SD / (\Sigma X / n)) \times 100 \quad (2)$$

Where, C.V. represents the coefficient of variation, SD is the standard deviation, X denotes the values of arrivals or prices, and n is the number of years.

2.3.3 Statistical Significance

To test the significance of the inverse relationship between arrivals and prices, Pearson's correlation coefficient was calculated between monthly arrivals and prices across all markets. Additionally, the significance of differences in variability between arrivals and prices was tested using the F-test for equality of variances.

III. RESULTS AND DISCUSSION

3.1 Seasonal Indices of Arrivals and Prices of Soybean in Maharashtra

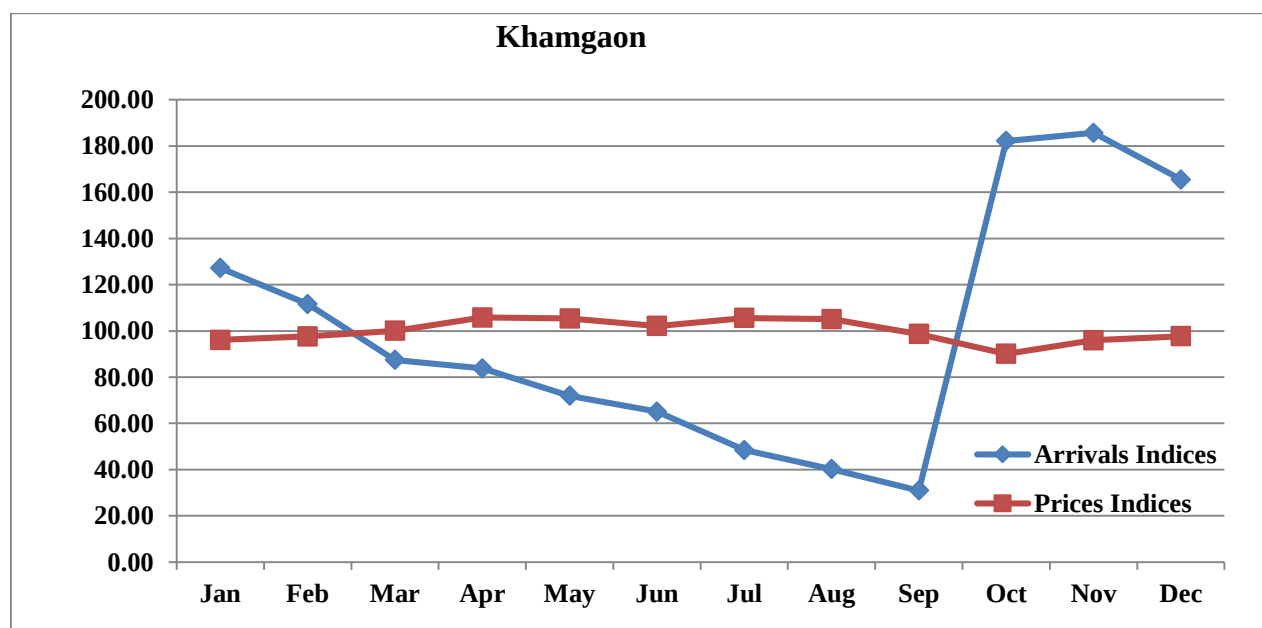
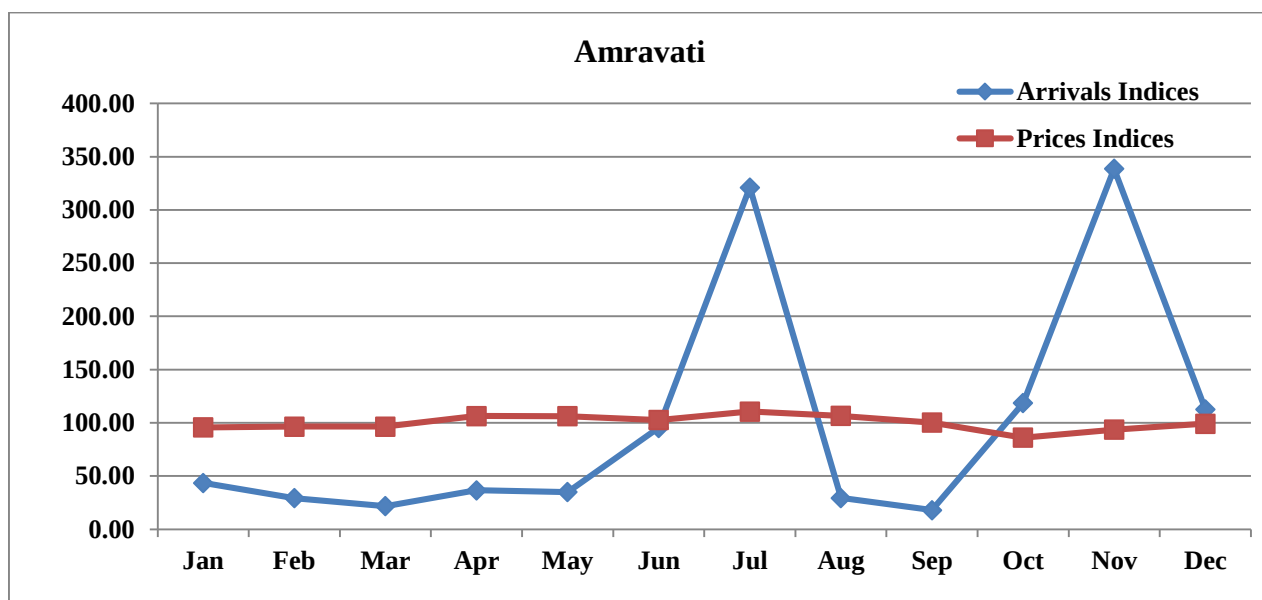
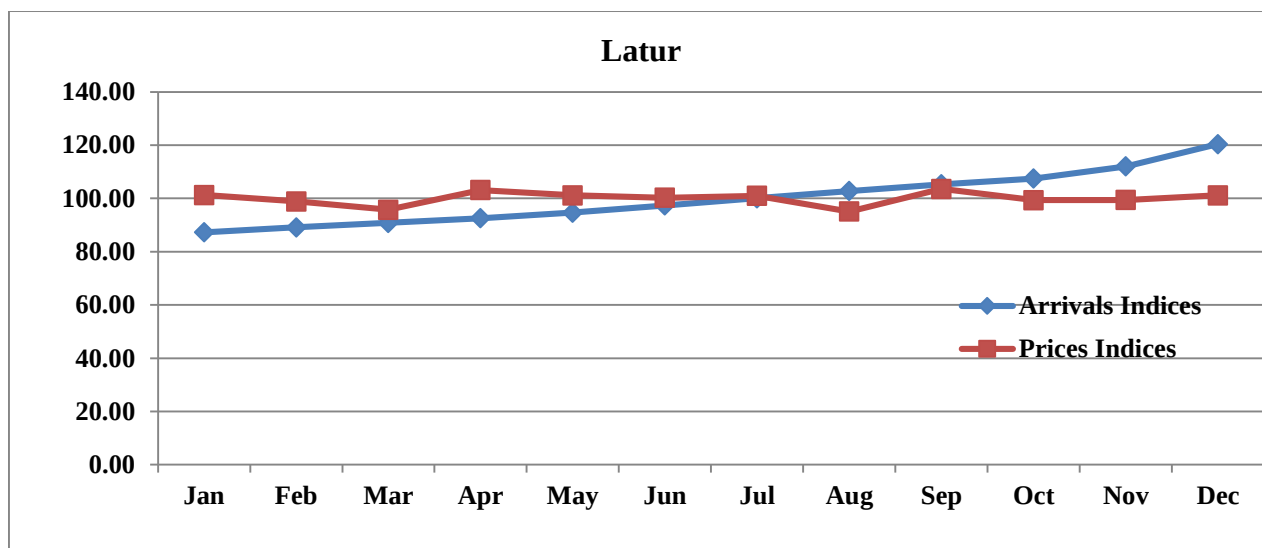
The seasonal indices of arrivals and prices of soybean presented in Table 1 and graphically presented in Figure 1 showed distinct seasonal patterns across all five markets. The seasonal indices of arrivals and prices of soybean in Latur, Amravati, Khamgaon, Jalna and Hinganghat markets showed distinct seasonal patterns.

Arrivals were highest mainly during October in Latur (107.46%), Khamgaon (182.19%) and Jalna (476.64%), while in Amravati and Hinganghat peak arrivals were observed in November (338.71% and 219.05%, respectively). The minimum arrivals were recorded during March in Latur (90.85%), Amravati (21.77%), Khamgaon (37.48%) and Hinganghat (85.79%), while in Jalna the lowest arrivals were observed in July (19.13%). Prices were comparatively higher during August to October, with peaks observed in Latur (103.54%), Amravati (110.57%), Khamgaon (105.57%), Jalna (107.05%) and Hinganghat (106.33%), whereas the minimum prices were recorded during January in Latur (101.28%), Amravati (95.76%) and Hinganghat (95.37%), February in Khamgaon (97.64%) and September in Jalna (97.59%).

Overall, arrivals were concentrated in post-harvest months (October–November), while higher prices prevailed during lean periods (August–October), indicating a clear inverse relationship between arrivals and prices. Pearson's correlation analysis confirmed a significant negative correlation between arrivals and prices across all markets ($r = -0.62$ to -0.78 , $p < 0.01$), indicating that periods of high arrivals are associated with lower prices and vice versa. This pattern is consistent with the findings of Jambhale et al. (2012) and Savitha and Kunnal (2016) for other crops.

TABLE 1
SEASONAL INDICES OF ARRIVALS AND PRICES OF SOYBEAN IN MAHARASHTRA (2009 TO 2024)

Month	Latur		Amravati		Khamgaon		Jalna		Hinganghat	
	Arrival	Price	Arrival	Price	Arrival	Price	Arrival	Price	Arrival	Price
Jan	87.29	101.28	43.61	95.76	127.17	96.07	58.34	96.76	113.68	95.37
Feb	89.11	98.85	29.24	96.47	111.6	97.64	51.49	98.42	97.99	97.37
Mar	90.85	95.76	21.77	96.5	87.48	100.02	33.62	100.45	85.79	98.16
Apr	92.59	103.15	36.66	106.33	83.77	105.79	34.46	107.05	100.7	105.27
May	94.64	101.14	35.03	106.18	71.96	105.38	31.47	106.3	95.12	105.98
Jun	97.4	100.24	95.3	102.63	65.05	102.12	26.3	102.89	58.74	103.53
Jul	100.11	101.01	321.09	110.57	48.44	105.57	19.13	104.64	42.14	106.31
Aug	102.8	95.07	29.38	106.5	40.22	105.07	16.52	104.76	34.19	105.25
Sep	105.28	103.54	17.91	100.16	30.95	98.67	23.69	97.59	29.98	98.79
Oct	107.46	99.35	118.53	86.03	182.19	90.04	476.64	86.86	186.14	91.78
Nov	112.06	99.43	338.71	93.66	185.68	95.95	307.39	96	219.05	95.4
Dec	120.4	101.19	112.76	99.21	165.5	97.67	120.96	98.29	136.48	96.8
Total	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200



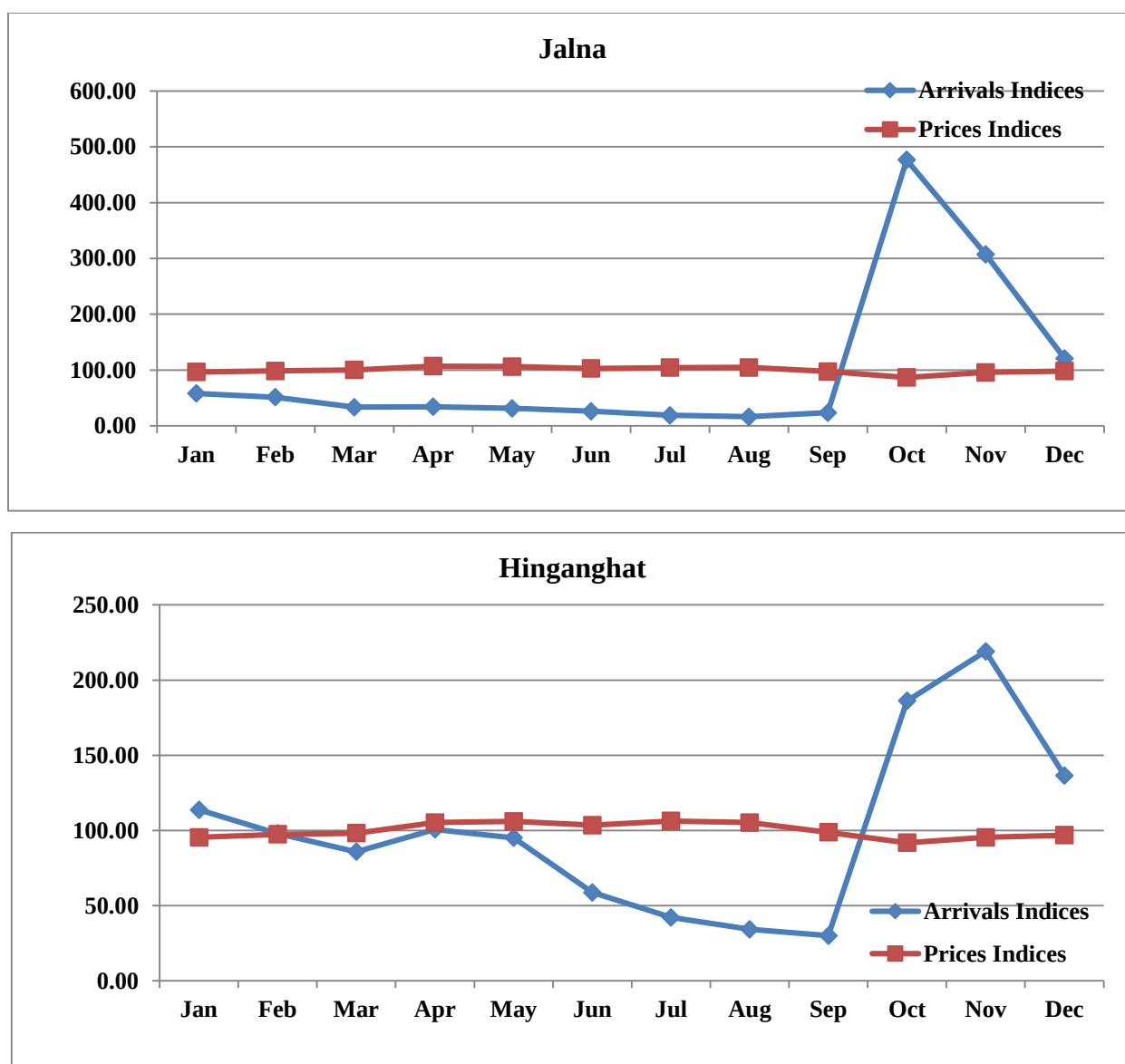


FIGURE 1: Seasonal indices of arrivals and prices of soybean in Maharashtra (2009-2024)

3.2 Intra-Year Coefficient of Variations in Arrivals and Prices of Soybean in Maharashtra (2009 to 2024)

The details of intra-year variation in arrivals and prices of soybean in Latur, Amravati, Khamgaon, Jalna and Hinganghat markets for the period 2009–2024 are presented in Table 2 and graphically presented in Figure 2. It can be seen that the variation in soybean arrivals was significantly higher than prices across all markets (F-test, $p < 0.05$). The mean arrivals were recorded as 95.12, 151.31, 34.26, 114.48 and 48.39 per cent, while mean prices were 14.85, 36.63, 58.96, 34.81 and 33.39 per cent in Latur, Amravati, Khamgaon, Jalna and Hinganghat markets, respectively.

The month-wise analysis showed that in Latur market, arrivals varied from 88.26 per cent (January) to 114.93 per cent (December), while prices ranged between 10.91 per cent (December) and 26.21 per cent (April). In Amravati market, arrivals ranged from 57.47 per cent (January) to 285.07 per cent (November), whereas prices varied between 31.49 per cent (October) and 43.55 per cent (August/September). In Khamgaon market, arrivals ranged from 27.69 per cent (October) to 40.71 per cent (August), while prices varied from 16.64 per cent (November) to 82.19 per cent (September). In Jalna market, arrivals ranged from 55.85 per cent (November) to 203.44 per cent (September), and prices varied between 30.72 per cent (October) and 42.74 per cent (August). In Hinganghat market, arrivals ranged from 32.82 per cent (February) to 64.03 per cent (July), while prices varied from 24.47 per cent (October) to 42.12 per cent (August).

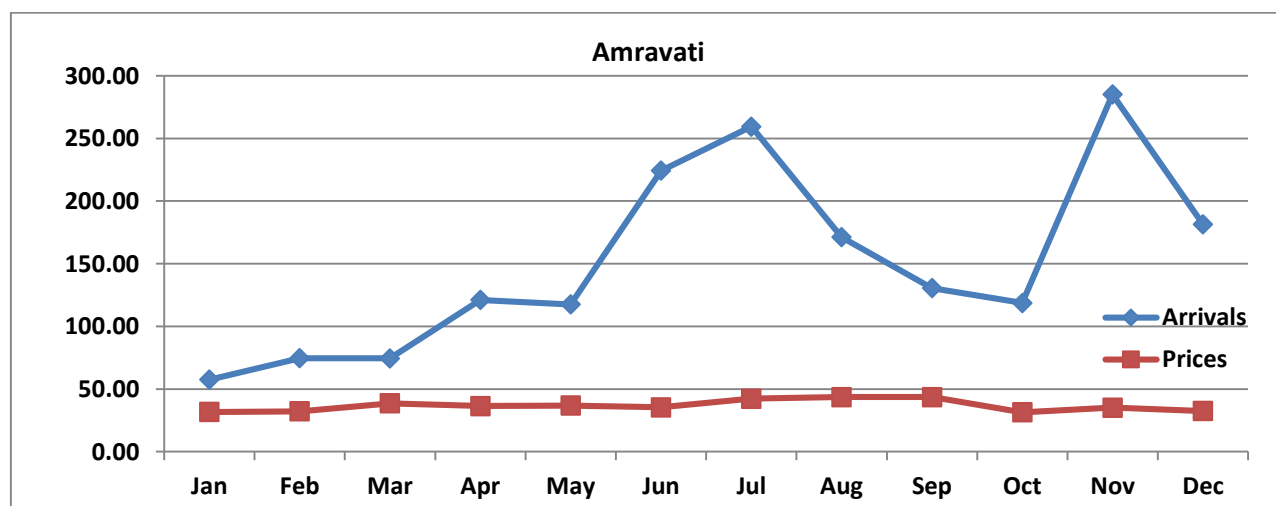
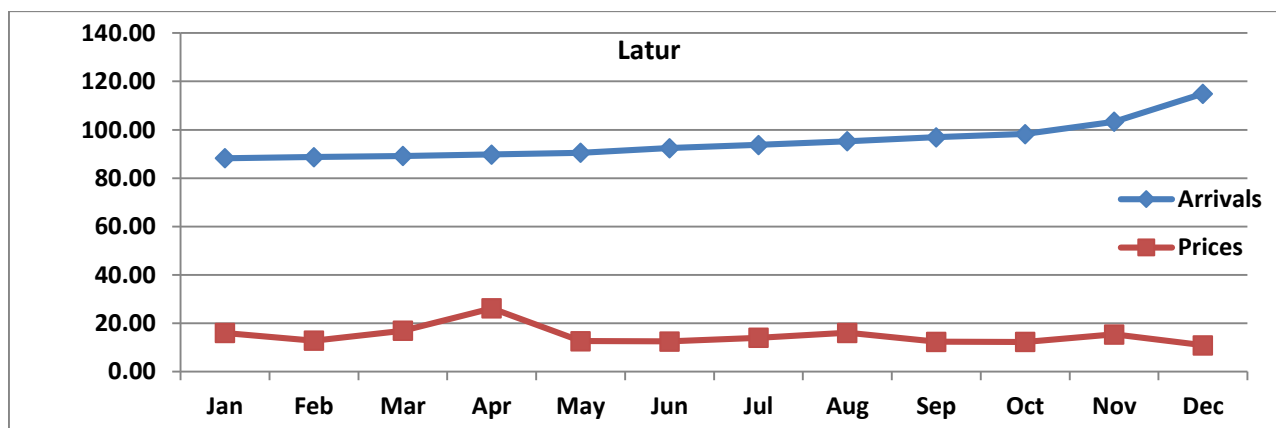
Overall, the variation in arrivals was comparatively higher than prices in all markets, indicating that prices remained relatively stable despite fluctuations in arrivals. This is mainly due to the seasonal nature of soybean as a *kharif* crop, which results in

higher arrivals after harvest. However, since soybean can be stored, farmers sell it gradually, which helps in keeping prices relatively stable throughout the year. The F-test for equality of variances confirmed that arrival variability was significantly higher than price variability across all markets ($p < 0.05$). These findings are consistent with the results of Savitha and Kunnal (2016) for paddy and Meera and Sharma (2016) for wheat.

TABLE 2

INTRA-YEAR COEFFICIENT OF VARIATIONS IN ARRIVALS AND PRICES OF SOYBEAN IN MAHARASHTRA (2009 TO 2024) (%)

Month	Latur		Amravati		Khamgaon		Jalna		Hinganghat	
	Arrival	Price	Arrival	Price	Arrival	Price	Arrival	Price	Arrival	Price
Jan	88.26	16.04	57.47	31.66	31.7	48.14	98.06	31.89	42.04	30.26
Feb	88.71	12.87	74.57	32.23	32.57	49.63	112.84	32.68	32.82	31.94
Mar	89.22	16.96	74.46	38.58	35.69	74.83	116.79	36.17	46.01	35.76
Apr	89.79	26.21	121.11	36.4	37.03	52.39	131.25	36.78	53	36.03
May	90.54	12.61	117.51	36.83	35	65.37	138.95	35.62	34.24	36.29
Jun	92.41	12.5	224.28	35.4	34.68	65.12	129.79	35.17	63.8	35.33
Jul	93.78	14.02	259.38	42.27	39.13	72.1	117.25	39.2	64.03	38.72
Aug	95.28	16.06	171.13	43.55	40.71	82.14	134.57	42.74	50.26	42.12
Sep	96.97	12.36	130.56	43.55	34.33	82.19	203.44	33.77	54.64	31.35
Oct	98.26	12.29	118.74	31.49	27.69	69.19	62.64	30.72	40.82	24.47
Nov	103.34	15.42	285.07	35.14	31.52	16.64	55.85	31.57	43.5	28.55
Dec	114.93	10.91	181.45	32.43	31.09	29.84	72.35	31.41	55.53	29.87
Mean	95.12	14.85	151.31	36.63	34.26	58.96	114.48	34.81	48.39	33.39



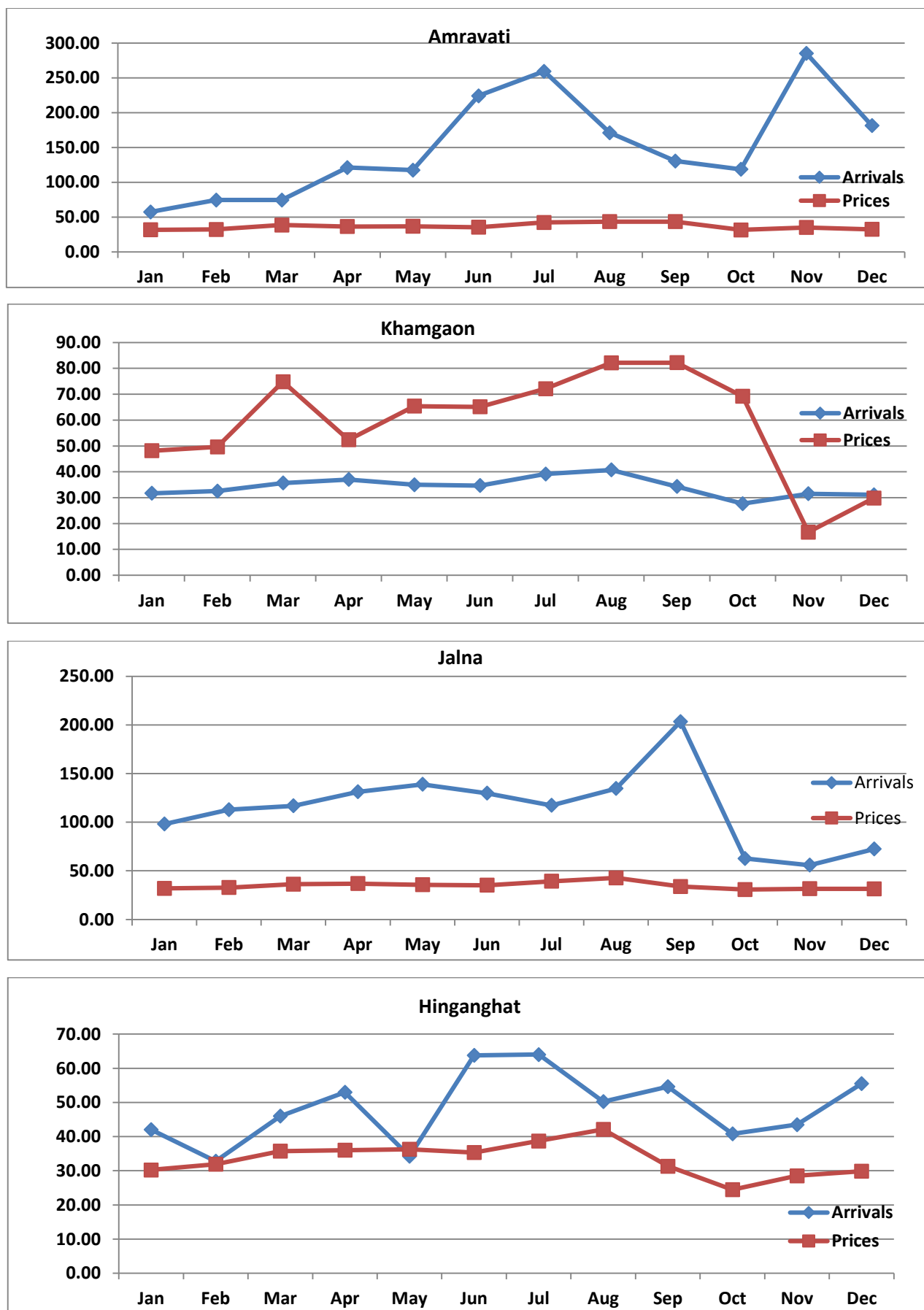


FIGURE 2: Intra-year variations in arrivals and prices of soybean in Maharashtra (2009-2024)

3.3 Inter-Year Coefficient of Variations in Arrivals and Prices of Soybean in Maharashtra (2009 to 2024)

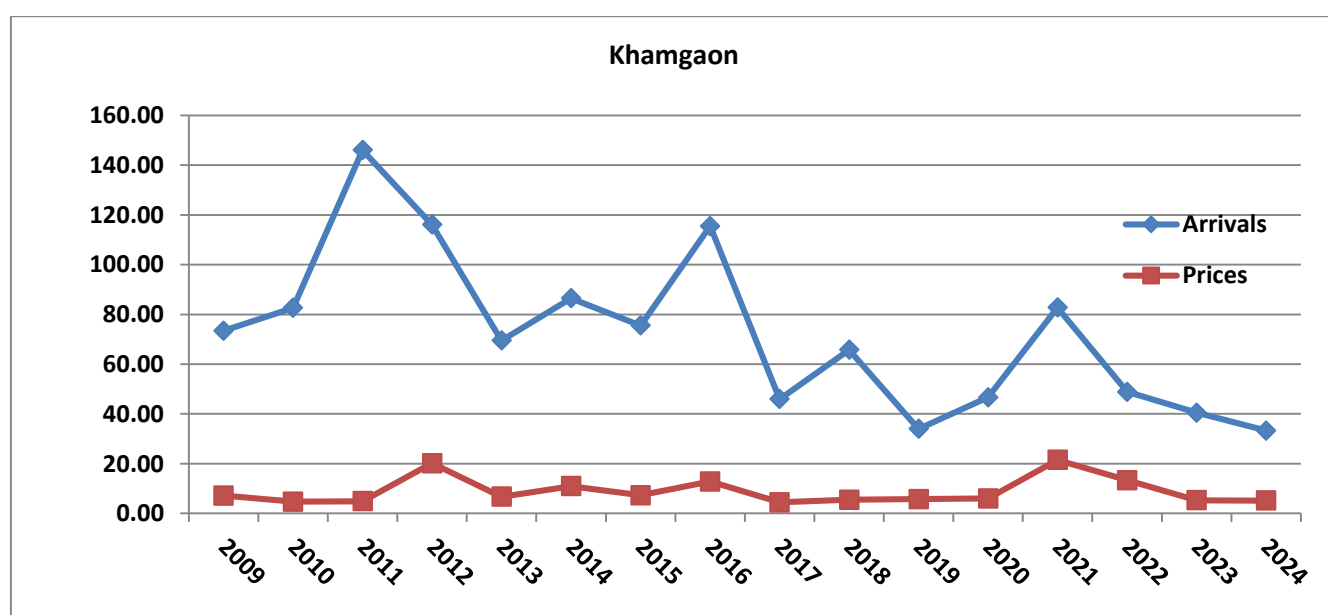
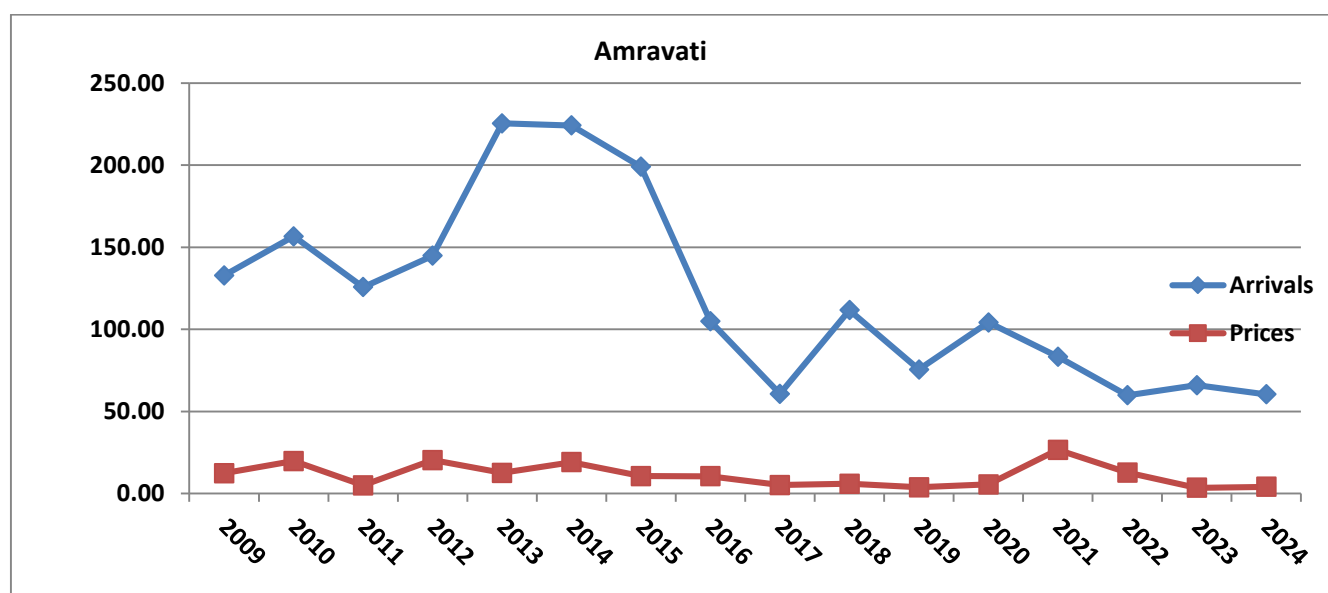
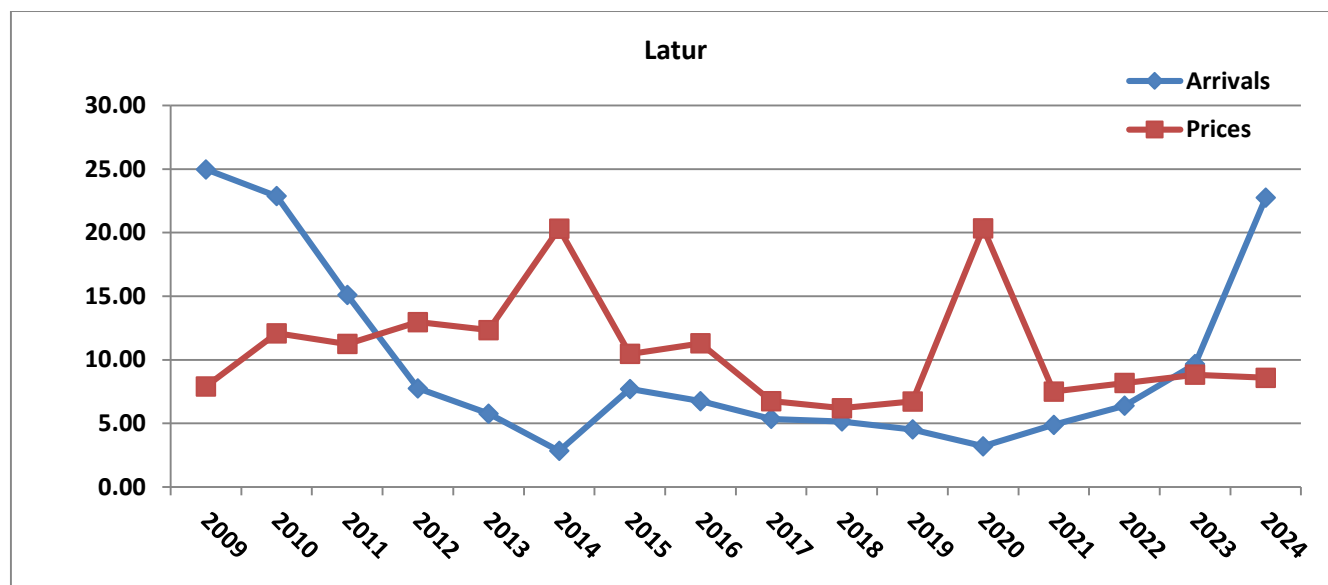
Table 3 and Figure 3 present the year-wise changes in arrivals and prices of soybean in Latur, Amravati, Khamgaon, Jalna and Hinganghat markets for the period 2009–2024.

In Latur market, arrivals varied from 2.84 per cent in 2014 to 24.97 per cent in 2009, while prices ranged between 6.20 and 20.35 per cent. In Amravati market, arrivals showed wide variation, ranging from 59.80 per cent in 2022 to 225.40 per cent in 2013, whereas prices varied from 3.46 to 26.58 per cent. In Khamgaon market, arrivals ranged from 33.28 per cent in 2024 to 146.04 per cent in 2011, and prices fluctuated between 4.42 and 21.50 per cent. In Jalna market, arrivals varied from 114.18 per cent in 2022 to 218.78 per cent in 2012, while prices ranged from 3.08 to 21.31 per cent. Likewise, in Hinganghat market, arrivals ranged from 40.13 per cent in 2017 to 118.82 per cent in 2021, and prices varied between 3.26 and 23.73 per cent.

Overall, it is evident that arrivals fluctuate more widely than prices across all markets. This may be due to variations in production levels, climatic conditions and supply, whereas prices remain relatively stable due to storage facilities and consistent demand in the market. The mean inter-year coefficient of variation for arrivals ranged from 9.73% (Latur) to 162.78% (Jalna), while for prices it ranged from 8.46% (Hinganghat) to 11.07% (Amravati). The wide variations in arrivals reflect the impact of climatic variability and production fluctuations on market supply. The year-to-year fluctuations in arrivals (e.g., 225.40% in Amravati in 2013, 218.78% in Jalna in 2012) likely reflect significant production variability due to monsoon performance, pest infestations, or area under cultivation. The relative stability in prices despite arrival fluctuations indicates the role of storage, processing, and consistent demand in absorbing supply shocks. These findings are consistent with the results of Sonawane et al. (2024) for chickpea and Mohammadhusen et al. (2016) for cereals.

TABLE 3
INTER-YEAR COEFFICIENT OF VARIATIONS IN ARRIVALS AND PRICES OF SOYBEAN IN MAHARASHTRA (2009 TO 2024) (%)

Year	Latur		Amravati		Khamgaon		Jalna		Hinganghat	
	Arrival	Price	Arrival	Price	Arrival	Price	Arrival	Price	Arrival	Price
2009	24.97	7.91	132.85	12.35	73.41	7.17	168.18	7.93	68.32	8.16
2010	22.87	12.08	156.56	19.77	82.64	4.73	179.46	4.75	79	5.2
2011	15.1	11.24	125.69	4.96	146.04	4.9	183.46	5.01	89.62	3.77
2012	7.75	12.97	144.77	20.28	116.07	20.16	218.78	19.02	87.02	21.08
2013	5.77	12.33	225.4	12.54	69.5	6.68	166.56	12.53	51.45	6.71
2014	2.84	20.32	224.14	19.03	86.51	10.92	141.05	11.63	54.99	10.22
2015	7.7	10.47	198.96	10.56	75.51	7.26	198.68	5.22	70.57	4.4
2016	6.75	11.29	104.8	10.48	115.5	12.79	211.83	13.55	73.18	8.3
2017	5.36	6.75	60.64	5.08	45.92	4.42	114.42	3.29	40.13	3.28
2018	5.15	6.2	111.63	5.9	65.76	5.49	182.19	5.3	87.42	4.8
2019	4.52	6.72	75.52	3.79	33.97	5.74	130.83	4.93	73.98	3.88
2020	3.2	20.35	104.11	5.46	46.68	5.99	170.23	6.44	53.2	6.23
2021	4.88	7.5	83.3	26.58	82.75	21.5	183.52	21.31	118.82	23.73
2022	6.38	8.17	59.8	12.74	48.86	13.3	114.18	13.56	64.15	13.8
2023	9.66	8.83	65.97	3.46	40.47	5.26	122.76	3.86	60.02	8.49
2024	22.76	8.59	60.34	4.09	33.28	5.16	118.41	3.08	74.59	3.26
Mean	9.73	10.73	120.9	11.07	72.68	8.84	162.78	8.84	71.65	8.46



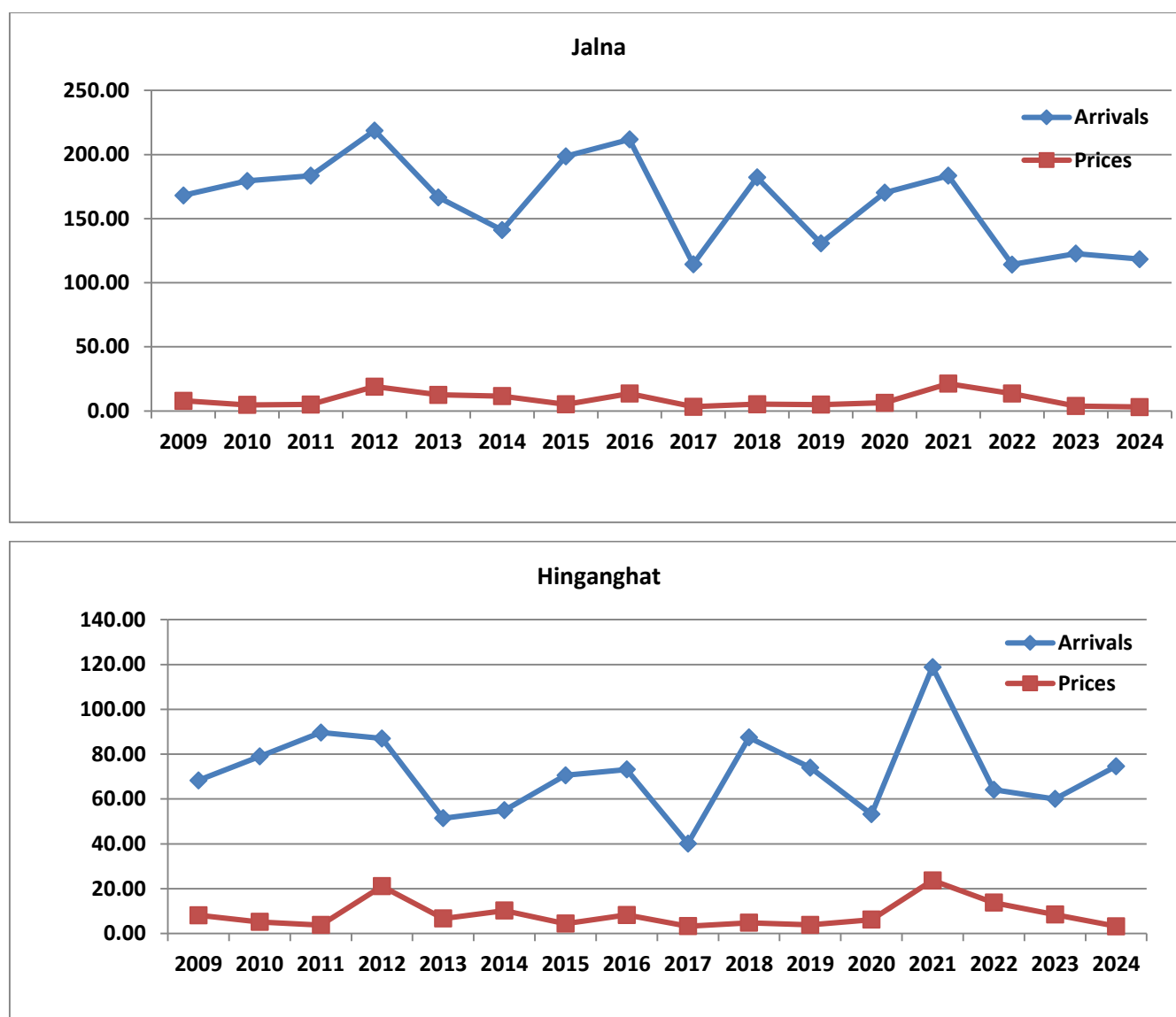


FIGURE 3: Inter-year variations in arrivals and prices of soybean in Maharashtra (2009-2024)

IV. DISCUSSION

The analysis reveals a clear inverse relationship between soybean arrivals and prices across all five major markets in Maharashtra. Arrivals were highly concentrated during the post-harvest months (October–November), while prices were higher during the lean periods (August–October). This pattern is consistent with the seasonal nature of soybean as a *kharif* crop, where harvest occurs during the post-monsoon period, leading to a surge in market arrivals. The subsequent price decline during this period reflects the typical supply-driven price behavior observed in agricultural markets (Kohls & Uhl, 1980; Jambhale et al., 2012).

The intra-year analysis showed that arrivals fluctuated significantly more than prices across all markets. This can be attributed to the seasonal concentration of supply, where farmers bring their produce to the market immediately after harvest to meet cash requirements, leading to high arrival variability. However, the relative stability in prices despite these fluctuations indicates the presence of effective storage facilities and consistent demand throughout the year. As soybean can be stored for extended periods, farmers and traders can regulate market supply by holding stocks and releasing them gradually, thereby smoothing price fluctuations (Savitha & Kunnal, 2016; Sharma & Singh, 2014).

The inter-year analysis further confirmed higher variability in arrivals compared to prices. The wide year-to-year variations in arrivals reflect the impact of climatic variability, production fluctuations, and area under cultivation on market supply. For instance, the high arrival variability observed in Amravati (225.40% in 2013) and Jalna (218.78% in 2012) likely reflects

significant production fluctuations due to monsoon variability, pest infestations, or changes in area under cultivation. In contrast, prices remained relatively stable, indicating the role of market integration, storage infrastructure, and policy interventions in absorbing supply shocks (Mahammadhusen et al., 2016; Sonawane et al., 2024).

The market-specific variations observed across the five APMC markets can be attributed to differences in production catchments, storage infrastructure, market integration, and trader behavior. Latur market, being located in a major soybean-producing district, showed relatively lower arrival variability compared to other markets, indicating better market infrastructure and storage facilities. In contrast, Jalna and Amravati markets exhibited higher arrival variability, possibly reflecting greater production fluctuations in their catchments or limited storage capacity.

The findings have important implications for soybean marketing and policy. The inverse relationship between arrivals and prices suggests that farmers who sell immediately after harvest receive lower prices, while those who can store and sell during lean periods realize better returns. This highlights the importance of strengthening storage and warehousing infrastructure to prevent distress sales and enable farmers to benefit from seasonal price increases. The relatively stable price behavior despite arrival fluctuations indicates that the market is functioning efficiently, but there is scope for improving price discovery through better market intelligence and price forecasting systems.

V. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The study indicates that Maharashtra has strong potential for increasing soybean production due to favourable conditions; however, seasonal concentration of arrivals during the post-harvest period leads to price fluctuations. The analysis clearly shows a significant inverse relationship between arrivals and prices ($p < 0.01$), with arrivals exhibiting significantly higher variability than prices across markets ($p < 0.05$). Despite fluctuations in supply, prices remain relatively stable due to storage possibilities and consistent demand. Overall, the soybean market is characterized by seasonal supply patterns and relatively stable pricing behavior.

The intra-year analysis revealed that arrival variability (CV: 34–151%) was 2–3 times higher than price variability (CV: 15–59%) across markets. The inter-year analysis further confirmed that arrivals (CV: 9.73–162.78%) exhibited greater variability than prices (CV: 8.46–11.07%). These variations are mainly influenced by production, climatic conditions, and supply factors. The relatively stable prices despite high arrival variability highlight the role of storage infrastructure and market integration in stabilizing prices.

5.2 Recommendations

To improve soybean production and price realization, the following recommendations are made:

- 1) **Strengthen Storage and Warehousing:** Investment in scientific storage facilities should be prioritized to prevent distress sales and enable farmers to store produce for sale during lean periods when prices are higher. Establishment of warehouse receipt systems and pledge financing can further enhance farmers' access to credit against stored produce.
- 2) **Price Support and Buffer Stocks:** The government should ensure effective price support mechanisms and maintain buffer stocks to stabilize prices during periods of excessive arrivals. This will help protect farmers from price crashes and ensure remunerative prices.
- 3) **Market Intelligence Systems:** Development of market intelligence systems providing real-time price information, arrival trends, and market forecasts will enable farmers and traders to make informed marketing decisions. Mobile-based advisory services and price forecasting tools should be promoted.
- 4) **Promote Value Addition:** Encouraging processing industries such as oil extraction, soybean meal production, and export-oriented processing will add value to the produce and create stable demand, reducing the pressure on primary markets during harvest season.
- 5) **Farmer Producer Organizations (FPOs):** Strengthening FPOs and cooperatives can facilitate collective marketing, reduce marketing costs, and enhance bargaining power of small and marginal farmers.
- 6) **Crop Diversification:** Promoting crop diversification and intercropping can reduce production risks and stabilize income, reducing the distress selling behavior observed during harvest periods.

- 7) **Scientific Storage and Quality Improvement:** Training farmers on scientific storage practices, moisture management, and quality improvement will reduce post-harvest losses and enhance the quality of produce, leading to better price realization.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

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Growth Performance and Nutrient Utilisation of *Clarias gariepinus* fed Turmeric (*Curcuma longa*) Based-Diet

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Abstract— Dietary supplementation with herbal extract and plant-based additives in aquaculture has been noted for various beneficial roles; to increase fish production through the improvement of immunity and other physiological dysfunctions related to fish health. A 56 days feeding trial was conducted to evaluate the growth performance and nutrient utilization of *Clarias gariepinus* juveniles fed turmeric (*Curcuma longa*) based diet. Ten fish were stocked in twelve tanks each subjected to four treatments with three replicates. Four experimental treatments were formulated with varying *Curcuma longa* concentration included at 0% (Control), 1%, 3% and 5% with the treatments designated as D1 (Control), D2, D3 and D4 respectively. The growth performances, nutrients utilisation as well as the effects of the diets on the water quality were determined. Fish fed D4 with an inclusion level of 5% *C. longa* gave the least growth performance in terms of mean weight gain (MWG), specific growth rate (SGR), feed intake, and protein efficiency ratio (PER). Fish fed D2 with an inclusion level of 1% of *C. longa* had the best food conversion ratio (FCR) and followed by the fish fed D3 which had 3% inclusion of *C. longa*. The FCR of the fish fed D2 and D3 were significantly higher ($p < 0.05$) than the fish fed other diets. Based on this study, it was concluded that the inclusion of turmeric in the diet of *Clarias gariepinus* should be minimized specifically within the range of 1% to 3% to enhance growth performance and improve nutrient utilization of the fish.

Keywords— *Clarias gariepinus*; turmeric (*Curcuma longa*); growth performance; nutrient utilization, survival rate.

I. INTRODUCTION

Aquaculture is the practice of cultivating aquatic plants and animals, such as fish, shellfish and algae in controlled environments like ponds, tanks and cages. It has become an essential component of global food production by addressing the increasing demand for protein as the global population grows. Traditional fisheries have faced challenges like overfishing, environmental degradation, and fluctuating wild fish stocks, making sustainable seafood sources critical (FAO, 2020). Aquaculture stepped in to fill this gap by providing a controlled environment for raising seafood, ensuring a more predictable and consistent supply. It is the fastest growing food sector over the past 20 years with an average annual growth rate of 37% (Tacon, 2009), which has however decreased 3.5% for the period 2016-2021 (Mair et al., 2023) with recent projections indicating lower growth rate of 1.6% for the period 2022-2032 (FAO, 2024).

In Nigeria, consumption and demand for fish protein is increasing due to its affordability (Eyo and Ekanem, 2011). *C. gariepinus* is widely cultured in Nigeria under intensive management (Adewolu et al., 2009; Chika and Nathaniel, 2014). It is regarded as one of the most important aquaculture candidate because of its ability to tolerate a wide range of environmental conditions, high stocking densities under culture conditions, fast growth rate, high yield and high market value (Babalola and Apata, 2006). Increased production of fry and fingerlings with attributes of faster growth rate and higher environmental tolerance is essential to ensuring fish food security in Nigeria. *C. gariepinus*, (family Claridae), is a key species in Nigerian aquaculture due to its high nutritional value and ease of farming. It is a rich source of high-quality protein, essential fatty acids, and micronutrients like iron and zinc, making it beneficial for addressing malnutrition in the country (Adewumi and Olaleye,

2011). According to Clay (2009), *C. gariepinus* is generally considered to be one of the most important tropical catfish species for aquaculture in West Africa.

Proper Nutrition is fundamental to the success of aquaculture operations. This involves the provision of balanced diet to meet the specific nutritional requirements of the cultured species to support growth, health and well-being (NRC, 2011). Proper growth of fish depends largely on good nutrition and this is more pronounced with fish in enclosure as they require adequate nutrition (Omoruwou and Edema, 2011). The primary components of fish diets include protein, lipids, carbohydrates, vitamins, and minerals which are very vital for the building block of the animal's body and growth development. According to Tacon and Metican (2015), feeding is the act of providing food to living organisms which is critical for optimal growth performance, health of cultured fish and feed efficiency. Feed is the most expensive input in a profitable fish production. It accounts for about 70-80% of the total cost of fish production (El-Sayed, 2021; Kehinde et al., 2006). Fish culture requires high quality feeds containing necessary nutrients and complementary feed additives to keep fish healthy, grow fast and become more environmental friendly. Feed additives are substances added to the diet in trace amount to provide mechanism by which such dietary deficiencies can be addressed which benefits not only the nutrition and thus the growth rate of the animal concerned, but also its health and welfare in modern day fish farming.

Turmeric, (*C. longa*) is a widely available and cost-effective herbal ingredient, known for its medicinal properties primarily due to the presence of curcumin, a bioactive compound with antioxidant, anti-inflammatory and antimicrobial activities (Rapti et al., 2024; Siagian et al., 2024; Aderemi and Alabi, 2023; Louis, 2009). Primarily, it is categorized as a phytochemicals and bioactive compounds including phenolic compounds, flavonoids, β -carotene, vitamin C and vitamin E. The use of turmeric as feed additives in aquaculture has shown promising results in various studies (Siagian et al., 2024; Pal et al., 2020; Mahmoud and El-Lamie, 2014) in which its supplementation enhanced nutrient digestibility and utilization in *Clarias gariepinus*. Improved protein efficiency ratio (PER) and apparent digestibility coefficient (ADC) have been reported in fish fed turmeric based diets, indicating better nutrient absorption and utilization (Kumar, 2018). Nutrient utilization is a critical factor in aquaculture, as it directly impacts the growth performance of fish and the overall efficiency of the production system. One of the challenges associated with plant-based diets is the presence of anti-nutritional factors that can inhibit the absorption of essential nutrients, leading to reduced growth rates in fish. Turmeric has been shown to improve nutrient utilization by enhancing the activity of digestive enzymes, such as proteases, amylases, and lipases, which are responsible for breaking down proteins, carbohydrates, and fats, respectively (Olatunji et al., 2020).

While several studies have examined turmeric supplementation in fish diets, the optimal inclusion level for *C. gariepinus* remains unclear, with conflicting results across different studies. Furthermore, most studies have focused on either growth performance or health parameters, but few have comprehensively examined both growth and nutrient utilization simultaneously. This study therefore aims to evaluate the growth performances and nutrient utilization of *Clarias gariepinus* fed turmeric based diet, with the specific objective of identifying the optimal turmeric inclusion level for maximizing growth performance and feed efficiency.

II. MATERIALS AND METHODS

2.1 Experimental Study Area

The research was carried out at the Wet laboratory in the Department of Fisheries and Aquaculture Management, Faculty of Agricultural Science Research Farm, Ekiti State University, Ado-Ekiti, Ekiti State, Nigeria. Geographically, Ado Ekiti is located on latitude 7°35' and 7°47' north of the equator and longitude 5°11' and 5°16' east of the Greenwich meridian with geographical coordinates of approximately 7.7130°N latitude and 5.2765°E longitude.

2.2 Feed Ingredients and Experimental Diets

Four iso-nitrogenous diets were formulated containing 40% crude protein using fish meal, soybean meal, groundnut cake, maize, wheat offal, vitamin or mineral premix, salt, vegetable oil and turmeric (*Curcuma longa*). The dietary ingredients including fish meal, soybean meal, groundnut cake, maize, wheat offal, and vitamin/mineral premix were purchased from Metrovet Nigeria Limited, Ado-Ekiti. The vegetable oil, salt and turmeric were purchased from King's market, Ado Ekiti. The four experimental diets were formulated with varied levels of turmeric powder at 0%, 1%, 3%, and 5% respectively. It was pelletized with pelleting machine of 2mm die size. The pellet was sun dried, packed in well labeled air tight containers and stored in a cool and dry place until use. Table 1 shows the gross composition of the experimental diets.

TABLE 1
THE GROSS COMPOSITION OF THE EXPERIMENTAL DIETS

Ingredients	Diet 1 Control 0%	Diet 2 1%	Diet 3 3%	Diet 4 5%
Fish meal 65%	23.2	23.2	23.2	23.2
Soybean meal 44%	23.2	23.2	23.2	23.2
Groundnut cake meal 50%	23.2	23.2	23.2	23.2
Maize 10%	12.95	12.95	12.95	12.95
Wheat offal 14%	12.95	12.95	12.95	12.95
Turmeric (<i>Curcuma longa</i>)	0	1	3	5
Lysine (g)	0.5	0.5	0.5	0.5
Vit/Min Premix (g)	2.5	2.5	2.5	2.5
Salt (g)	0.5	0.5	0.5	0.5
Veg oil (g)	0.5	0.5	0.5	0.5
Methionine (g)	0.5	0.5	0.5	0.5
Total	100	100	100	100

2.3 Experimental Fish

One hundred and fifty (150) juveniles of *C. gariepinus* was procured from Adebayo fish farm in Ado-Ekiti and acclimatized in aerated tanks at the Wet laboratory in the Department of Fisheries and Aquaculture Management, Faculty of Agricultural Science Research Farm, Ekiti State University, Ado-Ekiti, Ekiti State to adapt before commencement of the experiment. After the acclimation period, the fish were weighed and randomly distributed into four groups, each receiving one of the experimental diets. Each dietary treatment was replicated thrice.

2.4 Experimental Procedure

Twelve aquaria tanks (60 cm × 30 cm × 30 cm, approximately 54 L capacity) were randomly stocked with ten fish in each tank used for the experiment comprising of four dietary levels with three replicates in a completely randomized design experiment. Fish were fed twice daily (morning between 8am to 9am, and evening between 4pm to 5pm) at 5% of their body weight. The weight of the fish was taken weekly using an electronic kitchen Salter Scale-1036, UK, and the feeding rates was adjusted accordingly to determine the feed allowance. The water quality of the culture media was monitored and kept at optimum during the period of the feeding experiment. The water quality parameters evaluated during the feeding trial include temperature, dissolved Oxygen (mg/l), and pH. The temperature was measured in °C by the use of mercury-in-glass thermometer; the dissolved oxygen was measured by the use of titration method as described by AOAC (2010) while the pH was measured by the use of a pH meter (Model: pHCal|ANALAB|HSN Code: 90278990). Groundwater sourced from a borehole was used for the experiment, and the photoperiod was maintained at a natural light-dark cycle (approximately 12:12 hours). All experimental procedures were conducted in accordance with the ethical guidelines for animal research, and the study was approved by the Institutional Animal Ethics Committee.

2.5 Determination of Growth Performance and Nutrient Utilisation

Data on feed utilisation and growth performances were collected on weekly basis using electronic kitchen Salter Scale-1036, UK. The growth parameters were calculated following the method described by AOAC (2010) as follows:

- **Weight Gain:** This refers to the increase in body weight of fish during the experimental period, typically measured in grams. It's an important indicator of fish growth and health. $\text{Weight Gain (WG)} = \text{Final Weight (g) (FW)} - \text{Initial Weight (g) (IW)}$
- **Mean Weight Gain:** This is the average weight gain of a group of fish during the experimental period. It's a useful metric to evaluate the growth performance of fish populations. The formula to calculate mean weight gain is: $\text{Mean Weight Gain (MWG)} = \text{Total weight gain of fish (g)} / (\text{Number of fish})$

- **Specific Growth Rate (SGR):** is a measure of the rate of weight gain per unit of body weight per unit of time. It's a useful metric to evaluate the growth performance of fish, taking into account their initial size. The formula to calculate SGR is: $SGR = (\ln W_2 - \ln W_1) / \text{time} \times 100$. Where W_2 is the final weight in gram and W_1 is the initial weight in gram.
- **Food Conversion Ratio (FCR):** is a measure of the efficiency with which fish convert feed into body weight. It's an important metric to evaluate feed utilization and nutritional efficiency. The formula to calculate FCR is: $FCR = \text{Feed intake} / \text{Weight Gain}$
- **Protein Efficiency Ratio (PER):** is a measure of the efficiency with which fish utilize dietary protein for growth. It's used to evaluate the quality of protein sources in fish feed. The formula to calculate PER is: $PER = \text{Total weight gain (TWG)} / \text{Total protein consumed (TPC)}$
- **Food Intake:** This refers to the amount of feed consumed by fish during the experimental period. The formula to calculate food intake is: $FI = \text{Diet given} / \text{Number of fish}$
- **Survival Rate:** is the percentage of fish that survive over the experimental period. The formula to calculate Survival Rate is: $SR = (\text{Number of fish survived} / \text{Number of fish initially stocked}) \times 100$

2.6 Proximate Analysis

The proximate analysis comprising the moisture content, protein, ash content, crude fibre, fat and nitrogen free extract (NFE) of the test ingredient and fish before and after the experiment were determined using the methods of AOAC (2010).

2.7 Statistical Analysis

The data generated from the experiments was subjected to one-way analysis of variance (ANOVA) to determine the significant differences among mean of the treatment groups. Post hoc-tests (Tukey's HSD) was conducted to identify specific differences between means at ($p < 0.05$) significance level. All statistical analyses were performed using SPSS software (version 26.0, IBM Corp., Armonk, NY, USA).

III. RESULTS AND DISCUSSION

3.1 Proximate Analysis of the Diet

The result of the proximate analysis of the experimental diets is presented in Table 2. The moisture content were significantly different ($p < 0.05$) from each other. Diet 3 had the highest moisture content value of 9.84 ± 0.04 and the least was found in diet 2 which is 8.97 ± 0.01 . Diet 1 had the highest fat content of 7.29 ± 0.05 and diet 4 of 6.14 ± 0.02 had the lowest fat content. The fat were significantly different ($p < 0.05$) in all diet. The ash content and crude fibre followed the same trend with diet 1 recording the highest value and diet 4 recording the lowest. The protein of the diet were significantly different ($p < 0.05$) in all diet. Diet 4 had the highest protein value of 35.57 ± 0.03 and diet 1 had the least protein value of 28.19 ± 0.04 . Diet 2 had the highest Nitrogen free extract value of 29.61 ± 0.09 while diet 4 had the lowest which is 27.53 ± 0.09 .

TABLE 2
THE PROXIMATE COMPOSITION OF THE EXPERIMENTAL DIETS

Parameters	Diet 1 (Control)	Diet 2	Diet 3	Diet 4
Moisture	9.14 ± 0.03^c	8.97 ± 0.01^d	9.84 ± 0.04^a	9.44 ± 0.02^b
Fat	7.29 ± 0.05^a	6.65 ± 0.04^b	6.30 ± 0.02^c	6.14 ± 0.02^d
Ash	16.49 ± 0.07^a	15.73 ± 0.03^b	14.53 ± 0.03^c	13.68 ± 0.04^d
Protein	28.19 ± 0.04^d	30.31 ± 0.03^c	33.32 ± 0.02^b	35.57 ± 0.03^a
Fibre	9.87 ± 0.03^a	8.75 ± 0.05^b	8.06 ± 0.04^c	7.65 ± 0.03^d
NFE	29.03 ± 0.06^b	29.61 ± 0.09^a	27.96 ± 0.03^c	27.53 ± 0.09^d

Mean and standard deviation with different superscripts along the same row are significantly different ($p < 0.05$). NFE = Nitrogen Free Extract

3.2 Growth and Nutrient Utilization of the Experimental Fish

Table 3 shows the results of the growth and nutrient utilization of the experimental fish fed the various diets. Highest weight gain of 32.33 ± 2.35 was found in fish fed diet 1, followed by fish fed with diet 2 (23.83 ± 0.13). The least weight gain was found in fish fed with diet 4 (14.2 ± 0.67). The weight gain of all the diets were significantly different ($p < 0.05$) from each other. Fish fed diet 1 had the highest mean weight gain of 3.36 ± 0.36 and fish fed diet 4 had the lowest mean weight gain of 1.85 ± 0.05 . Diet 1, diet 2 and diet 3 were not significantly different ($p > 0.05$). Fish fed diet 1 survived most with the best value of 96.67% while fish fed diet 3 recorded the highest mortality (70.00 ± 10.00). The food conversion ratio (FCR) of the fish fed diet 2 had the best value of 0.79 ± 0.06 , while fish fed diet 1 had the poorest value of 1.23 ± 0.13 .

TABLE 3
GROWTH AND NUTRIENT UTILIZATION OF THE EXPERIMENTAL FISH

Parameters	Diet 1 (Control)	Diet 2	Diet 3	Diet 4
Initial weight	$71.87 \pm 6.07a$	$55.80 \pm 1.25b$	$63.30 \pm 3.64ab$	$63.37 \pm 2.72ab$
Final weight	$104.20 \pm 5.39a$	$79.63 \pm 1.28b$	$82.39 \pm 2.78b$	$77.57 \pm 3.41b$
Weight gain	$32.33 \pm 2.35a$	$23.83 \pm 0.13b$	$19.09 \pm 0.99c$	$14.20 \pm 0.67d$
MWG	$3.36 \pm 0.36a$	$2.87 \pm 0.19a$	$2.75 \pm 0.28a$	$1.85 \pm 0.05b$
SGR	$0.67 \pm 0.08a$	$0.64 \pm 0.02a$	$0.47 \pm 0.04b$	$0.36 \pm 0.00b$
Feed intake	4.10 ± 0.00	2.27 ± 0.00	2.49 ± 0.00	2.15 ± 0.00
FCR	$1.23 \pm 0.13a$	$0.79 \pm 0.06b$	$0.91 \pm 0.09b$	$1.16 \pm 0.03a$
PER	$1.14 \pm 0.08a$	$0.79 \pm 0.01b$	$0.57 \pm 0.03c$	$0.40 \pm 0.02d$
Survival rate	$96.67 \pm 5.77a$	$83.33 \pm 5.77ab$	$70.00 \pm 10.00b$	$76.67 \pm 5.77b$

Mean and standard deviation with different superscripts along the same row are significantly different ($p < 0.05$) from one another. Where; MWG = mean weight gain; SGR = specific growth rate; FCR = food conversion ratio; PER = protein efficiency ratio

3.3 Carcass Composition of the Experiment Fish

The carcass composition of the experimental fish are presented in Table 4. The moisture content of all the diets was not significantly different ($p > 0.05$) from each other. Fish fed diet 4 had highest moisture content value of 11.22 ± 0.20 and the least value was obtained in fish fed D1 (10.59 ± 0.56). Highest fat value was found in fish fed D1 (14.19 ± 0.08) and the lowest was obtained in diet 4 (12.94 ± 0.20). The fat contents in D2 and D3 were not significantly different ($p > 0.05$) from each other. Fish fed diet 1 had the highest protein content of 58.80 ± 0.11 and the lowest was found in fish fed diet 4 (53.63 ± 0.03). The protein contents of the fish were significantly different ($p < 0.05$) in all treatments.

TABLE 4
CARCASS COMPOSITION OF THE EXPERIMENTAL FISH

Parameters	Fish fed Diet 1 (Control)	Fish fed Diet 2	Fish fed Diet 3	Fish fed Diet 4
Moisture	$10.59 \pm 0.56a$	$11.04 \pm 0.27a$	$10.97 \pm 0.20a$	$11.22 \pm 0.20a$
Fat	$14.19 \pm 0.08a$	$13.48 \pm 0.07b$	$13.38 \pm 0.19b$	$12.94 \pm 0.20c$
Ash	$9.97 \pm 0.15c$	$10.44 \pm 0.04b$	$10.59 \pm 0.13ab$	$10.75 \pm 0.03a$
Protein	$58.80 \pm 0.11a$	$56.19 \pm 0.12b$	$55.31 \pm 0.26c$	$53.63 \pm 0.03d$
NFE	$6.27 \pm 0.82c$	$8.74 \pm 0.41b$	$9.75 \pm 0.28b$	$11.47 \pm 0.01a$

Mean and standard deviation with different superscript along the same row are significantly different ($p < 0.05$) from one another. Where; NFE = Nitrogen Free Extract

3.4 The Water Quality Parameters

Table 5 shows the results of the water quality parameters monitored during the experiment. The temperature and dissolved oxygen ranged from 19.33°C - 20°C and 5.46 - 6.51 mg/l respectively, while the pH value ranged between 6.48 - 6.71. There were no significant difference ($p>0.05$) between the treatment for the temperature and pH.

TABLE 5
WATER QUALITY PARAMETERS OF THE EXPERIMENTAL TREATMENTS

Treatment	Temp °C	pH	DO (mg/l)
D1	19.33±1.15	6.71±0.11	5.98±0.18b
D2	19.67±0.58	6.48±0.25	5.46±0.09c
D3	20.00±0.00	6.51±0.25	6.51±0.06a
D4	19.67±0.58	6.60±0.25	5.77±0.13b

Mean value with the same superscript in the same column are not significantly different ($P>0.05$). Where; DO = Dissolve Oxygen

3.5 Discussion

This study focused on the utilization of *Curcuma longa* in the diet of *C. gariepinus*. The results reflected the effects of turmeric (*Curcuma longa*) inclusion on the growth performance and nutrient utilization of *C. gariepinus*. The indices of growth examined in this study revealed that weight gain, mean weight gain and specific growth rate varied significantly ($p<0.05$) between dietary treatments. The study highlights the significant impact of diet composition on the growth, nutrient utilization, and survival of the experimental fish. Fish fed D1 showed the highest weight gain (32.33±2.35 g), suggesting the provision of an optimal nutrient balance for growth. In contrast, D4 resulted in the lowest weight gain (14.2±0.67 g), indicating potential nutritional imbalance due to excessive addition of turmeric in the diet. The statistically significant differences in weight gain ($p<0.05$) emphasize the importance of diet formulation in fish growth. The mean weight gain of D1 resulted in the highest mean weight gain (3.36±0.36 g) and Diet 4 the lowest (1.85±0.05 g). This concentration is considered optimal as turmeric supplementation in feed can enhance catfish digestion, thereby improving the absorption of feed nutrients as reported by Siagian and Heltonika (2023). However, no significant differences ($p>0.05$) were found among fish fed D1, D2, and D3, suggesting these diets provide similar benefits in terms of mean weight gain. Survival rates also varied across treatments. D1 had the highest survival rate (96.67%), indicating it supports both growth and overall health. On the other hand, D3 had the highest mortality rate (70.00%), possibly due to nutritional imbalances negatively affecting fish vitality.

Feed consumption is influenced by palatability. Palatability is the level of acceptance shown by cultivated animals to consume a given feed ingredient within a certain period. The palatability of feed is determined by the shape, size, taste, smell, aroma, and colour, which are the feed's physical and chemical factors. Feed efficiency, measured by the food conversion ratio (FCR), was analyzed. D2 recorded the best FCR (0.79±0.06), showing efficient feed utilization. Despite promoting the highest weight gain, D1 had the least efficient FCR (1.23±0.13), suggesting that more feed was required to achieve maximum growth. The feed conversion ratio obtained by fish containing 1% inclusion level of turmeric is lower in comparison with other diets. This suggests that a lower level of turmeric inclusion improved feed efficiency, possibly due to its known digestive enhancing properties (Adikwu, 2003). This implies that turmeric should be included in fish diet in a minimal amount. This study is in agreement with Fagnon et al. (2020) and Cahyani et al. (2021) who showed that the higher effect sizes observed when fed curcumin at lower inclusion levels and suggested that feeding low levels of phytochemicals might be beneficial and its content in turmeric should be analysed for quite homogeneous feed. These findings align with previous research, which emphasizes the importance of balanced diet formulation in aquaculture. Studies on African catfish (*C. gariepinus*) have shown that variations in crude protein levels significantly impact growth, FCR, and survival, reinforcing the need for optimized dietary formulations (Henry et al., 2019).

The reduced growth performance at higher turmeric inclusion levels (5%) may be attributed to several factors. High concentrations of phytochemicals can have anti-nutritional effects, including reduced feed palatability, interference with nutrient absorption, or toxicity at elevated doses. Curcumin, while beneficial at low concentrations, may exhibit pro-oxidant or inhibitory effects on digestive enzymes at higher levels, leading to reduced nutrient utilization and growth. Additionally, the

presence of other compounds in turmeric, such as essential oils and resins, may affect feed palatability and reduce feed intake at high inclusion levels.

The carcass composition of the fish shows the amount of protein retained in the fish body. The study revealed significant difference ($p < 0.05$) in protein values across the diet. The carcass crude protein of the control diet with no inclusion of turmeric had the highest value of 58.80 while fish fed diet 4 with 5% inclusion level of turmeric had the lowest protein value of 53.63. This result is consistent with the work of Akinwande et al. (2016), who reported that high levels of certain plant extracts in fish diets can lead to decreased protein deposition due to potential anti-nutritional factors or reduced feed palatability. The decreased protein deposition at higher turmeric levels may be attributed to reduced protein synthesis, increased protein catabolism, or impaired protein digestibility.

The water quality parameters in this study were monitored during the experimental period to assess their impact on *Clarias gariepinus*. The results showed variation in the parameters with significant differences ($p > 0.05$) observed among some of the dietary treatments, indicating that dietary composition may have to some extent influenced the water quality.

The recorded water temperature ranged from 19.33°C to 20°C. This is slightly below the optimal temperature range for *Clarias gariepinus*, which typically thrives in temperature between 25°C and 30°C (Ogunji and Awoke, 2017). Lower temperature can slow down metabolic activities and affect growth rate. This suboptimal temperature may have influenced the overall growth performance, potentially masking some of the effects of turmeric supplementation. Future studies should consider conducting experiments at optimal temperatures to fully evaluate the effects of turmeric.

The dissolved oxygen levels during the study ranged from 5.46 mg/l to 6.51 mg/l. The values fall within the acceptable range for *C. gariepinus*, which can tolerate DO level as low as 3 mg/l, though optimal level for growth are typically above 5 mg/l (Olowofeso et al., 2020; Torrains et al., 2015).

The pH value recorded ranged between 6.48 and 6.71 which is within the acceptable range for *Clarias gariepinus* (6.5-8.5) (Boyd and Tucker, 2022). A stable pH is essential for maintaining optimal enzymatic activity and overall physiological functions in fish. The slight variations among diets indicate that different feed formulation might have influenced water chemistry, potentially through variation in metabolic waste production.

IV. CONCLUSION AND RECOMMENDATION

The finding of this study indicates that turmeric (*Curcuma longa*) possesses potential as a functional feed additive for *C. gariepinus*. However, its inclusion in fish diets must be carefully regulated to prevent adverse effects on growth and nutrient utilization.

The results demonstrated that high levels of turmeric inclusion, specifically at 5% significantly reduced feed intake, growth performance and nutrient utilization. On the other hand, a moderate turmeric inclusion level of 1-3% showed better results compared to higher levels. The study strongly suggests that turmeric, when used as a dietary additive, should be included in minimal amounts to avoid negative effects on overall fish development. The reduced growth at higher turmeric levels may be attributed to anti-nutritional effects, reduced palatability, or interference with nutrient absorption at elevated concentrations.

Limitations of the Study: The study was conducted over a 56-day period, which may not capture long-term effects of turmeric supplementation. The study was conducted at a suboptimal temperature (19-20°C vs. optimal 25-30°C), which may have influenced growth performance. The study did not examine immune parameters, disease resistance, or histopathological effects. Future research should address these limitations.

Recommendations: The study recommends that future researchers should explore the effects of incorporating lower concentrations of turmeric, specifically within the range of 1% to 3%. The goal of such investigations would be to identify the optimal balance that maximizes both the health benefits of turmeric and its impact on the overall growth performance of the fish. By conducting these studies, researchers can determine whether lower turmeric levels still provide significant advantages in terms of immunity, disease resistance, and overall physiological well-being while maintaining or improving growth rates. Future studies should also examine the mechanisms underlying the observed effects, including digestive enzyme activity, gut microbiota composition, and immune function, to provide a more comprehensive understanding of turmeric's role in fish nutrition.

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CONFLICT OF INTEREST

The authors declare no conflict of interest regarding the publication of this manuscript.

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Free Proline Distribution in *Solanum surattense* from Rajasthan

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Abstract— *Solanum surattense* Burm.f. (Solanaceae) is a medicinally important herb widely distributed in the tropical and subtropical regions of India, including the arid and semi-arid areas of Rajasthan. The species is valued for its diverse ethnomedicinal and pharmacological properties and has been extensively studied for its phytochemical constituents. However, limited information is available regarding its biochemical adaptations to environmental stress, particularly proline metabolism. Proline is a key osmoprotectant that accumulates in plants under adverse conditions and plays a significant role in osmotic adjustment, membrane stabilization, redox regulation, and stress tolerance. The present study aimed to evaluate the organ-specific distribution of free proline in *S. surattense* collected from the Atoon region of Bhilwara District, Rajasthan. Free proline content was estimated in root, stem, leaf, fruit, and seed samples using the acid-ninhydrin colorimetric method of Bates et al. (1973), and absorbance was measured at 540 nm. The results revealed marked variation in proline accumulation among different plant organs. The highest proline content was recorded in the stem (0.4660 mg/gdw), followed by fruit (0.3731 mg/gdw), seed (0.2840 mg/gdw), leaf (0.1811 mg/gdw), and root (0.1462 mg/gdw). The stem exhibited nearly threefold higher proline concentration than the root, suggesting its important role in osmotic regulation, metabolite transport, and physiological adaptation under water-limited conditions. Moderate accumulation in fruits and seeds may be associated with reproductive development and storage functions. The observed pattern highlights the differential allocation of proline within plant organs and reflects the adaptive strategies of *S. surattense* in semi-arid environments. These findings provide baseline biochemical information and contribute to understanding the stress physiology and ecological resilience of this medicinally important species.

Keywords— *Solanum surattense*, free proline, specific organ accumulation, osmoprotectant, acid-ninhydrin technique, stress physiology, Rajasthan.

I. INTRODUCTION

The genus *Solanum surattense* Burm.f. (Family: Solanaceae) is found in all districts of Tamil Nadu as well as tropical and subtropical regions of Australia, Malaysia, South East Asia, and India (Mathew, 1983). There is discussion of *S. surattense*'s various therapeutic qualities (Chopra et al., 1956; Kirtikar & Basu, 1935; Anonymous, 1986; Mudhaliar, 1988).

In arid and semi-arid regions with limited access to water, aridity is a significant abiotic factor affecting plant growth, productivity, and ecosystem functioning. Climate change-related increases in aridity put plants under physiological stress, which triggers a variety of adaptation processes. One of the most crucial biochemical strategies for preserving cellular homeostasis, osmotic balance, and stress tolerance under water-deficit conditions is the accumulation of compatible osmolytes like proline (Handa et al., 1986; Ashraf & Foolad, 2007; Verbruggen & Hermans, 2008; Szabados & Savouré, 2010).

The most significant environmental limitation that affects ecosystem structure and functioning is aridity, which restricts water availability and puts plants under physiological stress (Harpole & Suding, 2011). Plants frequently display adaptive biochemical responses to rising aridity brought on by climate change, such as the buildup of osmoprotectants like proline, to

preserve cellular homeostasis and improve stress tolerance (Trenberth et al., 2014). Flavonoids, alkaloids, phenolic compounds, steroids, and glycosides are among the many bioactive components of the medicinally significant species *Solanum surattense* Burm.f. that contribute to pharmacological actions, including its many anti-inflammatory, hepatoprotective, antiasthmatic, and antioxidant qualities (Tekuri et al., 2019). Traditional medicine promotes significant use of *Solanum surattense*, a plant rich in bioactive phytochemicals (Boomiga et al., 2021).

Its physiological response to environmental stress, especially proline buildup, is still not sufficiently understood. The environmentally adapted medicinal plant *Solanum surattense* Burm.f. is recognized for its extensive range of pharmacological actions and rich phytochemical composition (Hasan et al., 2024). Recent investigation on ecophysiological studies have revealed that populations of *Solanum surattense* Burm.f. living in hyper-arid conditions accumulate far more free proline than populations from somewhat less stressed situations. The significance of proline metabolism in this medicinal species' adaptive strategy was highlighted by the positive correlations found between elevated proline concentration and improved osmotic adjustment, maintenance of cellular hydration, protection of photosynthetic machinery, and increased tolerance to drought-induced oxidative stress (Rafiq et al., 2025).

Although *Solanum surattense*'s medicinal, phytochemical, and pharmacological qualities have been extensively documented, and proline's physiological role as an osmoprotectant under drought and aridity stress in plants generally is well-established, no study has specifically measured free proline content in *Solanum surattense*. Thus, there is a clear gap between its known therapeutic significance and our knowledge of its stress physiology because the molecular foundation for its ecological adaptability and stress adaptation has not been investigated.

The current investigation's primary objective was to measure *Solanum surattense* free proline content using a conventional colorimetric measurement method. The results are anticipated to contribute to understanding of this therapeutic species' biochemical traits and establish the foundation for more research on its stress physiology, ecological adaptation, and possible uses in plant science.

II. MATERIALS AND METHODS

2.1 Study Area and Sample Collection

The plant material of *Solanum surattense* Burm.f. was collected from the Atoon region of Bhilwara District, Rajasthan, India, during the post-monsoon season (October–November). The region is characterized by a semi-arid climate with limited rainfall, high temperatures, and seasonal water stress. Healthy plants of uniform age were selected, and samples of root, stem, leaf, fruit, and seed were collected separately. The collected samples were washed with distilled water, air-dried, and stored for further analysis. Three independent replicates were taken for each plant organ.

2.2 Chemicals and Glassware

The following chemicals and glassware were used: Hydrochloric Acid (HCl), Glacial Acetic Acid (GAA), Ninhydrin Reagent, Toluene, Test tubes, Beaker, Pipette, and Whatman No. 1 filter paper.

2.3 Reagent Preparation

- **Hydrochloric Acid (HCl) Solution:** 20 millilitres of concentrated hydrochloric acid (HCl) were mixed with 8 millilitres of distilled water to produce a workable HCl solution.
- **Glacial Acetic Acid (GAA) Reagent:** 1 millilitre of glacial acetic acid and 50 millilitres of the prepared HCl solution were combined to create the GAA reagent.
- **Standard Solution of Sodium Nitrite:** 20 millilitres of sodium nitrite were dissolved in 100 millilitres of distilled water to form a standard sodium nitrite solution.
- **Ninhydrin Reagent:** 10 millilitres of ninhydrin solution were dissolved in 50 millilitres of distilled water.
- **Acid Ninhydrin Reagent:** The acid ninhydrin reagent was prepared by dissolving 1.25 g of ninhydrin in 30 mL of glacial acetic acid and 20 mL of 6 M phosphoric acid, following the method of Bates et al. (1973).

2.4 Proline Extraction and Estimation

After a few minor modifications, the acid-ninhydrin colorimetric method of Bates et al. (1973) was applied to calculate the free proline content. Fresh plant material (200 mg) was homogenized in 10 mL of 3% (w/v) aqueous sulphosalicylic acid. The homogenate was filtered using Whatman No. 1 filter paper.

Two millilitres of the filtrate were taken in a test tube, and 2 millilitres of acid ninhydrin reagent and 2 millilitres of glacial acetic acid were added. The mixture was incubated in a boiling water bath at 100°C for one hour. After incubation, the reaction mixture was quickly cooled in an ice bath to stop the reaction. The chromophore was extracted using 4 millilitres of toluene with vigorous shaking for 15–20 seconds. After phase separation, the upper toluene layer was collected, and absorbance was measured using a UV-visible spectrophotometer at 540 nm (or 520 nm as per the original method) against a toluene blank.

A standard curve was prepared using L-proline (0–100 µg/mL) to quantify the free proline concentration. The proline content was calculated using the following formula:

$$\text{Proline content } (\mu\text{mol g}^{-1} \text{ FW}) = \frac{(\mu\text{g proline/mL} \times \text{mL toluene}) / (115.5 \mu\text{g}/\mu\text{mole})}{(\text{g sample}) / 5} \quad (1)$$

Where the standard curve provides µg proline per mL, and the factor 115.5 is the molecular weight of proline.

Absorbance measurements were adjusted in relation to the maximum recorded absorbance value to enable comparative evaluation among plant organs. The formula below was utilized to calculate relative accumulation (Zar, 2010):

$$\text{Relative Accumulation (\%)} = \frac{\text{Absorbance of plant part}}{\text{Maximum absorbance}} \times 100 \quad (2)$$

Relative Accumulation (%) = (Absorbance of plant part / Maximum absorbance) × 100

2.5 Statistical Analysis

All analyses were performed in triplicate, and results are expressed as mean ± standard deviation (SD). One-way analysis of variance (ANOVA) was performed to test for significant differences in proline content among the different plant organs, followed by Tukey's post-hoc test for pairwise comparisons. Statistical significance was set at $p < 0.05$. All statistical analyses were performed using SPSS software (version 26.0, IBM Corp., Armonk, NY, USA).

III. RESULTS

The accumulation of free proline varied clearly and consistently across the organs of *Solanum surattense*, as indicated by absorbance values obtained at 540 nm (Table 1). The stem showed the highest absorbance value (0.4660) of all the organs examined, indicating the metabolite's maximal concentration and suggesting its significant role in the plant's transport, storage, and active metabolic processes. The fruit had the second-highest absorbance (0.3731), suggesting significant accumulation probably related to fruit maturation, reproductive development, and nutrient storage.

TABLE 1
ORGAN-WISE VARIATION IN ABSORBANCE (540 NM) REFLECTING PROLINE ACCUMULATION IN SOLANUM SURATTENSE BURM.F.

S. No.	Plant Part	Absorbance (540 nm)	Relative Accumulation (%)
1	Root	0.1462	31.4
2	Stem	0.466	100
3	Leaf	0.1811	38.9
4	Fruit	0.3731	80.1
5	Seed	0.284	60.9

The metabolite's function in promoting seed viability and ensuring effective germination may be reflected in the seed's moderate absorbance value (0.2840). While photosynthesis and active metabolic activities are mostly found in the leaf, the leaf showed a somewhat lower absorbance (0.1811), indicating that the accumulation of this molecule is not necessarily correlated

with metabolic or photosynthetic activity. Among all the organs, the root had the lowest absorbance value (0.1462), in contrast to its primary function in absorbing nutrients and water rather than storing metabolites.

Overall, the organ-wise trend was as follows: **stem > fruit > seed > leaf > root**. This suggests that organs related to storage, reproduction, and structural support (stem, fruit, and seed) accumulate this metabolite more than organs mainly involved in absorption and photosynthesis (root and leaf). The organ-specific regulation of biochemical accumulation in *Solanum surattense* is highlighted by this differential distribution, which may also represent the organ's physiological adaptability and stress-related metabolic strategy in the Aravalli region of Rajasthan.

Statistical Analysis: One-way ANOVA revealed significant differences in proline content among the five plant organs ($F = 12.45$, $df = 4, 10$, $p < 0.001$). Post-hoc analysis (Tukey's HSD) indicated that the stem contained significantly higher proline than all other organs ($p < 0.05$), while the root showed significantly lower proline than the stem, fruit, and seed ($p < 0.05$). The differences between leaf and root were not statistically significant ($p > 0.05$). Values are expressed as mean $\pm$ SD ($n = 3$).

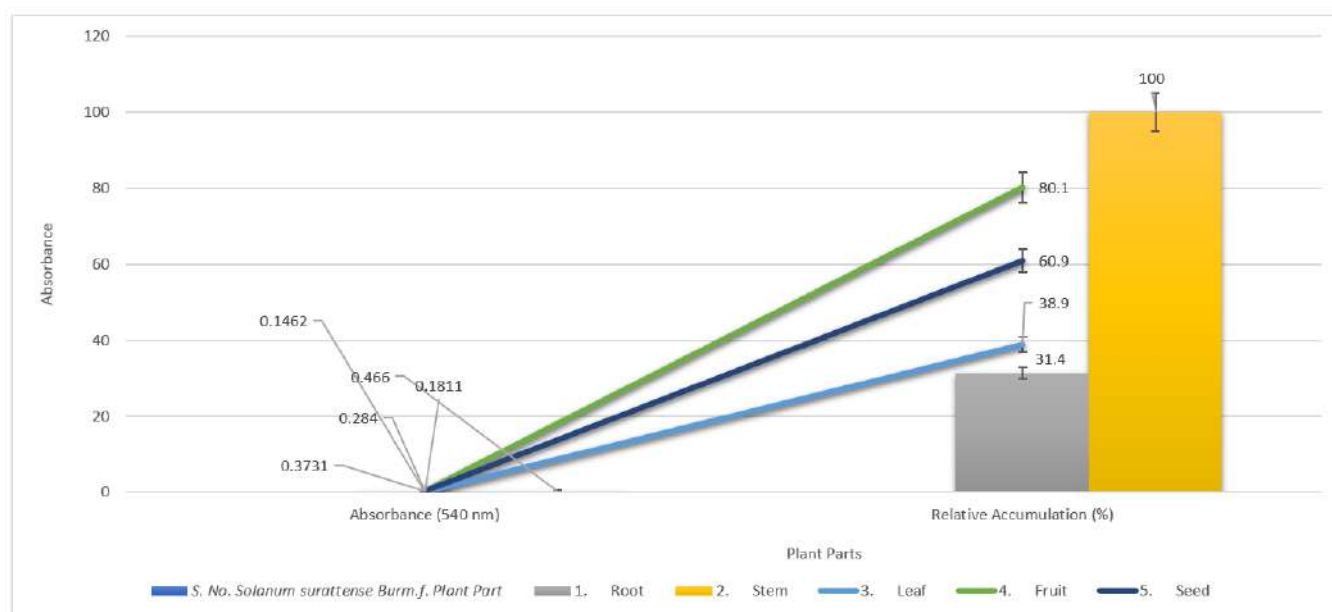


FIGURE 1: Organ-wise Variation in Absorbance (540 nm) Reflecting Proline Accumulation in *Solanum surattense* Burm.f.

IV. DISCUSSION

In *Solanum surattense* Burm.f., the current study found a clear organ-specific pattern of free proline accumulation that went as follows: **stem > fruit > seed > leaf > root**. The tissue-specific regulation of proline metabolism is highlighted by this uneven distribution, and it provides important information regarding the physiological adaptation methods of this medicinally significant species growing in the semi-arid Aravalli region of Rajasthan.

Proline is a versatile biocompatible solute that is crucial to how plants respond to environmental stressors, especially salinity, drought, and temperature changes. It helps maintain cellular redox homeostasis under stress, protect photosynthetic machinery, stabilize cellular membranes and proteins, regulate osmotic pressure, and detoxify reactive oxygen species (ROS) (Ashraf & Foolad, 2007; Verbruggen & Hermans, 2008; Szabados & Savouré, 2010).

The largest proline buildup seen in *S. surattense*'s stem may suggest that this organ has a greater need for osmotic control and cellular defense when water is low. Increased proline concentration may help sustain cellular hydration and metabolic stability during times of environmental stress, since stems serve as important structural and transport tissues. Numerous drought-tolerant plant species have been shown to exhibit similar organ-dependent variations in proline accumulation, indicating a close relationship between proline distribution and tissue-specific physiological requirements (Rafiq et al., 2025). For instance, studies on other medicinal plants from arid regions have reported higher proline accumulation in stems and reproductive tissues compared to roots and leaves (Ashraf & Foolad, 2007; Handa et al., 1986).

Proline may play a functional role in reproductive development, as evidenced by the somewhat higher proline concentration found in fruits and seeds. Proline accumulation in reproductive tissues has been demonstrated to help maintain metabolic activity throughout seed development and maturation, stabilize macromolecules, and guard against cellular damage caused by dehydration (Handa et al., 1986). Therefore, increased proline accumulation in reproductive organs in *S. surattense* may be an adaptation mechanism that promotes seed survival and reproductive success in semi-arid environments.

On the other hand, decreased proline levels in roots and leaves indicate that this metabolite is distributed differently throughout plant organs. Due to their direct exposure to environmental changes, leaves are commonly cited as important sites of stress-induced proline deposition; however, the reduced accumulation seen in *S. surattense* indicates this species might use an organ-specific stress tolerance approach. Stress protection in these tissues may be facilitated by additional physiological mechanisms, such as phenolic buildup, antioxidant defense systems, and control of water-use efficiency.

The moderate proline accumulation in seeds (0.2840 mg/gdw) is consistent with the role of proline in protecting embryonic tissues during desiccation and promoting germination under stress conditions (Szabados & Savouré, 2010). The relatively lower proline content in roots (0.1462 mg/gdw) suggests that roots may rely on other osmoregulatory mechanisms, such as the accumulation of other compatible solutes (e.g., glycine betaine) or adjustments in root architecture, to cope with water stress.

The findings of this study are consistent with those of Rafiq et al. (2025), who reported elevated proline accumulation in *S. surattense* populations from hyper-arid conditions compared to less stressed populations. The organ-specific pattern observed in the present study further refines our understanding of proline's role in this species by demonstrating that proline is not uniformly distributed but is preferentially allocated to organs with specific physiological functions. This differential allocation likely reflects the plant's adaptive strategy to optimize resource use and stress tolerance in a water-limited environment.

The connection between proline accumulation and medicinal properties warrants further investigation. Proline is known to influence the biosynthesis of secondary metabolites, including alkaloids and phenolic compounds, which are characteristic of *S. surattense* (Hasan et al., 2024; Tekuri et al., 2019). The higher proline content in stems and fruits may be correlated with the accumulation of bioactive compounds in these organs, which could have implications for the medicinal quality of the plant material. However, this hypothesis requires direct experimental validation.

Overall, this work provides new perspectives on the organ-wise distribution of free proline and increases our knowledge of *Solanum surattense*'s biochemical adaptation to Rajasthan's semi-arid climate. Further studies on seasonal variation, comparative populations from various habitats, and relationships between proline accumulation and other stress-responsive metabolites, such as phenolic compounds and antioxidant enzymes, will shed light on this species' complete stress tolerance mechanism.

V. CONCLUSION

Using the acid-ninhydrin colorimetric method, the current study successfully measured and compared the total free proline content of five distinct organs of *Solanum surattense* Burm.f. that were taken from the Atoon region of Bhilwara, Rajasthan: root, stem, leaf, fruit, and seed. In comparison to primarily absorptive and photosynthetic organs, structural, reproductive, and storage-associated organs accumulate significantly higher levels of this osmoprotectant, according to the results, which showed a clear organ-specific pattern of proline accumulation in the order **stem > fruit > seed > leaf > root**.

These findings show that proline has a specific and organ-specific function in *Solanum surattense*'s physical adaptation, possibly supporting osmotic control, structural stability, and reproductive defense in the semi-arid climate of the Aravalli region. The nearly threefold higher proline concentration in the stem compared to the root underscores the importance of this organ in osmotic regulation and stress adaptation.

Since *S. surattense* is a well-known medicinal species, the current biochemical data not only improves our knowledge of its stress physiology but also establishes a basis for future studies that relate osmolyte accumulation to its pharmaceutical importance and ecological resilience. The organ-specific distribution of proline may influence the production and accumulation of bioactive compounds, which are responsible for the species' medicinal properties.

Limitations of this Study: The study was conducted on plants from a single location and during a single season, which may limit the generalizability of the findings. Seasonal variations in proline content were not assessed. The study did not measure other stress-responsive metabolites or correlate proline accumulation with the production of bioactive compounds. Future research should address these limitations by incorporating seasonal sampling, multiple locations, and metabolomic analysis.

Future Research Directions: Future studies should investigate the seasonal variation in proline content, compare populations from different habitats, examine the relationship between proline accumulation and the production of bioactive compounds, and explore the genetic and molecular basis of organ-specific proline regulation in *S. surattense*.

Overall, this study fills a gap in the biochemical characterization of this medicinally and ecologically significant species by providing new baseline data on proline distribution in *S. surattense*. It also promotes more research into the species' stress-adaptive mechanisms under various seasonal and environmental conditions.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this research. The study was conducted independently, and the authors have no financial, personal, academic, or professional relationships that could have influenced the research outcomes, data interpretation, or manuscript preparation.

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***In vitro* bio efficacy of biocontrol agents against *Colletotrichum truncatum* associated with leaf blight disease of Linseed in India**

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Abstract— Leaf blight caused by *Colletotrichum truncatum* is an important fungal disease of linseed (*Linum usitatissimum* L.) that can reduce crop growth and productivity. Considering the ecological concerns associated with excessive fungicide use, the present study evaluated the *in vitro* efficacy of *Trichoderma asperellum* and *Pseudomonas fluorescens* against *C. truncatum* using the dual culture technique. Among *T. asperellum* treatments, *T*₁ showed the greatest antagonistic activity, restricting pathogen growth to 25.40 ± 0.52 mm with 70.80% inhibition, followed by *T*₂ (26.80 ± 0.63 mm; 69.20%) and *T*₃ (27.65 ± 0.58 mm; 68.22%), compared with 87.00 ± 0.00 mm in the control. Among *P. fluorescens* treatments, *T*₂ was most effective, limiting mycelial growth to 29.10 ± 0.56 mm and achieving 66.65% inhibition, followed by *T*₁ (31.25 ± 0.78 mm; 64.18%) and *T*₃ (32.53 ± 0.75 mm; 62.72%), against 87.25 ± 0.73 mm in the control. Overall, *T. asperellum* exhibited superior antagonistic activity. This study demonstrates that promising biocontrol agents identified through *in vitro* screening could serve as environmentally compatible components of an integrated disease management strategy for the management of *C. truncatum*-induced leaf blight in linseed.

Keywords— Antagonism, biocontrol agents, biological control, *Colletotrichum truncatum*, dual culture technique, leaf blight, linseed.

I. INTRODUCTION

Linseed (*Linum usitatissimum* L.), commonly known as flaxseed, is an important traditional *rabi* oilseed crop cultivated during the winter season. Its significance is attributed to its high-quality seed oil, nutritional value, and industrial applications. The crop also serves as a valuable component of diversified cropping systems because of its adaptability to relatively poor soils and water-limited conditions. Linseed oil is widely used in the food, cosmetic, and eco-material industries owing to its desirable fatty acid composition and functional properties (Zanetti et al., 2013). Based on morphological characteristics and end use, the crop is broadly classified into two types: seed type (linseed), primarily cultivated for oil production and fibre type (flax), grown mainly for fibre production. In India, cultivated varieties are predominantly seed types and are grown primarily for oil extraction (Singh, 2016; Biradar et al., 2016).

Linseed seeds generally contain approximately 33–47% oil, depending on genotype, environmental conditions, and other factors. The oil is particularly valued for its high concentration of essential fatty acids and is an important plant-based source of omega-3 fatty acids, especially alpha-linolenic acid (ALA), which constitutes approximately 55% of the total fatty acids. In India, a substantial proportion of linseed oil is utilized for industrial purposes, including the manufacture of boiled, borated, epoxidized, aluminate, urethane, and isomerized oils (Mueed et al., 2022). During 2021–22, linseed was cultivated in India on approximately 2.0 lakh hectares, producing about 1.2 lakh metric tonnes, with an average productivity of 659 kg ha⁻¹. The crop is cultivated extensively in Madhya Pradesh, Rajasthan, Bihar, Uttar Pradesh, Assam, Jharkhand, and several other states. Madhya Pradesh accounts for the largest area under cultivation, with approximately 1.16 lakh hectares and a production of about 0.55 lakh tonnes, although its productivity remains relatively low at approximately 474 kg ha⁻¹ (APEDA, 2022).

Despite its economic and nutritional importance, linseed production is affected by several biotic constraints, particularly fungal diseases that reduce plant growth, yield, and seed quality (Patel et al., 2023). Leaf blight is an important disease that reduces photosynthetic area and may cause premature defoliation and yield loss. *Colletotrichum truncatum* is an important fungal pathogen causing necrotic leaf lesions that may enlarge and coalesce under warm and humid conditions. Its survival in infected crop residues can contribute to disease persistence and subsequent outbreaks (Sampathkumar et al., 2025). A distinct leaf blight caused by *Colletotrichum truncatum* was recently observed in linseed fields of Karnataka, and this pathogen–disease association is newly reported in India (Sampathkumar et al., 2025).

Management of fungal leaf blight diseases mainly depends on synthetic fungicides. However, their repeated and excessive use can lead to fungicide resistance, chemical residues, environmental pollution, disruption of beneficial microorganisms, and increased production costs. Therefore, sustainable and eco-friendly disease-management methods are needed. Biological control using beneficial microorganisms such as *Trichoderma*, *Pseudomonas*, and *Bacillus* offers a promising alternative. These microorganisms suppress plant pathogens through competition, production of antimicrobial compounds and cell-wall-degrading enzymes, mycoparasitism, and inhibition by volatile compounds. Some biocontrol agents also promote plant growth and induce systemic resistance, making them useful components of integrated disease management (Islam et al., 2024).

However, the efficacy of biocontrol agents varies depending on the antagonist, pathogen isolate, environmental conditions, and interactions between the organisms. Therefore, preliminary *in vitro* screening is an important step in identifying efficient antagonists before their evaluation under greenhouse and field conditions. The dual-culture technique provides a simple and reliable method for assessing direct antagonistic interactions by measuring the ability of a biocontrol agent to restrict the radial growth of a target pathogen under controlled conditions. Such screening enables the selection of promising antagonists for subsequent evaluation and integration into sustainable disease-management programmes (Nguyen et al., 2025; Tyagi et al., 2024).

As this pathogen–disease association is newly reported in India and information on its management is limited, the present study was undertaken to evaluate the *in vitro* bio-efficacy of selected biocontrol agents against *C. truncatum* by assessing their ability to inhibit mycelial growth and identifying the most effective antagonists.

II. MATERIALS AND METHODS

2.1 Survey and Collection of Diseased Samples

A systematic roving field survey was conducted during the *rabi* seasons of 2023–24 and 2024–25 in major linseed-growing districts of North Karnataka. During the survey, linseed plants exhibiting characteristic symptoms of leaf blight were recorded. Diseased leaf samples representing typical symptoms were collected from different locations, placed in sterile paper bags, transported to the laboratory, and processed for isolation and identification of the associated fungal pathogen and subsequent studies.

2.2 Isolation and Identification of the Fungal Pathogen

Diseased linseed leaves exhibiting characteristic leaf blight symptoms were gathered from different locations during the roving field survey and transported to the laboratory in sterile paper bags for further processing. The samples were washed thoroughly under running tap water to remove adhering soil and debris. Small pieces of diseased leaf tissue measuring approximately 5 × 5 mm were excised from the advancing margin of the lesions, ensuring that both healthy and infected tissues were included. The tissue pieces were surface sterilized with 2% sodium hypochlorite for 1–2 min, followed by three rinses with sterile distilled water. The sterilized pieces were blotted dry on sterile filter paper and aseptically placed on potato dextrose agar (PDA) plates supplemented with streptomycin to suppress bacterial contamination. The plates were incubated at 28 ± 2 °C and monitored periodically for fungal growth. The fungal colonies emerging from the infected tissues were subcultured onto fresh PDA plates to obtain pure cultures. The purified isolates were maintained on PDA slants at 4 °C for further studies (Sampathkumar et al., 2026). Identification of the fungal pathogen was initially based on cultural and morphological characteristics, including colony colour, texture, growth pattern, pigmentation, hyphal characteristics, and reproductive structures. The fungal isolates were examined microscopically using a compound microscope to record their morphological characteristics. The observed features were compared with published taxonomic descriptions and relevant literature for preliminary identification (He et al., 2016). Molecular confirmation of the pathogen identity was performed as part of an earlier study (Sampathkumar et al., 2025), where the isolates were confirmed as *C. truncatum* using multi-gene phylogeny (ITS, *ACT*, *TUB2*, and *GAPDH* sequences).

2.3 Collection and Isolation of Biocontrol Agents

Trichoderma asperellum and *Pseudomonas fluorescens* were obtained from commercially available talc-based formulations developed by the University of Horticultural Sciences, Bagalkot. These formulations were used as sources for isolating the biocontrol agents. The biocontrol agents were isolated from the formulations and cultured on suitable media to obtain pure cultures. *T. asperellum* was identified based on colony characteristics such as colour, texture, growth pattern and pigmentation, along with microscopic features such as conidiophores, phialides and conidia. *P. fluorescens* was identified based on its colony characteristics, pigmentation and microscopic features. The observed characteristics were compared with standard taxonomic descriptions and published literature to confirm their identity.

2.4 In vitro Antagonistic Activity of Biocontrol Agents against the Fungal Pathogen

The antagonistic efficacy of the biocontrol agents against the pathogen was evaluated using the dual culture technique described by Dennis and Webster (1971) on potato dextrose agar (PDA) medium.

2.4.1 Dual Culture Assay of *Trichoderma asperellum*

Approximately 20 mL of molten PDA medium was poured into sterile Petri plates and allowed to solidify. A 5-mm-diameter mycelial disc was cut from a 10-day-old culture of the pathogen using a sterile cork borer and placed near the periphery of one side of the PDA plate. Similarly, a 5-mm-diameter disc of the antagonist, *T. asperellum*, was placed near the opposite periphery of the same plate. Plates inoculated only with the pathogen served as controls. All inoculated plates were incubated at 28 ± 2 °C for 7 days. Each treatment was maintained with three replicates. After incubation, when the pathogen colony in the control plates reached approximately 90 mm in diameter, the radial growth of the pathogen was measured.

2.4.2 Dual Culture Assay of *Pseudomonas fluorescens*

For evaluation of the bacterial antagonist, a 5-mm-diameter mycelial disc of the test fungus was placed at the centre of a PDA plate. *Pseudomonas fluorescens* was streaked on either side of the fungal inoculum at an appropriate distance. Plates inoculated only with the pathogen served as controls. All plates were incubated at 28 ± 2 °C for 7 days. Following incubation, the radial growth of the pathogen was measured and compared with that of the control.

2.5 Calculation of Mycelial Growth Inhibition

The percentage inhibition of mycelial growth of the pathogen by the antagonists was calculated using the formula described by Vincent (1927).

$$\text{Mycelial inhibition (\%)} = \frac{C-T}{C} \times 100 \quad (1)$$

where:

C = radial growth of the pathogen in the control plate

T = radial growth of the pathogen in the treatment plate containing the antagonist

The percentage inhibition of mycelial growth was calculated using the same formula for both *Trichoderma asperellum* and *Pseudomonas fluorescens* treatments.

2.6 Statistical Analysis

The data on the *in vitro* efficacy of the biocontrol agents were statistically analysed using one-way analysis of variance (ANOVA) at the $P < 0.05$ significance level in SPSS version 16.0 (SPSS Inc., USA). Treatment means were separated using Tukey's honestly significant difference (HSD) test.

III. RESULTS

3.1 Identification of *Colletotrichum truncatum*

A systematic field survey was conducted during the *rabi* seasons of 2023–24 and 2024–25 across the linseed-growing districts of North Karnataka. During the survey, linseed plants exhibiting characteristic symptoms of leaf blight were observed. The disease was characterized by dark, sunken, circular to irregular lesions that frequently developed into shot-hole-like necrotic areas on the leaves (Fig. 1). Symptomatic leaf samples were collected from the surveyed locations and subjected to pathogen isolation. After 7 days of incubation, the developing fungal mycelium was transferred to fresh potato dextrose agar (PDA) plates, followed by single-spore isolation, which resulted in the recovery of four pure fungal isolates.

On PDA, the fungal colonies were circular with smooth margins. Initially, the colonies exhibited white to light-gray mycelial growth, which gradually turned dark gray with increasing incubation time. The reverse side of the colonies showed dense, dark-gray pigmentation with distinct zonation and well-defined concentric rings. After 10 days of incubation, numerous black acervuli developed abundantly on the colony surface, measuring 117–153 μm in diameter (Fig. 2A). The acervuli were spherical and produced numerous setae. The setae were rigid, linear, dark brown to black, straight at the base, and rounded at the apex, measuring 49–53 μm in length and 1.5–2.0 μm in width ($n = 10$). The conidia were hyaline, aseptate, smooth-walled, and characteristically curved, with nearly parallel sides. Conidial dimensions ranged from 15.8–20.1 μm in length and 2.6–3.9 μm in width ($n = 50$). The conidia possessed a truncate basal end and gradually tapered towards an acute, distinctly curved apical end. Granular cytoplasmic contents were clearly visible within the conidia (Fig. 2B).

Based on the cultural and morphological characteristics, the fungal pathogen associated with leaf blight of linseed was identified as *Colletotrichum truncatum* (He et al., 2016). The identity was further confirmed using multi-gene phylogeny (ITS, ACT, TUB2, and GAPDH sequences) in an earlier study (Sampathkumar et al., 2025).



FIGURE 1: Leaf blight of linseed. A: Field symptoms showing brown to dark brown, necrotic lesions on leaves with progressive drying and blighting; B: Close-up view of characteristic leaf lesions; C: Microscopic view of the associated fungal structures.

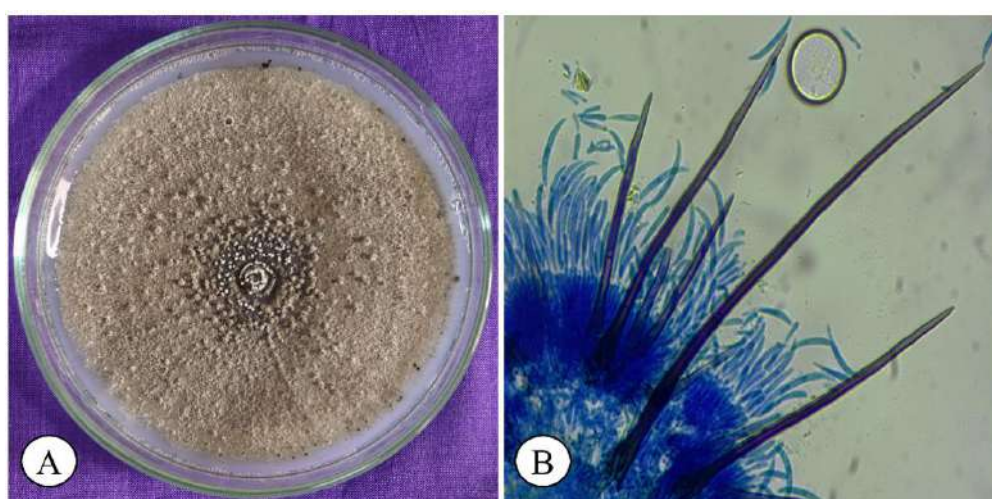


FIGURE 2: Cultural and microscopic characteristics of *Colletotrichum truncatum*. A: Colony morphology of *C. truncatum* on potato dextrose agar (PDA), showing characteristic colony growth and pigmentation after incubation; B: Microscopic view showing acervuli/conidiophores and numerous falcate, sickle-shaped conidia characteristic of *C. truncatum*.

3.2 In vitro Antagonistic Activity of Biocontrol Agents against the Fungal Pathogen

The biocontrol agents were successfully isolated from their respective formulations and obtained as pure cultures. Based on cultural and microscopic characteristics, the isolates were identified as *Trichoderma asperellum* and *Pseudomonas fluorescens*. Their observed characteristics were consistent with standard taxonomic descriptions, confirming their identity.

3.2.1 Dual Culture Assay of *Trichoderma asperellum* Against *Colletotrichum truncatum*

The *in vitro* assay demonstrated that *Trichoderma asperellum* effectively suppressed the mycelial growth of *Colletotrichum truncatum* compared with the untreated control (Table 1). Among the treatments, T₁ exhibited the highest antagonistic activity, recording the lowest mycelial growth (25.40 ± 0.52 mm) and maximum inhibition (70.80%). This was followed by T₂, which restricted pathogen growth to 26.80 ± 0.63 mm and resulted in 69.20% inhibition, while T₃ recorded 27.65 ± 0.58 mm growth with 68.22% inhibition. In contrast, the untreated control showed maximum mycelial growth (87.00 ± 0.00 mm) and no inhibition. These findings demonstrate the considerable antagonistic potential of *T. asperellum* against *C. truncatum*, with T₁ being the most effective treatment under *in vitro* conditions (Fig. 3).

TABLE 1
IN VITRO EVALUATION OF *Trichoderma asperellum* AGAINST *Colletotrichum truncatum*

Treatment	Mycelial growth of <i>C. truncatum</i> (mm) (Mean $\pm$ SE)	Growth Inhibition (%)
T ₁	25.40 ± 0.52	70.8
T ₂	26.80 ± 0.63	69.2
T ₃	27.65 ± 0.58	68.22
Control	87.00 ± 0.00	0.00
SE $\pm$	0.58	—
CD at 5%	1.84	—

Mycelial growth of *C. truncatum* was recorded after 7 days of incubation. Each treatment was replicated three times.

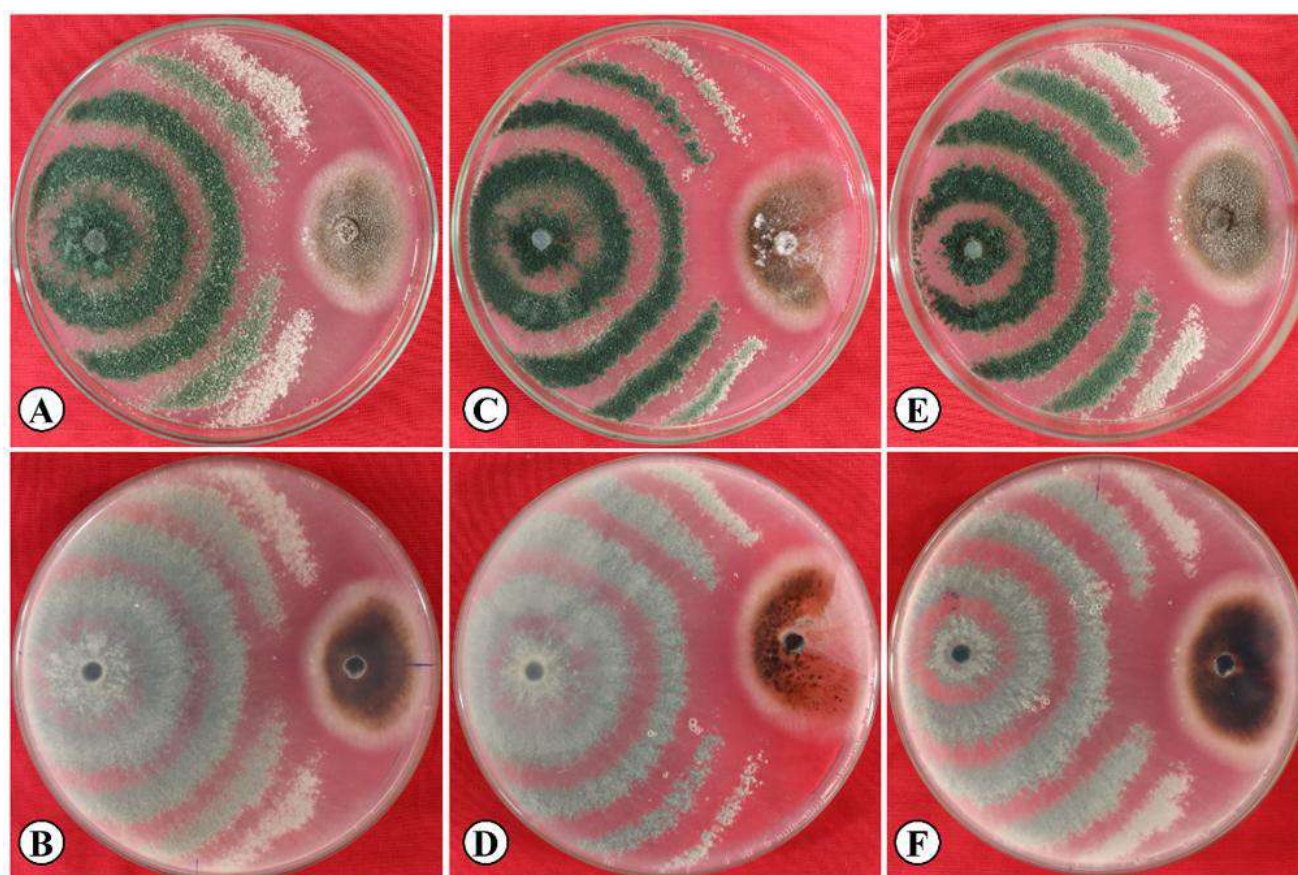


FIGURE 3: Antagonistic activity of *Trichoderma asperellum* against *Colletotrichum truncatum* in a dual culture assay, showing inhibition of the radial growth of the pathogen by the biocontrol agent.

3.2.2 Dual culture assay of *Pseudomonas fluorescens* against *Colletotrichum truncatum*

Similarly, the *in vitro* evaluation of *Pseudomonas fluorescens* revealed substantial suppression of *C. truncatum* growth in all treatments compared with the untreated control (Table 2). Mycelial growth ranged from 29.10 to 32.53 mm across the treatments, whereas the control recorded 87.25 ± 0.73 mm. T₂ was the most effective treatment, resulting in the lowest mycelial growth (29.10 ± 0.56 mm) and highest inhibition (66.65%). T₁ followed with 31.25 ± 0.78 mm growth and 64.18% inhibition, whereas T₃ recorded 32.53 ± 0.75 mm growth and 62.72% inhibition. Overall, *P. fluorescens* exhibited appreciable antagonistic activity against *C. truncatum*, with T₂ showing the greatest suppression of pathogen growth under *in vitro* conditions (Fig. 4).

TABLE 2
IN VITRO EVALUATION OF *Pseudomonas fluorescens* AGAINST *Colletotrichum truncatum*

Treatment	Mycelial Growth of <i>C. truncatum</i> (mm) (Mean $\pm$ SE)	Growth Inhibition (%)
T ₁	31.25 ± 0.78	64.18
T ₂	29.10 ± 0.56	66.65
T ₃	32.53 ± 0.75	62.72
Control	87.25 ± 0.73	0.00
SE $\pm$	0.41	—
CD at 5%	1.33	—

Mycelial growth of *C. truncatum* recorded after 7 days of incubation. Each treatment is replicated three times.

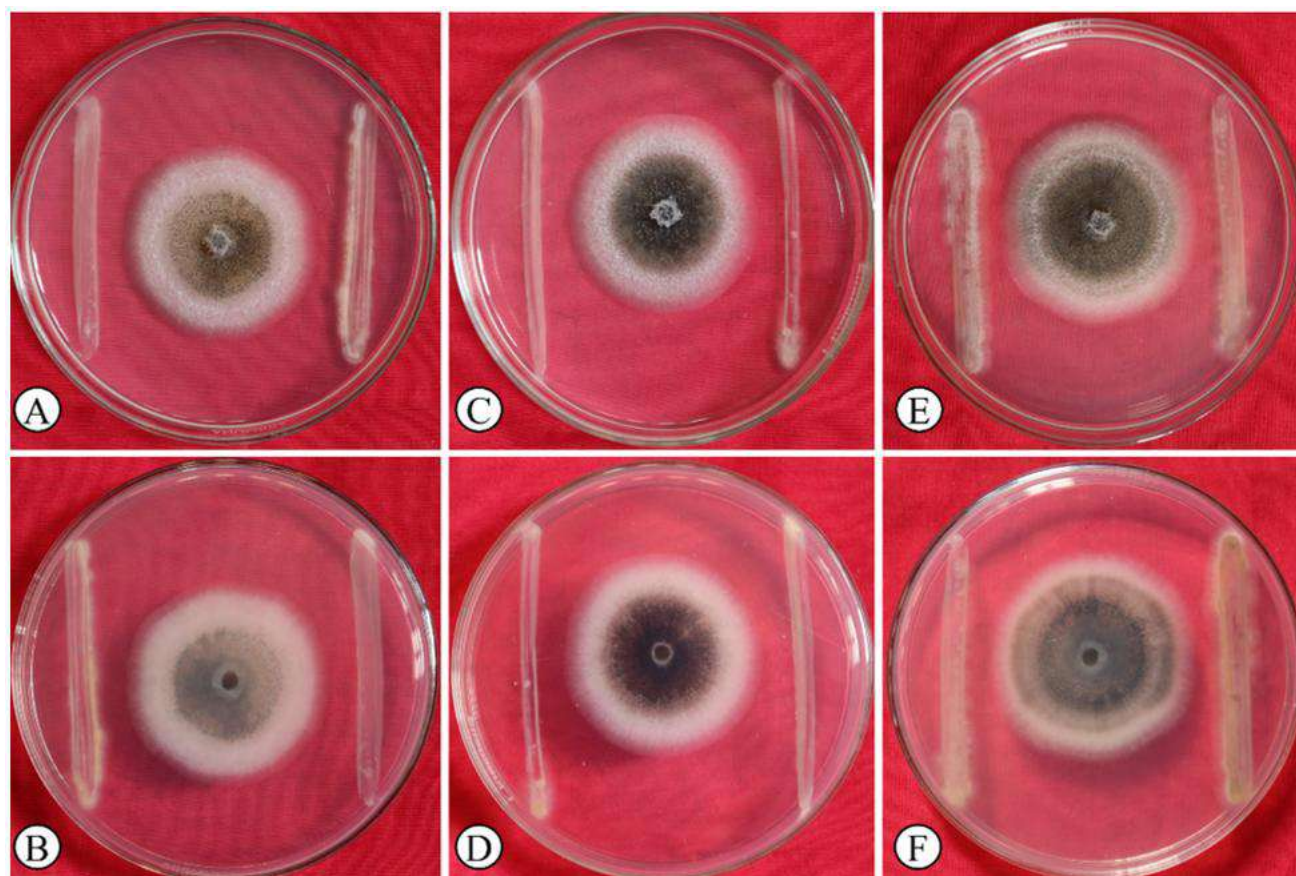


FIGURE 4: Antagonistic activity of *Pseudomonas fluorescens* against *Colletotrichum truncatum* in a dual culture assay, showing inhibition of the radial growth of the pathogen by the biocontrol agent.

IV. DISCUSSION

The *in vitro* evaluation of biocontrol agents against *Colletotrichum truncatum*, the pathogen responsible for leaf blight of linseed (*Linum usitatissimum* L.), revealed that *Trichoderma asperellum* and *Pseudomonas fluorescens* effectively inhibited the mycelial growth of the pathogen. These results suggest that both biocontrol agents have good antagonistic potential and could be used as eco-friendly components in the integrated management of linseed leaf blight.

Among the tested biocontrol agents, *Trichoderma asperellum* exhibited considerable antagonistic activity against *C. truncatum*. Reduction in radial growth of the pathogen in dual-culture assays may be attributed to several mechanisms operating either individually or simultaneously. *Trichoderma* is well known for its rapid growth and competitive ability, enabling it to efficiently colonize the available space and utilize nutrients that would otherwise be accessible to the pathogen. Such competition restricts the establishment and subsequent growth of *C. truncatum*. The findings agree with Aljabali et al. (2025) and Kumar and Tripathi (2018), who reported the strong antagonistic potential of *Trichoderma* spp. against phytopathogenic fungi, further supporting the efficacy of *T. asperellum* as a promising biocontrol agent. The superior performance of T₁ among the *Trichoderma* treatments may be attributed to isolate-specific differences in growth rate, sporulation capacity, or production of antifungal metabolites.

The antagonistic effect exhibited by *Pseudomonas fluorescens* against *C. truncatum* also highlights their potential as bacterial biocontrol agents. Fluorescent *Pseudomonas* species are efficient colonizers and are known to suppress several plant-pathogenic fungi through multiple mechanisms (Tamin et al., 2019). Their inhibitory effect may be associated with the production of antifungal metabolites, antibiotics, siderophores, hydrolytic enzymes and other secondary metabolites. Siderophore production is particularly important because it enables *Pseudomonas* to efficiently sequester iron from the surrounding environment, thereby reducing its availability to competing microorganisms, including fungal pathogens (Vanitha & Ramjegathesh, 2014). This nutrient competition can consequently restrict the growth and development of *C. truncatum*. The variation in inhibition among the *Pseudomonas* treatments (T₁, T₂, T₃) likely reflects differences in the production of these antagonistic compounds or differences in growth rate and colonization efficiency.

Differences in percentage inhibition among the tested *Trichoderma* and *Pseudomonas* isolates may be due to differences in their antagonistic ability, growth rate, competition and production of antifungal compounds and lytic enzymes (Kuzmanovska et al., 2018). The sensitivity of *C. truncatum* to different antagonists may also affect the level of inhibition. Therefore, selecting highly effective isolates is important for successful biological control.

The strong *in vitro* suppression of *C. truncatum* by the effective *Trichoderma* and *Pseudomonas* isolates is particularly important from the perspective of sustainable disease management. Biological control agents can potentially reduce dependence on fungicides and thereby minimize problems associated with chemical residues, environmental contamination and the development of fungicide-resistant pathogen populations. Moreover, *Trichoderma* and plant growth-promoting *Pseudomonas* strains may provide additional benefits through rhizosphere competence, nutrient mobilization, plant-growth promotion and induction of host defence responses (Lahlali et al., 2022; Ayaz et al., 2023).

Although the *in vitro* results showed good antagonistic activity, they should be considered only as an initial indication of biocontrol potential. The effectiveness of biocontrol agents under greenhouse and field conditions may vary due to factors such as temperature, soil conditions, moisture, microbial competition, inoculum level, formulation and method of application (Ahmad et al., 2026). The present study showed that *Trichoderma asperellum* and *Pseudomonas fluorescens* were effective against *Colletotrichum truncatum*. Therefore, the most effective isolates identified in the *in vitro* study should be further tested under pot and field conditions to confirm their ability to manage leaf blight of linseed. Future research should also investigate the compatibility of these biocontrol agents with other disease management practices and their effects on crop growth and yield.

V. CONCLUSION

This study confirms the *in vitro* efficacy of *Trichoderma asperellum* and *Pseudomonas fluorescens* against *Colletotrichum truncatum*, the causal agent of leaf blight in linseed. Among the tested biocontrol agents, *T. asperellum* (T₁) exhibited the highest antagonistic activity, restricting pathogen growth to 25.40 ± 0.52 mm with 70.80% inhibition, followed by *P. fluorescens* (T₂), which limited mycelial growth to 29.10 ± 0.56 mm with 66.65% inhibition. Both biocontrol agents significantly suppressed the mycelial growth of the pathogen compared to untreated controls.

The study provides baseline information for the biological management of linseed leaf blight caused by *C. truncatum*, a newly reported pathogen–disease association in India. The promising results obtained from *in vitro* screening warrant further evaluation of the most effective isolates under greenhouse and field conditions. Integration of these biocontrol agents into sustainable disease management strategies could reduce dependence on synthetic fungicides and contribute to environmentally friendly linseed production.

- **Limitations of the Study:** This study was conducted under controlled *in vitro* conditions, and the efficacy of the biocontrol agents may vary under field conditions due to environmental factors, microbial competition, and other variables. The mechanisms of antagonism were not specifically investigated, and pathogenicity testing was not performed in this study (though the pathogen identity was confirmed molecularly in earlier work). Future research should focus on evaluating the selected biocontrol agents under greenhouse and field conditions and investigating their mechanisms of action.
- **Future Research Directions:** Future studies should include (i) evaluation of the most effective isolates under pot and field conditions, (ii) investigation of the mechanisms of antagonism (e.g., production of volatile compounds, chitinase activity, siderophore production), (iii) compatibility testing with other disease management practices, (iv) formulation and application optimization, and (v) assessment of the impact of biocontrol agents on crop growth and yield.

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CONFLICT OF INTEREST

The author declares no conflict of interest regarding the publication of this manuscript.

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Screening of Rice Genotypes for Resistant to Rice Leaf Folder, *Cnaphalocrocis medinalis* Guenee and Identification of Associated Morphological Traits

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Abstract— Screening of 23 rice promising genotypes based on per cent damaged leaves revealed that eleven genotypes were found moderately resistant viz., Kala Namak (12.32%), GNR-3 (13.41%), GNR-5 (13.45%), GRH-2 (13.92%), GNR-7 (14.43%), GR-15 (16.02%), Mahsuri (16.52%), GNRH-1 (16.62%), GR-17 (16.89%), GNR-2 (19.02%) and NVSR-396 (19.34%) (Scale-3). Whereas, two genotypes were found susceptible i.e. GNR-4 (37.32%) and GR-11 (39.11%) (Scale-7) and one genotype TN-1 (54.86%) was found the highly susceptible (Scale-9). The plant height exhibited the highly significant negative correlation with per cent damaged leaves ($r = -0.6157$) and number of larvae ($r = -0.5621$), while others parameters were found non-significant positive and negative correlation. The highest grain and straw yield were recorded in GRH-2 (5946 & 6667 kg/ha) and lowest were recorded in TN-1 (3874 and 4559 kg/ha), respectively. Grain and straw yield exhibited the highly significant negative correlation with per cent damaged leaves ($r = -0.5882$ and $r = -0.5828$, respectively) and number of larvae ($r = -0.5776$ and $r = -0.5711$, respectively) indicated that there was decrease in yield with increase in infestation and vice-versa.

Keywords— Rice, Screening, Morphological traits, Leaf folder, *Cnaphalocrocis medinalis*.

I. INTRODUCTION

Rice (*Oryza sativa* Linnaeus) belongs to the family of grasses (Poaceae) with most important cereal crops worldwide. It is grown over 120 million hectares to produce 600 million tonnes of grain with an average productivity of 5000 kg/ha (Jakarpong and Wiboon, 2017). India ranks first by covering the largest area (45 per cent) under rice and ranks second by contributing total food grain production of the world. In India rice is grown in 43.86 million hectares with 112 million tonnes production and the average productivity is about 2600 kg/ha (Anon., 2020). Rice production is confined to South and Middle Gujarat with wide range of agro-climatic variation within and between individual zones. Rice production is limited by both biotic and abiotic stresses of which insect pests alone caused about 25 per cent losses (Dhaliwal et al., 2007), hence there is need to reduce the yield losses due to major pests and diseases. Rice crop is attacked by more than 100 species of insects, out of them 20 species can cause economic damage during different stages of the crop (Jakarpong and Wiboon, 2017). Rice leaf folder is one of the most serious and most important pest of rice crop in Indian subcontinent (Shanmungam et al., 2006). Out of eight species of leaf folders, the widest spread and important one is *Cnaphalocrocis medinalis* (Guenee) (Pyralidae: Lepidoptera) (Bhatti, 1995). It was earlier considered a minor pest but now a days it assumed major pest status. Due to rice leaf folder, the loss may reach up to 63 to 80 per cent as reported by Rajendran et al. (1986). Host plant resistance is an important component of integrated pest management (IPM) for sustainable rice production. Screening of rice genotypes for resistance to leaf folder and

identification of associated morphological traits can facilitate the development of resistant varieties, thereby reducing dependence on chemical insecticides. The present study was therefore undertaken to screen promising rice genotypes for resistance to rice leaf folder and to identify morphological traits associated with resistance.

II. MATERIALS AND METHODS

The field investigation on screening and morphological basis of resistance of rice genotypes against leaf folder was carried out at Main Rice Research Centre, Navsari Agricultural University, Navsari, Gujarat during *Kharif-2020* and 2021 (Plate 1). Following twenty three rice genotypes viz., NAUR-1, GNR-2, GNR-3, GNR-4, GNR-5, GNR-6, GNR-7, IR-28, NVSR-392, NVSR-395, NVSR-396, GNRH-1, GR-15, GR-17, Mahsuri, GR-101, Krishna Kamod, GAR-13, Kala Namak, Chittimuthyalu and GRH-2. Along with state susceptible GR-11 and national susceptible check TN-1 were transplanted for screening against leaf folder. The experiment was laid out in a randomized completely block design with twenty three treatments and two replications. Each entry was planted in five rows of 1.95 meter length with a spacing 20 × 15 cm. Recommended agronomical practices of manure and fertilizer dose @ FYM: 10 tonnes/ha and N-P-K: 100-30-00 kg/ha was applied. No plant protection measures were provided to create optimum conditions for pest multiplication.

The observations of per cent leaf damage and numbers of larvae were recorded at 7th days after the commencement of pest appearance. From each genotype, 10 hills were selected randomly from each replication. Observations were recorded by counting the total number of larvae, leaves per 10 hills and total number of damaged leaves (Only if one-third of leaf area is damaged) per 10 hills. Thereafter, all the observations were recorded regularly at an interval of 15 days up to the harvest of crop. The highest per cent damaged leaves were taken for final interpretation. Per cent leaf damage was calculated by following formula given by Netam and Gupta (2015).

$$\text{Leaf damage (\%)} = \frac{\text{Total number of damaged leaves}}{\text{Total number of leaves (Healthy + Damaged)}} \times 100 \quad (1)$$

Morphological parameters were recorded from each genotype at the time of the highest per cent damaged leaves, morphological parameters for the same was considered for final interpretation from randomly selected five plants of each genotype from each replication. The rice genotypes were evaluated for various morphological traits, viz., plant height (cm), total number of tillers per hill, leaf length (cm), leaf thickness (mm), leaf width (cm), leaf colour, days to 50 per cent flowering and phyllotaxy.

2.1 Categorization of Rice Genotypes on the Basis of Damaged Leaves

Categorization of rice genotypes on the basis of damaged leaves was done by using Standard Evaluation System (SES, 2013) developed by IIRR for estimating relative resistance/susceptibility. The rice genotypes were categorized based on the percentage of damaged leaves using a 0-9 scale. A scale of 0 (no damage) was classified as highly resistant/immune, while 1 (1-10% damaged leaves) was categorized as resistant. A scale of 3 (11-20%) was considered moderately resistant, whereas 5 (21-35%) was classified as moderately susceptible. A scale of 7 (36-50%) was categorized as susceptible and a scale of 9 (51-100%) was considered highly susceptible.



PLATE 1: Screening of rice genotypes against rice leaf folder, *C. medinalis* during Kharif-2020 & 2021]

III. RESULTS AND DISCUSSION

3.1 Screening Based on Per Cent Damaged Leaves and Number of Larvae

The results revealed that all rice genotypes and checks showed varying levels of rice leaf folder infestation during *Kharif* 2020 and 2021. Based on pooled data, the percentage of damaged leaves ranged from 12.32% in Kala Namak to 54.86% in TN-1. Eleven genotypes viz., Kala Namak, GNR-3, GNR-5, GRH-2, GNR-7, GR-15, Mahsuri, GNRH-1, GR-17, GNR-2 and NVSR-396 showed a moderately resistant reaction (SES-3). Nine genotypes showed moderately susceptible, two susceptible and TN-1 highly susceptible reactions. The lowest larval population was recorded in Kala Namak (2.20 larvae), while the highest was observed in TN-1 (7.33 larvae). Lower larval population was generally associated with lower leaf damage. These findings are in agreement with Punithavalli et al. (2013) and Ashrith et al. (2020), who reported differential resistance among rice genotypes to leaf folder infestation. The identification of moderately resistant genotypes is particularly important as they can serve as donors in breeding programmes for developing leaf-folder-resistant rice varieties.

TABLE 1
SCREENING OF RICE GENOTYPES ON THE BASIS OF PER CENT DAMAGED LEAVES (KHARIF-2020, 2021 & POOLED)

Sr. No.	Genotype	Damaged leaves (%)			Scale	Reaction
		Kharif-2020	Kharif-2021	Pooled		
1	GNR-6	28.34 (22.60)*	29.38 (24.12)*	28.86 (23.36)*	5	MS
2	IR-28	30.36 (25.58)	31.35 (27.08)	30.86 (26.33)	5	MS
3	NVSR-392	34.20 (31.61)	35.09 (33.06)	34.65 (32.34)	5	MS
4	NVSR-395	33.93 (31.18)	34.81 (32.60)	34.37 (31.89)	5	MS
5	NVSR-396	25.61 (18.73)	26.52 (19.96)	26.07 (19.34)	3	MR
6	GNRH-1	23.34 (15.76)	24.70 (17.49)	24.03 (16.62)	3	MR
7	NAUR-1	28.82 (23.31)	29.64 (24.51)	29.23 (23.91)	5	MS
8	GNR-2	25.31 (18.35)	26.26 (19.68)	25.79 (19.02)	3	MR
9	GNR-3	20.58 (12.41)	22.23 (14.41)	21.42 (13.41)	3	MR
10	GNR-5	20.96 (12.86)	21.97 (14.04)	21.47 (13.45)	3	MR
11	GNR-7	21.67 (13.65)	22.92 (15.22)	22.30 (14.43)	3	MR
12	GR-15	23.05 (15.36)	24.08 (16.69)	23.57 (16.02)	3	MR
13	GR-17	23.82 (16.35)	24.63 (17.43)	24.23 (16.89)	3	MR
14	Mahsuri	23.37 (15.84)	24.42 (17.21)	23.90 (16.52)	3	MR
15	GNR-4	37.16 (36.61)	38.02 (38.02)	37.59 (37.32)	7	S
16	GR-101	29.96 (24.95)	31.55 (27.39)	30.76 (26.17)	5	MS
17	Krishna Kamod	30.21 (25.47)	31.51 (27.46)	30.87 (26.47)	5	MS
18	GAR-13	28.41 (22.67)	29.50 (24.29)	28.96 (23.48)	5	MS
19	Kala Namak	19.77 (11.47)	21.23 (13.17)	20.51 (12.32)	3	MR
20	Chittimuthyalu	28.76 (23.20)	30.25 (25.42)	29.51 (24.31)	5	MS
21	GRH-2	21.34 (13.28)	22.40 (14.57)	21.87 (13.92)	3	MR
22	GR-11	38.03 (38.00)	39.36 (40.22)	38.70 (39.11)	7	S
23	TN-1	47.07 (53.59)	48.54 (56.13)	47.80 (54.86)	9	HS
S. Em. ±		1.86	1.9	1.87	-	-
C.D. at 5%		5.45	5.57	5.47	-	-
C.V. (%)		9.38	9.21	9.24	-	-

Figures in the parentheses are original values, while those outside are arcsine transformed values.

MR: Moderately Resistant, MS: Moderately Susceptible, S: Susceptible and HS: Highly Susceptible

TABLE 2
SCREENING OF RICE GENOTYPES ON THE BASIS OF NUMBER OF LARVAE (KHARIF-2020, 2021 & POOLED)

Sr. No.	Genotype	Number of larvae			Av. % DL	Scale	Reaction
		Kharif-2020	Kharif-2021	Pooled			
1	GNR-6	1.94 (3.30)*	2.01 (3.56)*	1.98 (3.43)*	28.86 (23.36)	5	MS
2	IR-28	2.13 (4.05)	2.16 (4.15)	2.14 (4.10)	30.86 (26.33)	5	MS
3	NVSR-392	2.29 (4.75)	2.31 (4.85)	2.30 (4.80)	34.65 (32.34)	5	MS
4	NVSR-395	2.26 (4.60)	2.29 (4.75)	2.27 (4.68)	34.37 (31.89)	5	MS
5	NVSR-396	1.83 (2.85)	1.95 (3.30)	1.89 (3.08)	26.07 (19.34)	3	MR
6	GNRH-1	1.70 (2.40)	1.76 (2.60)	1.73 (2.50)	24.03 (16.62)	3	MR
7	NAUR-1	2.14 (4.10)	2.11 (3.95)	2.13 (4.03)	29.23 (23.91)	5	MS
8	GNR-2	1.81 (2.80)	1.86 (2.95)	1.83 (2.88)	25.79 (19.02)	3	MR
9	GNR-3	1.63 (2.15)	1.68 (2.35)	1.65 (2.25)	21.42 (13.41)	3	MR
10	GNR-5	1.64 (2.20)	1.71 (2.45)	1.68 (2.33)	21.47 (13.45)	3	MR
11	GNR-7	1.61 (2.10)	1.74 (2.55)	1.68 (2.33)	22.30 (14.43)	3	MR
12	GR-15	1.70 (2.40)	1.88 (3.05)	1.79 (2.73)	23.57 (16.02)	3	MR
13	GR-17	1.79 (2.70)	1.87 (3.00)	1.83 (2.85)	24.23 (16.89)	3	MR
14	Mahsuri	1.79 (2.70)	1.83 (2.85)	1.81 (2.78)	23.90 (16.52)	3	MR
15	GNR-4	2.28 (4.70)	2.21 (4.40)	2.25 (4.55)	37.59 (37.32)	7	S
16	GR-101	2.07 (3.85)	2.14 (4.10)	2.11 (3.98)	30.76 (26.17)	5	MS
17	Krishna Kamod	2.21 (4.40)	2.20 (4.35)	2.21 (4.38)	30.87 (26.47)	5	MS
18	GAR-13	2.10 (3.90)	2.12 (4.00)	2.11 (3.95)	28.96 (23.48)	5	MS
19	Kala Namak	1.61 (2.10)	1.67 (2.30)	1.64 (2.20)	20.51 (12.32)	3	MR
20	Chittimuthyalu	2.13 (4.05)	2.14 (4.10)	2.14 (4.08)	29.51 (24.31)	5	MS
21	GRH-2	1.63 (2.15)	1.76 (2.60)	1.69 (2.38)	21.87 (13.92)	3	MR
22	GR-11	2.57 (6.10)	2.75 (7.05)	2.66 (6.58)	38.70 (39.11)	7	S
23	TN-1	2.69 (6.75)	2.90 (7.90)	2.80 (7.33)	47.80 (54.86)	9	HS
S. Em. ±		0.09	0.1	0.09	1.87	-	-
C.D. at 5%		0.27	0.29	0.25	5.47	-	-
C.V. (%)		6.63	6.74	6.03	9.24	-	-

Figures in the parentheses are original values, while those outside are square root ($\sqrt{X+0.5}$) transformed values.
% DL: Per cent damaged leaves, MR: Moderately Resistant, MS: Moderately Susceptible, S: Susceptible and HS: Highly Susceptible

3.2 Resistance Based on Morphological Characters

Pooled data revealed that longer plant height, more tillers, thicker and broader leaves, green leaf colour and late flowering were generally associated with lower rice leaf folder infestation. Genotypes with long plant height recorded the lowest damaged

leaves ($17.51 \pm 4.45\%$) and larval population (2.91 ± 0.73), whereas short plants showed the highest infestation ($31.39 \pm 9.90\%$). More tillers, thicker and broader leaves also showed comparatively lower leaf damage and larval population. Green-coloured leaves recorded the lowest damage ($18.34 \pm 5.11\%$) and larval population (3.00 ± 0.80), while light and dark green leaves showed higher infestation. Late-flowering genotypes exhibited lower damage ($21.28 \pm 6.47\%$) than early-flowering genotypes ($25.62 \pm 12.10\%$). All 23 genotypes possessed spiral phyllotaxy and therefore no variation in this trait could be associated with resistance.

The association between morphological traits and resistance can be explained through several mechanisms. Longer plant height may reduce oviposition preference by making plants less accessible to adult moths or may create a microclimate less favourable for larval development. Thicker and broader leaves may provide physical barriers to larval feeding and folding, while green leaf colour may be associated with lower sugar content or higher silica deposition, making leaves less palatable. Late flowering may result in asynchrony between susceptible crop stages and peak pest populations. These findings are in agreement with Punithavalli et al. (2013), who reported a positive association of leaf width and total productive tillers with rice leaf folder infestation, and Ashrith et al. (2020), who found significant positive association of leaf width with leaf folder infestation.

TABLE 3
INFLUENCE OF DIFFERENT MORPHOLOGICAL CHARACTERS OF GENOTYPE ON PER CENT DAMAGED LEAVES AND NUMBER OF LARVAE (KHARIF-2020, 2021 & POOLED)

Plant character	Category	Range	Damaged leaves (%)	Number of larvae	Range	Damaged leaves (%)	Number of larvae	Range	Damaged leaves (%)	Number of larvae
		Kharif-2020			Kharif-2021			Pooled		
Plant height (cm)	Long	≥ 114 (13)	16.75 ± 4.40	2.79 ± 0.80	≥ 112 (13)	18.17 ± 4.51	3.63 ± 1.64	≥ 113 (13)	17.51 ± 4.45	2.91 ± 0.73
	Short	< 114 (10)	30.51 ± 9.77	4.48 ± 1.14	< 112 (10)	32.26 ± 10.03	4.09 ± 0.58	< 113 (10)	31.39 ± 9.90	4.63 ± 1.30
Total tiller	More	≥ 14 (15)	20.24 ± 6.96	3.16 ± 0.96	≥ 14 (15)	21.77 ± 6.99	3.41 ± 0.79	≥ 14 (14)	21.00 ± 6.98	3.32 ± 0.87
	Less	< 14 (8)	26.60 ± 12.37	4.21 ± 1.49	< 14 (8)	28.38 ± 12.70	4.38 ± 1.83	< 14 (9)	27.49 ± 12.53	4.18 ± 1.68
Leaf length (cm)	Long	≥ 58 (10)	22.34 ± 8.29	3.59 ± 1.26	≥ 57 (10)	23.83 ± 8.52	4.26 ± 1.71	≥ 57 (10)	21.07 ± 6.52	3.92 ± 1.60
	Short	< 58 (13)	25.11 ± 11.09	3.48 ± 1.29	< 57 (13)	24.76 ± 11.25	3.71 ± 1.42	< 57 (13)	25.44 ± 11.74	3.59 ± 1.35
Leaf thickness (mm)	Thick	> 0.267 (10)	20.39 ± 7.11	3.26 ± 0.94	> 0.266 (10)	21.94 ± 7.17	3.36 ± 0.76	> 0.266 (10)	20.82 ± 7.74	3.31 ± 0.85
	Thin	< 0.267 (13)	24.53 ± 11.35	3.73 ± 1.45	< 0.266 (13)	26.21 ± 11.63	4.12 ± 1.64	< 0.266 (13)	25.29 ± 11.08	3.93 ± 1.54
Leaf width (cm)	Broad	> 1.268 (12)	21.18 ± 8.17	3.38 ± 1.21	> 1.275 (12)	22.23 ± 8.68	3.54 ± 1.20	> 1.272 (12)	21.92 ± 8.29	3.42 ± 1.15
	Narrow	< 1.268 (11)	24.43 ± 11.35	3.71 ± 1.34	< 1.275 (11)	26.67 ± 11.11	4.12 ± 1.54	< 1.272 (11)	25.31 ± 11.43	3.97 ± 1.46
Leaf colour	Light green	(7)	27.01 ± 12.99	3.99 ± 1.61	(7)	28.82 ± 13.42	4.54 ± 1.90	(7)	27.91 ± 13.20	4.27 ± 1.75
	Green	(10)	17.61 ± 5.08	2.90 ± 0.87	(10)	19.07 ± 5.15	3.09 ± 0.73	(10)	18.34 ± 5.11	3.00 ± 0.80
	Dark green	(6)	26.68 ± 7.89	4.03 ± 0.90	(6)	27.97 ± 7.66	4.42 ± 0.34	(6)	27.12 ± 7.78	4.05 ± 0.86
DFF	Early	> 93 (12)	24.72 ± 11.96	3.80 ± 1.47	> 95 (12)	26.52 ± 12.25	4.08 ± 1.70	> 94 (12)	25.62 ± 12.10	3.94 ± 1.57
	Late	< 93 (11)	20.56 ± 6.48	3.18 ± 0.91	< 95 (11)	21.99 ± 6.45	3.47 ± 0.82	< 94 (11)	21.28 ± 6.47	3.35 ± 0.88
Phyllotaxy	Spiral	(23)	22.73 ± 9.95	3.53 ± 1.28	(23)	24.35 ± 10.16	3.79 ± 1.39	(23)	23.54 ± 10.06	3.66 ± 1.32

3.3 Correlation Coefficient (r) of Different Morphological Characters

Result on pooled revealed that the plant height exhibited highly significant negative correlation with per cent damaged leaves ($r = -0.6157$) and number of larvae ($r = -0.5621$) implying increase in the plant height corresponds with decrease of the infestation and vice-versa. Per cent damaged leaves exhibited non-significant negative correlation with total numbers of tiller ($r = -0.3223$), leaf length ($r = -0.2064$) and leaf thickness ($r = -0.1481$). It exhibited non-significant positive correlation with leaf width ($r = 0.0101$) and days to 50% flowering ($r = 0.0578$). While in case of number of larvae, it exhibited non-significant negative correlation with total numbers of tiller ($r = -0.2981$), leaf length ($r = -0.1732$), leaf thickness ($r = -0.0991$) and leaf

width ($r = -0.0686$). It exhibited non-significant positive correlation with days to 50% flowering ($r = 0.0746$) (Table 6). Ashrith et al. (2020) found that significant positive association (0.932) found with leaf width at midpoint. Among the morphological characters studied, only the number of trichomes and leaf width (cm) showed significant correlation with rice leaf folder infestation.

TABLE 4
CORRELATION COEFFICIENT (r) OF DIFFERENT MORPHOLOGICAL CHARACTERS OF GENOTYPES WITH PERCENT DAMAGED LEAVES AND NUMBER OF LARVAE DURING KHARIF-2020

SN	Genotype	Plant height (cm)	Total tiller/hill	Leaf			DFF	Reaction (% DL)
				Length (cm)	Thickness (mm)	Width (cm)		
1	GNR-6	100	13	56	0.275	0.650	75	MS
2	IR-28	92	13	37	0.255	0.725	75	MS
3	NVSR-392	108	13	64	0.245	1.110	74	MS
4	NVSR-395	105	14	61	0.260	1.125	72	MS
5	NVSR-396	120	14	64	0.260	1.275	71	MR
6	GNRH-1	119	15	50	0.245	1.225	81	MR
7	NAUR-1	122	15	64	0.280	1.350	91	MS
8	GNR-2	101	12	57	0.270	1.500	95	MR
9	GNR-3	123	14	56	0.270	1.150	85	MR
10	GNR-5	121	15	58	0.270	1.350	105	MR
11	GNR-7	116	14	57	0.255	1.475	100	MR
12	GR-15	126	15	67	0.215	1.675	91	MR
13	GR-17	115	15	54	0.240	1.500	84	MR
14	Mahsuri	118	19	89	0.360	1.175	111	MR
15	GNR-4	97	15	50	0.275	2.000	106	S
16	GR-101	106	12	55	0.245	1.375	108	MS
17	Krishna Kamod	134	17	56	0.305	0.975	101	MS
18	GAR-13	106	15	51	0.260	1.475	100	MS
19	Kala Namak	136	13	55	0.255	1.050	113	MR
20	Chittimuthyalu	114	15	58	0.335	1.235	106	MS
21	GRH-2	130	12	58	0.275	1.270	89	MR
22	GR-11	102	13	58	0.260	1.275	103	S
23	TN-1	102	12	55	0.225	1.225	103	HS
S. Em. $\pm$		4.02	0.95	1.70	0.01	0.04	1.86	-
C.D. at 5%		11.78	2.77	4.99	0.02	0.13	5.47	-
C.V. (%)		5.00	9.46	4.16	4.13	4.81	2.83	-
(r) value for % DL		-0.6050**	-0.2544 ^{NS}	-0.1701 ^{NS}	-0.1815 ^{NS}	0.0109 ^{NS}	0.0431 ^{NS}	-
(r) value for NL		-0.5584**	-0.1822 ^{NS}	-0.1497 ^{NS}	-0.0803 ^{NS}	-0.0607 ^{NS}	0.0669 ^{NS}	-

DFF: Days to 50% flowering, % DL: Per cent damaged leaves, NL: Number of larvae, R: Resistant, MR: Moderately Resistant, MS: Moderately Susceptible, S: Susceptible and HS: Highly Susceptible

TABLE 5

CORRELATION COEFFICIENT (r) OF DIFFERENT MORPHOLOGICAL CHARACTERS OF GENOTYPES WITH PER CENT DAMAGED LEAVES AND NUMBER OF LARVAE DURING KHARIF-2021

Sr. No.	Genotype	Plant height (cm)	Total tiller/hill	Leaf			DFF	Reaction (% DL)
				Length (cm)	Thickness (mm)	Width (cm)		
1	GNR-6	98	13	54	0.275	0.675	77	MS
2	IR-28	90	13	39	0.260	0.800	77	MS
3	NVSR-392	106	11	60	0.255	1.075	76	MS
4	NVSR-395	103	15	61	0.265	1.100	74	MS
5	NVSR-396	118	14	66	0.255	1.300	73	MR
6	GNRH-1	117	15	52	0.260	1.225	83	MR
7	NAUR-1	122	15	62	0.270	1.300	93	MS
8	GNR-2	101	12	56	0.270	1.475	97	MR
9	GNR-3	123	14	56	0.270	1.255	87	MR
10	GNR-5	121	15	58	0.275	1.475	105	MR
11	GNR-7	114	15	55	0.245	1.525	102	MR
12	GR-15	124	14	67	0.200	1.600	93	MR
13	GR-17	112	15	54	0.250	1.375	86	MR
14	Mahsuri	114	19	85	0.345	1.200	113	MR
15	GNR-4	99	15	50	0.270	2.100	110	S
16	GR-101	104	12	55	0.250	1.350	108	MS
17	Krishna Kamod	130	15	56	0.300	1.000	103	MS
18	GAR-13	104	14	53	0.265	1.400	102	MS
19	Kala Namak	134	13	56	0.250	1.050	115	MR
20	Chittimuthyalu	112	15	57	0.330	1.200	108	MS
21	GRH-2	126	12	58	0.275	1.300	91	MR
22	GR-11	100	13	57	0.255	1.300	105	S
23	TN-1	98	12	55	0.235	1.250	105	HS
S. Em. ±		3.65	0.73	1.49	0.01	0.04	1.48	-
C.D. at 5%		10.72	2.15	4.36	0.02	0.11	4.35	-
C.V. (%)		4.63	7.43	3.66	4.20	4.00	2.21	-
(r) value for % DL		-0.6225**	-0.3019 ^{NS}	-0.2200 ^{NS}	-0.1241 ^{NS}	0.0094 ^{NS}	0.0720 ^{NS}	-
(r) value for NL		-0.5618**	-0.3132 ^{NS}	-0.1646 ^{NS}	-0.1380 ^{NS}	-0.0755 ^{NS}	0.0795 ^{NS}	-

DFF: Days to 50% flowering, % DL: Per cent damaged leaves, NL: Number of larvae, R: Resistant, MR: Moderately Resistant, MS: Moderately Susceptible, S: Susceptible and HS: Highly Susceptible

TABLE 6
CORRELATION COEFFICIENT (r) OF DIFFERENT MORPHOLOGICAL CHARACTERS OF GENOTYPES WITH PER CENT DAMAGED LEAVES AND NUMBER OF LARVAE (POOLED OF 2020 & 2021)

Sr. No.	Genotype	Plant height (cm)	Total tiller/hill	Leaf			DFF	Reaction (% DL)
				Length (cm)	Thickness (mm)	Width (cm)		
1	GNR-6	99	13	55	0.275	0.663	76	MS
2	IR-28	91	13	38	0.260	0.763	76	MS
3	NVSR-392	107	12	62	0.250	1.093	75	MS
4	NVSR-395	104	15	61	0.263	1.113	73	MS
5	NVSR-396	119	14	65	0.260	1.288	72	MR
6	GNRH-1	118	15	51	0.253	1.225	82	MR
7	NAUR-1	122	15	63	0.265	1.325	92	MS
8	GNR-2	101	12	57	0.270	1.488	96	MR
9	GNR-3	123	14	56	0.268	1.203	86	MR
10	GNR-5	121	15	58	0.273	1.413	105	MR
11	GNR-7	115	15	56	0.250	1.500	101	MR
12	GR-15	125	15	67	0.208	1.638	92	MR
13	GR-17	114	15	54	0.245	1.438	85	MR
14	Mahsuri	116	19	87	0.353	1.188	112	MR
15	GNR-4	98	15	50	0.270	2.050	108	S
16	GR-101	105	12	55	0.250	1.363	108	MS
17	Krishna Kamod	132	16	56	0.303	0.988	102	MS
18	GAR-13	105	15	52	0.263	1.438	101	MS
19	Kala Namak	135	14	56	0.253	1.050	114	MR
20	Chittimuthyalu	113	15	58	0.333	1.218	107	MS
21	GRH-2	128	12	58	0.275	1.285	90	MR
22	GR-11	101	13	56	0.263	1.288	104	S
23	TN-1	100	12	55	0.230	1.238	104	HS
S. Em. ±		2.59	0.68	0.98	0.01	0.03	1.49	-
C.D. at 5%		7.60	2.01	2.89	0.02	0.08	4.37	-
C.V. (%)		3.25	6.89	2.41	3.30	3.02	2.24	-
(r) value for % DL		-0.6157**	-0.3223 ^{NS}	-0.2064 ^{NS}	-0.1481 ^{NS}	0.0101 ^{NS}	0.0578 ^{NS}	-
(r) value for NL		-0.5621**	-0.2981 ^{NS}	-0.1732 ^{NS}	-0.0991 ^{NS}	-0.0686 ^{NS}	0.0746 ^{NS}	-

DFF: Days to 50% flowering, % DL: Per cent damaged leaves, NL: Number of larvae, MR: Moderately Resistant, MS: Moderately Susceptible, S: Susceptible and HS: Highly Susceptible

3.4 Grain and Straw Yield of Different Rice Genotypes

Pooled data (Table 7) revealed that GRH-2 recorded the highest grain yield (5946 kg/ha) and was at par with GNR-3 (5738 kg/ha), GNR-5 (5723 kg/ha), GR-15 (5679 kg/ha), GAR-13 (5546 kg/ha), NAUR-1 (5436 kg/ha), GR-17 (5423 kg/ha) and GNR-7 (5362 kg/ha). Grain yield among the remaining genotypes ranged from 3431 kg/ha in Krishna Kamod to 4941 kg/ha in GNRH-1.

Similarly, GRH-2 recorded the highest straw yield (6667 kg/ha), which was at par with GNR-3 (6487 kg/ha), GNR-5 (6472 kg/ha), GR-15 (6436 kg/ha), GAR-13 (6282 kg/ha), NAUR-1 (6169 kg/ha), GR-17 (6159 kg/ha) and GNR-7 (6097 kg/ha). Among the remaining genotypes, straw yield ranged from 4026 kg/ha in Chittimuthyalu to 5651 kg/ha in GNRH-1. Overall, the genotypes showing better performance and lower leaf folder infestation also exhibited comparatively higher grain and straw yields.

TABLE 7
GRAIN AND STRAW YIELD OF DIFFERENT RICE GENOTYPES AND ITS CORRELATION (r) WITH PERCENT DAMAGED LEAVES AND NUMBER OF LARVAE (KHARIF-2020, 2021 & POOLED)

Sr. No.	Genotype	Grain Yield (Kg/ha)			Straw Yield (Kg/ha)			Reaction (% DL)
		2020	2021	Pooled	2020	2021	Pooled	
1	GNR-6	3933	3923	3928	4559	4523	4538	MS
2	IR-28	3662	3636	3649	4246	4241	4241	MS
3	NVSR-392	3579	3554	3567	4118	4149	4133	MS
4	NVSR-395	3579	3641	3610	4179	4246	4215	MS
5	NVSR-396	4226	4200	4213	4913	4795	4851	MR
6	GNRH-1	4979	4903	4941	5810	5497	5651	MR
7	NAUR-1	5446	5426	5436	6323	6021	6169	MS
8	GNR-2	4697	4621	4659	5451	5226	5338	MR
9	GNR-3	5759	5718	5738	6682	6297	6487	MR
10	GNR-5	5749	5697	5723	6656	6292	6472	MR
11	GNR-7	5400	5323	5362	6272	5928	6097	MR
12	GR-15	5697	5662	5679	6621	6256	6436	MR
13	GR-17	5441	5405	5423	6308	6010	6159	MR
14	Mahsuri	4503	4477	4490	5231	5062	5144	MR
15	GNR-4	3954	3954	3954	4590	4549	4569	S
16	GR-101	4133	4097	4115	5092	4692	4892	MS
17	Krishna Kamod	3436	3426	3431	4246	4056	4149	MS
18	GAR-13	5554	5538	5546	6426	6138	6282	MS
19	Kala Namak	4092	4054	4073	4759	4656	4708	MR
20	Chittimuthyalu	3467	3410	3438	4026	4021	4026	MS
21	GRH-2	5985	5908	5946	6836	6503	6667	MR
22	GR-11	4154	4077	4115	4821	4708	4764	S
23	TN-1	3913	3836	3874	4615	4497	4559	HS
S. Em. $\pm$		209	228	217	248	227	233	-
C.D. at 5%		613	668	637	727	665	682	-
C.V. (%)		6.45	7.09	6.74	6.56	6.23	6.28	-
Correlation coefficient (r) % DL		-0.5844**	-0.5919**	-0.5882**	-0.5827**	-0.5824**	-0.5828**	
Correlation coefficient (r) NL		-0.6107**	-0.5422**	-0.5776**	-0.6066**	-0.5310**	-0.5711**	

% DL: Per cent damaged leaves, NL: Number of larvae, MR: Moderately Resistant, MS: Moderately Susceptible, S: Susceptible and HS: Highly Susceptible

3.5 Correlation Coefficient (r) of Grain and Straw Yield

Result on pooled revealed that the grain yield exhibited highly significant negative correlation with per cent damaged leaves ($r = -0.5882$) and number of larvae ($r = -0.5776$) implying increase in the infestation corresponds with decrease of the grain yield and vice-versa. Straw yield exhibited highly significant negative correlation with per cent damaged leaves ($r = -0.5828$) and number of larvae ($r = -0.5711$) implying increase in the infestation corresponds with decrease of the straw yield and vice-versa. Bautista et al. (1984) have clearly shown that loss in yield was positively related. In their studies, 17.5 per cent infested leaves, resulted in 16.5 per cent yield loss and a loss of 21.3 per cent yield occurred with 26.6% DL. Thus, past reports support the present findings. Cumulative effect of loss in chlorophyll reduced photosynthate availability and altered water relations caused by the leaf folder injury to flag leaf led to greater yield loss in rice (Padmavathi et al., 2013).

IV. DISCUSSION

The screening of 23 rice genotypes against leaf folder revealed significant variation in resistance levels, with eleven genotypes exhibiting moderately resistant reactions. The identification of these genotypes is particularly valuable as they can serve as

donors in breeding programmes for developing leaf-folder-resistant rice varieties. The consistent performance of genotypes like Kala Namak, GNR-3, GNR-5, and GRH-2 across both seasons indicates stable resistance, which is desirable for breeding purposes.

The association between morphological traits and resistance observed in this study provides insights into the mechanisms underlying resistance. The highly significant negative correlation between plant height and infestation parameters ($r = -0.6157$ for % DL and $r = -0.5621$ for larval population) suggests that taller genotypes may be less preferred by adult moths for oviposition or may provide a less favourable microclimate for larval development. This finding is consistent with previous reports by Punithavalli et al. (2013) and Ashrith et al. (2020). The non-significant correlations of other morphological traits with infestation indicate that these traits may have weaker or inconsistent effects on resistance, possibly due to the complex nature of plant-insect interactions.

The significant negative correlation between grain yield and infestation parameters ($r = -0.5882$ for % DL and $r = -0.5776$ for larval population) clearly demonstrates the impact of leaf folder infestation on yield. Genotypes with lower infestation levels, such as GRH-2 (13.92% DL), GNR-3 (13.41% DL), and GNR-5 (13.45% DL), recorded higher grain yields (5946, 5738, and 5723 kg/ha, respectively). Conversely, susceptible genotypes like TN-1 (54.86% DL) recorded the lowest grain yield (3874 kg/ha). The yield loss is likely due to the reduction in photosynthetic area caused by leaf folder damage, which affects photosynthate availability and grain filling (Padmavathi et al., 2013).

The moderately resistant genotypes identified in this study, particularly those with high yield potential such as GRH-2, GNR-3, and GNR-5, are promising candidates for use in breeding programmes. Their utilization could contribute to the development of leaf-folder-resistant rice varieties and support integrated pest management (IPM) strategies. However, the mechanisms underlying the observed resistance need further investigation, including biochemical factors such as silica content, total phenols, and other secondary metabolites that may contribute to resistance.

V. CONCLUSION

The rice genotypes viz., Kala Namak, GNR-5, GNR-3, GRH-2, GNR-7, GR-15, GNRH-1, Mahsuri, GR-17, GNR-2 and NVSR-396 have been proved moderately resistant or least susceptible. Therefore, these genotypes could be utilized in further breeding programme. Their utilization could contribute to the development of leaf-folder-resistant rice varieties and support integrated pest management (IPM). Morphological traits associated with lower leaf folder infestation included longer plant height, more tillers, longer and thicker leaves, broader leaves, green leaf colour and late flowering. The highly significant negative correlation between plant height and infestation parameters suggests that plant height is an important morphological trait for resistance. Phyllotaxy showed no apparent effect on leaf folder infestation. Grain and straw yield exhibited highly significant negative correlations with per cent damaged leaves and larval population, confirming the impact of leaf folder infestation on yield. Thus, these resistant genotypes and associated morphological traits can be effectively utilized in breeding programmes for developing rice varieties with enhanced resistance to leaf folder.

Limitations of the Study: The study was conducted at a single location (Navsari, Gujarat) over two seasons. The genotype $\times$ environment interaction was not examined, and the mechanisms underlying the observed resistance were not investigated. Biochemical analysis (silica content, total phenols, etc.) was not performed. Future research should include multi-location trials, biochemical analysis, and investigation of the mechanisms of resistance (antixenosis, antibiosis, tolerance) in the identified moderately resistant genotypes.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Chemical and Biochemical Responses of Rice Genotypes against Rice Leaf Folder, *Cnaphalocrocis medinalis* Guenee

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Abstract— Investigations on impact of chemical constitution of leaves on per cent damaged leaves and number of larvae showed the highly significant positive correlation with nitrogen ($r=0.8899$ and 0.8768) and phosphorus ($r=0.7623$ and 0.7756 , respectively) content. However, per cent damaged leaves and number of larvae showed non-significant positive correlation with magnesium ($r=0.2699$ and 0.1999), sulphur ($r=0.1523$ and 0.0310), iron ($r=0.1322$ and 0.0338), and zinc ($r=0.3023$ and 0.3668 , respectively) contents. Whereas, per cent damaged leaves and number of larvae showed the highly significant negative correlation with potassium content ($r=-0.8240$ and -0.7937), non-significant negative correlation with calcium ($r=-0.3229$ and -0.3243), manganese ($r=-0.1946$ and -0.2801) and copper ($r=-0.1248$ and -0.0751 , respectively) contents. The results on biochemical constitution of leaves of test genotypes revealed that per cent damaged leaves and number of larvae showed the highly significant positive correlation with crude protein ($r=0.9025$ and 0.8838), total chlorophyll ($r=0.8749$ and 0.8234), total soluble sugar ($r=0.8338$ and 0.8163) and moisture ($r=0.5263$ and 0.5534 , respectively) content.

Keywords— Rice, Screening, Chemical, Biochemical, Resistance, Leaf folder, *Cnaphalocrocis medinalis*.

I. INTRODUCTION

Rice (*Oryza sativa* L.) belongs to the family Poaceae and is one of the most important cereal crops worldwide. It serves as a staple food for more than two billion people, particularly in developing countries, where it plays a vital role in food security, nutrition, employment and rural livelihoods (Appala et al., 2018). Rice is grown over 120 million hectares to produce 600 million tonnes of grain with an average productivity of 5000 kg/ha (Jakarpong and Wiboon, 2017). In India, farmers grow many kinds of cereals, among them rice is grown in 43.86 million hectares, the production level is 112 million tonnes and the average productivity is about 2600 kg/ha. Rice is grown in almost all the states in the country. The insect-pest incidence is one of the major constraints for crop failure due to outbreaks of insect-pests have been reported worldwide (Reddy, 2013). Among various pests of rice, rice leaf folder is one of the most serious and most important pest of rice crop in Indian subcontinent.

It was earlier considered a minor pest but now a days it assumed major pest status. The shift in pest status is mainly attributed to changes in crop management practices, increased insecticides applications and weather parameters (Chakraborty and Deb, 2011). According to Bhanu and Reddy (2008), in favorable conditions leaf folder affected crop adversely resulting in severe loss in India. The loss may extend up to 63 to 80 per cent depending on agro-ecological situations as reported by Rajendran et al. (1986). Host plant resistance is an important component of integrated pest management (IPM) for sustainable rice production. Understanding the chemical and biochemical basis of resistance can facilitate the development of resistant varieties, thereby reducing dependence on chemical insecticides. The present study was therefore undertaken to investigate the chemical and biochemical basis of resistance in rice genotypes against rice leaf folder.

II. MATERIALS AND METHODS

The field and laboratory investigations on screening of rice genotypes, chemical and biochemical basis of resistance against leaf folder was carried out at Main Rice Research Centre and PG Research Laboratory, Dept. of Agricultural Chemistry and Soil Science, Navsari Agricultural University, Navsari, Gujarat during *Kharif* 2020 and 2021. Twenty-three rice genotypes viz., NAUR-1, GNR-2, GNR-3, GNR-4, GNR-5, GNR-6, GNR-7, IR-28, NVSR-392, NVSR-395, NVSR-396, GNRH-1, GR-15, GR-17, Mahsuri, GR-101, Krishna Kamod, GAR-13, Kala Namak, Chittimuthyalu and GRH-2. Along with state susceptible GR-11 and national susceptible check TN-1 were transplanted for screening against leaf folder. The experiment was laid out in a randomized completely block design with twenty three treatments and two replications. Each entry was planted in five rows of 1.95 meter length with a spacing 20 × 15 cm. Recommended agronomical practices of manure and fertilizer dose @ FYM: 10 tonnes/ha and N-P-K: 100-30-00 kg/ha was applied. No plant protection measures were provided to create optimum conditions for pest multiplication.

The observations of per cent leaf damage and numbers of larvae were recorded at 7th days after the commencement of pest appearance. From each genotype, 10 hills were selected randomly from each replication. Observations were recorded by counting the total number of larvae, leaves per 10 hills and total number of damaged leaves (Only if one-third of leaf area is damaged) per 10 hills. Thereafter, all the observations were recorded regularly at an interval of 15 days up to the harvest of crop. The highest per cent damaged leaves were taken for final interpretation. Per cent leaf damage was calculated by following formula given by Netam and Gupta (2015).

$$\text{Leaf damage (\%)} = \frac{\text{Total number of damaged leaves}}{\text{Total number of leaves (Healthy + Damaged)}} \times 100 \quad (1)$$

2.1 Categorization of Rice Genotypes on the Basis of Damaged Leaves

Categorization of rice genotypes on the basis of damaged leaves was done by using Standard Evaluation System (SES, 2013) developed by IIRR for estimating relative resistance/susceptibility. The rice genotypes were categorized based on the percentage of damaged leaves using a 0-9 scale. A scale of 0 (no damage) was classified as highly resistant/immune, while 1 (1-10% damaged leaves) was categorized as resistant. A scale of 3 (11-20%) was considered moderately resistant, whereas 5 (21-35%) was classified as moderately susceptible. A scale of 7 (36-50%) was categorized as susceptible and a scale of 9 (51-100%) was considered highly susceptible.

2.2 Study of Chemical and Biochemical Basis of Resistance in Rice Genotypes against Rice Leaf Folder

In the present investigation, the third leaf from the apex was randomly collected from ten plants of each genotype in each replication at the peak incidence of rice leaf folder. The genotypes were evaluated for resistance or susceptibility based on the percentage of damaged leaves. The collected leaf samples were further analyzed for their chemical and biochemical constituents to determine their association with resistance to rice leaf folder. Plant samples were digested separately for the estimation of nitrogen and other nutrient elements following the method suggested by Bhargava and Raghupathi (1993).

2.2.1 Chemical Constituents of Resistance

Estimation of chemical constituents of rice were determine as per method suggested by following authors.

Nutrient	Procedure	Author
Nitrogen	Micro-kjeldahl's method	Kjeldahl (1883)
Phosphorus	Vanadomolybdo phosphoric yellow colour	Jackson (1973)
Potassium	Flame photometric method	Jackson (1973)
Ca and Mg	E. D. T. A. method	Jackson (1973)
Sulphur	Turbidimetric method	Tabatabai and Bremner (1970)
Iron, Manganese, Zinc and Copper	Atomic absorption spectrophotometric method	Jackson (1973)

2.2.2 Biochemical Constituents of Resistance

- **Crude Protein (%):** Crude Protein equation to work out per cent protein content separately: "% Protein = % N × 6.25."

- **Total Phenol (mg/g):** Total phenol content in the leaf samples was estimated by the method described by Malik and Singh (1980).
- **Total Chlorophyll (mg/g):** Total chlorophyll content in the leaves was estimated using the dimethyl sulphoxide (DMSO) method described by Hiscox and Israelstam (1979).
- **Total Soluble Sugar (mg/g):** Total soluble sugar content was estimated using the phenol–sulphuric acid method as described by Bhatnagar et al. (2006).
- **Silica (%):** Silica content in the leaves of each rice genotype was estimated following the procedure described by Jackson (1967).
- **Moisture Content (%):** The moisture content of the leaf samples was determined by the method described by Bhargava and Raghupathi (1993).
- **Ash Content (%):** Weight about 10 g of powder in to crucible. Heated it with burner, using a flame about 2 cm high and support a crucible. About 7 cm above the flame heated till vapor almost cease to be evolved, then lower the dish and heat more strongly until all the carbon is burnt off. Cool the ash and weight ash and calculate the per cent of total ash.
- **Calculation:** Weight of empty dish = X, Weight of sample taken = Y, Weight of dish + Ash = Z and Weight of ash = (Z-X) gm.



Plate 1: Flame photometer



Plate 2: Spectrophotometer



Plate 3: Atomic absorption spectrophotometer



Plate 4: Nitrogen digestion and distillation system



III. RESULTS AND DISCUSSION

3.1 Resistance Based on Chemical Content

3.1.1 Nitrogen content (%)

Nitrogen content among the rice genotypes ranged from 0.25 to 0.45%, with an average of 0.34%. TN-1 recorded the highest nitrogen content (0.45%) which was at par with GNR-4 and GR-11 (0.40%), while Kala Namak recorded the lowest (0.25%), at par with GRH-2 (0.29%). Moderately susceptible genotypes generally had higher nitrogen content (0.34–0.38%), whereas moderately resistant genotypes had lower levels (0.25–0.33%). Nitrogen content showed highly significant positive correlations with damaged leaves ($r=0.8899$) and larval population ($r=0.8768$). This suggests that higher nitrogen content in leaves may provide better nutrition for the larvae, leading to higher infestation. Nitrogen is a key nutrient for insect growth and development, and higher nitrogen content in plant tissues is often associated with increased herbivory.

3.1.2 Phosphorus content (%)

Phosphorus content showed limited variation in relation to leaf folder damage. The highest phosphorus content was recorded in TN-1 (0.21%) which was at par with GR-11 (0.19%) and NAUR-1 (0.18%), while the lowest was observed in GR-17 (0.06%) followed by GNR-5, GNR-7 and NVSR-396 (0.07–0.09%). Moderately resistant genotypes had lower phosphorus content (0.06–0.14%) than moderately susceptible genotypes (0.14–0.18%). Phosphorus content exhibited highly significant positive correlations with damaged leaves ($r=0.7623$) and larval population ($r=0.7756$), indicating that higher phosphorus content was associated with greater leaf folder infestation.

Overall, both nitrogen and phosphorus contents exhibited highly significant positive correlations with leaf folder infestation, indicating that genotypes with higher nitrogen and phosphorus contents generally tended to support greater leaf damage and larval population. In contrast, moderately resistant genotypes generally possessed comparatively lower nitrogen and phosphorus contents. This may be due to the role of nitrogen and phosphorus as essential nutrients for insect growth and development.

3.1.3 Potassium content (%)

Potassium content ranged from 1.05 to 2.40%, with an average of 1.84%. The highest potassium content was recorded in Kala Namak (2.40%), while the lowest was observed in TN-1 (1.05%). Susceptible, moderately susceptible and moderately resistant genotypes showed potassium contents of 1.15–1.22, 1.54–1.92 and 1.80–2.40%, respectively. Potassium content exhibited highly significant negative correlations with damaged leaves ($r=-0.8240$) and larval population ($r=-0.7937$). Higher potassium content may contribute to resistance by improving plant vigour and stress tolerance, or by affecting the nutritional quality of leaves for insect herbivores.

3.1.4 Calcium content (%)

Calcium content was highest in NAUR-1 (0.36%) and lowest in GRH-2 and GR-11 (0.10%). Calcium showed a non-significant negative correlation with damaged leaves ($r=-0.3229$) and larval population ($r=-0.3243$).

3.1.5 Magnesium content (%)

Magnesium content was highest in GNR-7 (0.68%) and lowest in Mahsuri (0.28%). It showed a non-significant positive correlation with damaged leaves ($r=0.2699$) and larval population ($r=0.1999$).

3.1.6 Sulphur content (%)

Sulphur content ranged from 0.02 to 0.19%, with the highest in GNR-4 (0.19%) and the lowest in several moderately resistant genotypes (0.02%). Sulphur showed a non-significant positive correlation with damaged leaves ($r=0.1523$) and larval population ($r=0.0310$).

3.1.7 Iron content (%)

Iron content was highest in GNR-4 (0.059%) and lowest in GNR-3 (0.018%). It showed a non-significant positive correlation with damaged leaves ($r=0.1322$) and larval population ($r=0.0338$).

3.1.8 Manganese content (%)

Manganese content was highest in GNR-2 (0.077%) and lowest in Chittimuthyalu (0.025%). It showed a non-significant negative correlation with damaged leaves ($r=-0.1946$) and larval population ($r=-0.2801$).

3.1.9 Zinc content (ppm)

Zinc content was highest in GR-11 (44.00 ppm) and lowest in GNR-2 (10.75 ppm). Zinc showed a non-significant positive correlation with damaged leaves ($r=0.3023$) and larval population ($r=0.3668$).

3.1.10 Copper content (ppm)

Copper content was highest in GR-101 (16.05 ppm) and lowest in NVSR-396 (6.80 ppm). Moderately resistant genotypes had 6.80–12.85 ppm, while moderately susceptible genotypes had 8.50–16.05 ppm. Copper showed a non-significant negative correlation with damaged leaves ($r=-0.1248$) and larval population ($r=-0.0751$).

Overall, calcium, manganese and copper showed negative, while magnesium, sulphur, iron and zinc showed positive associations with leaf folder infestation; however, all correlations were non-significant. The non-significant correlations for secondary nutrients and micronutrients suggest that these elements may have limited direct influence on leaf folder resistance under the present experimental conditions, or that their effects may be masked by interactions with other factors. According to Chavan (2013), white earheads showed significant positive correlation with plant nitrogen and significant negative correlation with potassium content. Gajjar (2017) reported that nitrogen and phosphorous content had significant positive correlation and calcium, magnesium, sulphur, ferrous, manganese & zinc content showed non-significant positive correlation, while copper content showed non-significant negative correlation with per cent damaged leaves and number of larvae. But in case of calcium and manganese, these findings are in controversy with present findings due to different type genotype and environmental conditions prevailing during the study period. According to Ashrith et al. (2020), potassium content was significantly more with the resistant check TKM 6 (17.902 mg/g). Kumar et al. (2021) reported that the amount of nitrogen & phosphorous was recorded higher in the susceptible genotype, while potassium was found significantly higher in resistant genotypes.

TABLE 1

SCREENING OF RICE GENOTYPES ON THE BASIS OF PER CENT DAMAGED LEAVES AND NUMBER OF LARVAE
(KHARIF-2020, 2021 & POOLED)

SN	Genotype	Damaged leaves (%)			Number of larvae			Based on % DL	
		Kharif-2020	Kharif-2021	Pooled	Kharif-2020	Kharif-2021	Pooled	Scale	Reaction
1	GNR-6	28.34 (22.60)*	29.38 (24.12)*	28.86 (23.36)*	1.94 (3.30)#	2.01 (3.56)#	1.98 (3.43)#	5	MS
2	IR-28	30.36 (25.58)	31.35 (27.08)	30.86 (26.33)	2.13 (4.05)	2.16 (4.15)	2.14 (4.10)	5	MS
3	NVSR-392	34.20 (31.61)	35.09 (33.06)	34.65 (32.34)	2.29 (4.75)	2.31 (4.85)	2.30 (4.80)	5	MS
4	NVSR-395	33.93 (31.18)	34.81 (32.60)	34.37 (31.89)	2.26 (4.60)	2.29 (4.75)	2.27 (4.68)	5	MS
5	NVSR-396	25.61 (18.73)	26.52 (19.96)	26.07 (19.34)	1.83 (2.85)	1.95 (3.30)	1.89 (3.08)	3	MR
6	GNRH-1	23.34 (15.76)	24.70 (17.49)	24.03 (16.62)	1.70 (2.40)	1.76 (2.60)	1.73 (2.50)	3	MR
7	NAUR-1	28.82 (23.31)	29.64 (24.51)	29.23 (23.91)	2.14 (4.10)	2.11 (3.95)	2.13 (4.03)	5	MS
8	GNR-2	25.31 (18.35)	26.26 (19.68)	25.79 (19.02)	1.81 (2.80)	1.86 (2.95)	1.83 (2.88)	3	MR
9	GNR-3	20.58 (12.41)	22.23 (14.41)	21.42 (13.41)	1.63 (2.15)	1.68 (2.35)	1.65 (2.25)	3	MR
10	GNR-5	20.96 (12.86)	21.97 (14.04)	21.47 (13.45)	1.64 (2.20)	1.71 (2.45)	1.68 (2.33)	3	MR
11	GNR-7	21.67 (13.65)	22.92 (15.22)	22.30 (14.43)	1.61 (2.10)	1.74 (2.55)	1.68 (2.33)	3	MR
12	GR-15	23.05 (15.36)	24.08 (16.69)	23.57 (16.02)	1.70 (2.40)	1.88 (3.05)	1.79 (2.73)	3	MR
13	GR-17	23.82 (16.35)	24.63 (17.43)	24.23 (16.89)	1.79 (2.70)	1.87 (3.00)	1.83 (2.85)	3	MR
14	Mahsuri	23.37 (15.84)	24.42 (17.21)	23.90 (16.52)	1.79 (2.70)	1.83 (2.85)	1.81 (2.78)	3	MR
15	GNR-4	37.16 (36.61)	38.02 (38.02)	37.59 (37.32)	2.28 (4.70)	2.21 (4.40)	2.25 (4.55)	7	S
16	GR-101	29.96 (24.95)	31.55 (27.39)	30.76 (26.17)	2.07 (3.85)	2.14 (4.10)	2.11 (3.98)	5	MS
17	Krishna Kamod	30.21 (25.47)	31.51 (27.46)	30.87 (26.47)	2.21 (4.40)	2.20 (4.35)	2.21 (4.38)	5	MS
18	GAR-13	28.41 (22.67)	29.50 (24.29)	28.96 (23.48)	2.10 (3.90)	2.12 (4.00)	2.11 (3.95)	5	MS
19	Kala Namak	19.77 (11.47)	21.23 (13.17)	20.51 (12.32)	1.61 (2.10)	1.67 (2.30)	1.64 (2.20)	3	MR
20	Chittimuthyalu	28.76 (23.20)	30.25 (25.42)	29.51 (24.31)	2.13 (4.05)	2.14 (4.10)	2.14 (4.08)	5	MS
21	GRH-2	21.34 (13.28)	22.40 (14.57)	21.87 (13.92)	1.63 (2.15)	1.76 (2.60)	1.69 (2.38)	3	MR
22	GR-11	38.03 (38.00)	39.36 (40.22)	38.70 (39.11)	2.57 (6.10)	2.75 (7.05)	2.66 (6.58)	7	S
23	TN-1	47.07 (53.59)	48.54 (56.13)	47.80 (54.86)	2.69 (6.75)	2.90 (7.90)	2.80 (7.33)	9	HS
S. Em. ±		1.86	1.9	1.87	0.09	0.1	0.09	-	-
C.D. at 5%		5.45	5.57	5.47	0.27	0.29	0.25	-	-
C.V. (%)		9.38	9.21	9.24	6.63	6.74	6.03	-	-

Figures in the parentheses are original values, while those outside are arcsine transformed values.

#Figures in the parentheses are original values, while those outside are square root ($\sqrt{X+0.5}$) transformed values.

% DL: % Damaged leaves, MR: Moderately Resistant, MS: Moderately Susceptible, S: Susceptible and HS: Highly Susceptible

3.2 Resistance Based on Biochemical Content

3.2.1 Crude protein (%)

Crude protein content ranged from 1.59 to 2.84%, with the highest in TN-1 (2.84%) and lowest in Kala Namak (1.59%). It showed highly significant positive correlations with damaged leaves ($r=0.9025$) and larval population ($r=0.8838$). Higher protein content in leaves may provide better nutrition for the larvae, supporting their growth and development, leading to higher infestation.

3.2.2 Total phenol (mg/g)

Phenol content was highest in Kala Namak (2.21 mg/g) and lowest in TN-1 (1.69 mg/g). It exhibited highly significant negative correlations with damaged leaves ($r=-0.7706$) and larval population ($r=-0.7675$), indicating higher phenol content was associated with lower infestation. Phenols are known to act as feeding deterrents and antimicrobial compounds, contributing to plant defense against herbivores.

3.2.3 Total chlorophyll (mg/g)

Chlorophyll content ranged from 2.56 to 5.33 mg/g, with the highest in GNR-4 (5.33 mg/g) and lowest in GNR-7 (2.56 mg/g). It showed highly significant positive correlations with damaged leaves ($r=0.8749$) and larval population ($r=0.8234$). Higher chlorophyll content may indicate better plant vigour and nutrition, which may attract more herbivores or support better larval development.

3.2.4 Total soluble sugar (mg/g)

Sugar content ranged from 0.70 to 2.12 mg/g, with the highest in TN-1 (2.12 mg/g) and lowest in Kala Namak (0.70 mg/g). It showed highly significant positive correlations with damaged leaves ($r=0.8338$) and larval population ($r=0.8163$). Higher sugar content may provide a readily available energy source for larvae, increasing their survival and development.

3.2.5 Silica (%)

Silica content ranged from 3.04 to 4.58%, with the highest in Kala Namak (4.58%) and lowest in TN-1 (3.04%). Silica exhibited highly significant negative correlations with damaged leaves ($r=-0.8765$) and larval population ($r=-0.8547$), indicating its possible role in resistance. Silica acts as a physical barrier, increasing leaf toughness and reducing digestibility for herbivores.

3.2.6 Moisture content (%)

Moisture content was highest in TN-1 (59.45%) and lowest in GNR-2 (45.73%). It showed highly significant positive correlations with damaged leaves ($r=0.5263$) and larval population ($r=0.5534$). Higher moisture content may indicate better plant vigour and succulence, which may be more attractive to herbivores.

3.2.7 Ash content (%)

Ash content ranged from 5.17 to 10.07%, with the highest in GR-17 (10.07%) and lowest in IR-28 (5.17%). It showed a significant negative correlation with damaged leaves ($r=-0.4266$) and a non-significant negative correlation with larval population ($r=-0.3851$).

Overall, higher protein, chlorophyll, sugar and moisture contents were associated with greater leaf folder infestation, whereas higher phenol and silica contents were associated with reduced infestation. These findings agree with earlier reports highlighting the role of phenols and silica in rice resistance to leaf folder. Chavan (2013) reported a significant positive correlation between protein content and white earheads, while total phenol showed a significant negative correlation. Padmavathi et al. (2013) observed that leaf folder injury reduced chlorophyll and photosynthate availability, affecting water relations and increasing yield loss. Han et al. (2015) reported higher silicon content in leaf folder resistant rice varieties. Gajjar (2017) found that protein, chlorophyll and sugar were positively correlated, whereas phenol and silica were negatively correlated with leaf damage and larval population. Patel et al. (2017) reported silica content in rice straw ranging from 3.52 to 9.80% in Middle Gujarat. Ashrith et al. (2020) observed higher silicon and phenol contents in resistant genotypes and higher total sugar in susceptible genotypes. Tang et al. (2020) reported that fresh rice straw may contain up to 65.45% moisture.

TABLE 2
EFFECT OF NITROGEN, PHOSPHORUS, POTASSIUM, CALCIUM AND MAGNESIUM CONTENT OF RICE
GENOTYPES ON LEAF FOLDER INFESTATION

S. No.	Genotype	Nitrogen (%)	Phosphorus (%)	Potassium (%)	Calcium (%)	Magnesium (%)	Damaged leaves (%)	Number of larvae	Reaction (% DL)
1	GNR-6	0.36	0.14	1.54	0.27	0.47	23.36	3.43	MS
2	IR-28	0.37	0.15	1.8	0.17	0.51	26.33	4.1	MS
3	NVSR-392	0.38	0.14	1.85	0.13	0.51	32.34	4.8	MS
4	NVSR-395	0.35	0.14	1.88	0.12	0.43	31.89	4.68	MS
5	NVSR-396	0.3	0.09	2.19	0.29	0.4	19.34	3.08	MR
6	GNRH-1	0.31	0.13	1.91	0.14	0.41	16.62	2.5	MR
7	NAUR-1	0.37	0.18	1.81	0.36	0.43	23.91	4.03	MS
8	GNR-2	0.31	0.12	2	0.17	0.37	19.02	2.88	MR
9	GNR-3	0.32	0.11	2.05	0.18	0.44	13.41	2.25	MR
10	GNR-5	0.33	0.07	1.94	0.13	0.4	13.45	2.33	MR
11	GNR-7	0.32	0.07	1.95	0.23	0.68	14.43	2.33	MR
12	GR-15	0.31	0.13	2.33	0.28	0.6	16.02	2.73	MR
13	GR-17	0.33	0.06	1.94	0.22	0.39	16.89	2.85	MR
14	Mahsuri	0.31	0.13	2.17	0.13	0.28	16.52	2.78	MR
15	GNR-4	0.4	0.17	1.22	0.18	0.55	37.32	4.55	S
16	GR-101	0.34	0.14	1.68	0.14	0.41	26.17	3.98	MS
17	Krishna Kamod	0.34	0.14	1.92	0.12	0.4	26.47	4.38	MS
18	GAR-13	0.35	0.15	1.83	0.15	0.3	23.48	3.95	MS
19	Kala Namak	0.25	0.11	2.4	0.21	0.49	12.32	2.2	MR
20	Chittimuthyalu	0.38	0.14	1.63	0.21	0.3	24.31	4.08	MS
21	GRH-2	0.29	0.14	1.8	0.1	0.45	13.92	2.38	MR
22	GR-11	0.4	0.19	1.15	0.1	0.53	39.11	6.58	S
23	TN-1	0.45	0.21	1.05	0.11	0.57	54.86	7.33	HS
GM		0.34	0.14	1.82	0.18	0.45	23.54	3.66	-
S. Em. ±		0.01	0.01	0.06	0.01	0.03	2.82	0.34	-
C.D. at 5 %		0.04	0.03	0.16	0.03	0.08	8.28	0.98	-
C.V. (%)		6.11	9.57	4.3	9.13	8.74	16.95	12.97	-
Corr. coefficient (r) of Nitrogen (%)		-	-	-	-		0.8899**	0.8768**	-
Corr. coefficient (r) of Phosphorus (%)		-	-	-	-		0.7623**	0.7756**	-
Corr. coefficient (r) of Potassium (%)		-	-	-	-		-0.8240**	-0.7937**	-
Corr. coefficient (r) of Calcium (%)		-	-	-	-		-0.3229 ^{NS}	-0.3243 ^{NS}	-
Corr. coefficient (r) of Magnesium (%)		-	-	-	-		0.2699 ^{NS}	0.1999 ^{NS}	-

MR: Moderately Resistant, MS: Moderately Susceptible, S: Susceptible and HS: Highly Susceptible

TABLE 3
EFFECT OF SULPHUR, IRON, MANGANESE, ZINC AND COPPER CONTENT OF RICE GENOTYPES ON LEAF FOLDER INFESTATION

SN	Genotype	Sulphur (%)	Iron (%)	Manganese (%)	Zinc (ppm)	Copper (ppm)	Damaged leaves (%)	Number of larvae	Reaction (% DL)
1	GNR-6	0.36	0.052	0.048	34.25	8.7	23.36	3.43	MS
2	IR-28	0.06	0.049	0.054	33	11.3	26.33	4.1	MS
3	NVSR-392	0.04	0.051	0.05	22.95	8.5	32.34	4.8	MS
4	NVSR-395	0.03	0.035	0.065	30.05	8.65	31.89	4.68	MS
5	NVSR-396	0.03	0.051	0.063	18.4	6.8	19.34	3.08	MR
6	GNRH-1	0.08	0.051	0.071	19.5	10.6	16.62	2.5	MR
7	NAUR-1	0.09	0.031	0.07	11.45	10.35	23.91	4.03	MS
8	GNR-2	0.06	0.035	0.077	10.75	12.85	19.02	2.88	MR
9	GNR-3	0.03	0.018	0.075	11.8	7.7	13.41	2.25	MR
10	GNR-5	0.03	0.038	0.068	43.35	10.6	13.45	2.33	MR
11	GNR-7	0.08	0.021	0.064	27.2	8.8	14.43	2.33	MR
12	GR-15	0.08	0.023	0.053	20.95	9.45	16.02	2.73	MR
13	GR-17	0.04	0.034	0.07	24.95	11.5	16.89	2.85	MR
14	Mahsuri	0.03	0.03	0.059	25.8	8.7	16.52	2.78	MR
15	GNR-4	0.06	0.059	0.064	27.9	6.86	37.32	4.55	S
16	GR-101	0.19	0.045	0.044	27.05	16.05	26.17	3.98	MS
17	Krishna Kamod	0.02	0.042	0.051	36.15	8.75	26.47	4.38	MS
18	GAR-13	0.11	0.027	0.048	30.1	12	23.48	3.95	MS
19	Kala Namak	0.02	0.037	0.056	28.95	8.65	12.32	2.2	MR
20	Chittimuthyalu	0.02	0.025	0.025	35.85	10.6	24.31	4.08	MS
21	GRH-2	0.02	0.024	0.051	33.65	8.6	13.92	2.38	MR
22	GR-11	0.02	0.024	0.052	44	8.8	39.11	6.58	S
23	TN-1	0.04	0.022	0.06	32.85	8.55	54.86	7.33	HS
GM		0.05	0.04	0.06	27.43	0.45	9.71	3.66	-
S. Em. ±		0.01	0	0	1.41	0.03	0.39	0.34	-
C.D. at 5%		0.01	0.01	0.01	4.12	0.08	1.15	0.98	-
C.V. (%)		13.92	10.42	9.19	7.24	8.74	5.71	12.97	-
Corr. coefficient (r) of Sulphur (%)		-	-	-	-		0.1523 ^{NS}	0.0310 ^{NS}	-
Corr. coefficient (r) of Iron (%)		-	-	-	-		0.1322 ^{NS}	0.0338 ^{NS}	-
Corr. coefficient (r) of Manganese (%)		-	-	-	-		-0.1946 ^{NS}	-0.2801 ^{NS}	-
Corr. coefficient (r) of Zinc (%)		-	-	-	-		0.3023 ^{NS}	0.3668 ^{NS}	-
Corr. coefficient (r) of Copper (%)		-	-	-	-		-0.1248 ^{NS}	-0.0751 ^{NS}	-

MR: Moderately Resistant, MS: Moderately Susceptible, S: Susceptible and HS: Highly Susceptible

TABLE 4
EFFECT OF CRUDE PROTEIN, TOTAL PHENOL AND TOTAL CHLOROPHYLL CONTENT OF RICE GENOTYPES
ON LEAF FOLDER INFESTATION

SN	Genotype	Crude protein (%)	Total phenol (mg/g)	Total chlorophyll (mg/g)	Damaged Leaves (%)	Number of larvae	Reaction (% DL)
1	GNR-6	2.22	1.97	3.74	23.36	3.43	MS
2	IR-28	2.3	1.91	4.28	26.33	4.1	MS
3	NVSR-392	2.37	1.7	4.74	32.34	4.8	MS
4	NVSR-395	2.21	1.86	4.62	31.89	4.68	MS
5	NVSR-396	1.86	1.86	3.39	19.34	3.08	MR
6	GNRH-1	1.95	1.95	3.95	16.62	2.5	MR
7	NAUR-1	2.34	1.94	3.85	23.91	4.03	MS
8	GNR-2	1.96	1.86	3.51	19.02	2.88	MR
9	GNR-3	2.01	2.14	2.67	13.41	2.25	MR
10	GNR-5	2.04	2.16	2.73	13.45	2.33	MR
11	GNR-7	1.98	2	2.56	14.43	2.33	MR
12	GR-15	1.94	1.87	2.95	16.02	2.73	MR
13	GR-17	2.07	1.96	3.06	16.89	2.85	MR
14	Mahsuri	1.92	1.93	2.91	16.52	2.78	MR
15	GNR-4	2.5	1.86	5.33	37.32	4.55	S
16	GR-101	2.12	1.91	4.22	26.17	3.98	MS
17	Krishna Kamod	2.11	1.91	4.11	26.47	4.38	MS
18	GAR-13	2.16	1.95	3.6	23.48	3.95	MS
19	Kala Namak	1.59	2.21	3.57	12.32	2.2	MR
20	Chittimuthyalu	2.35	1.94	3.92	24.31	4.08	MS
21	GRH-2	1.83	2	2.73	13.92	2.38	MR
22	GR-11	2.48	1.75	4.48	39.11	6.58	S
23	TN-1	2.84	1.69	5.17	54.86	7.33	HS
GM		2.14	1.92	3.74	23.54	3.66	-
S. Em. ±		0.09	0.07	0.18	2.82	0.34	-
C.D. at 5%		0.27	0.21	0.53	8.28	0.98	-
C.V. (%)		6.11	5.16	6.83	16.95	12.97	-
Correlation coefficient (r) of Crude protein (%)		-	-		0.9025**	0.8838**	-
Correlation coefficient (r) of Total Phenol (mg/g)		-	-		-0.7706**	-0.7675**	-
Correlation coefficient (r) of Total Chlorophyll (mg/g)		-	-		0.8749**	0.8234**	-

MR: Moderately Resistant, MS: Moderately Susceptible, S: Susceptible and HS: Highly Susceptible

TABLE 5
EFFECT OF TOTAL SOLUBLE SUGAR, SILICA, MOISTURE AND ASH CONTENT OF RICE GENOTYPES ON LEAF FOLDER INFESTATION

SN	Genotype	Total soluble sugar (mg/g)	Silica (%)	Moisture (%)	Ash (%)	Damaged Leaves (%)	Number of larvae	Reaction (% DL)
1	GNR-6	1.16	3.87	48.32	6.98	23.36	3.43	MS
2	IR-28	1.32	3.8	54.31	5.17	26.33	4.1	MS
3	NVSR-392	1.61	3.59	56.79	7.01	32.34	4.8	MS
4	NVSR-395	1.6	3.8	51.62	5.88	31.89	4.68	MS
5	NVSR-396	1.04	3.81	49.62	6.9	19.34	3.08	MR
6	GNRH-1	0.88	3.83	46.05	8.43	16.62	2.5	MR
7	NAUR-1	1.11	3.74	55.43	6.12	23.91	4.03	MS
8	GNR-2	1.07	3.76	45.73	6.16	19.02	2.88	MR
9	GNR-3	0.91	4.19	53.22	9.84	13.41	2.25	MR
10	GNR-5	0.83	4.11	54.64	8.52	13.45	2.33	MR
11	GNR-7	0.99	4.18	56.57	6.05	14.43	2.33	MR
12	GR-15	0.82	3.88	51.62	5.67	16.02	2.73	MR
13	GR-17	1.03	3.9	46.07	10.07	16.89	2.85	MR
14	Mahsuri	1.96	3.98	49.2	7.06	16.52	2.78	MR
15	GNR-4	1.86	3.57	56.71	6.44	37.32	4.55	S
16	GR-101	1.33	3.78	52.19	8.14	26.17	3.98	MS
17	Krishna Kamod	1.33	3.68	52.61	8.01	26.47	4.38	MS
18	GAR-13	1.18	3.98	54.89	6.12	23.48	3.95	MS
19	Kala Namak	0.7	4.58	55.2	9.2	12.32	2.2	MR
20	Chittimuthyalu	1.22	4.01	56.33	8.87	24.31	4.08	MS
21	GRH-2	0.75	4.06	51.8	8.92	13.92	2.38	MR
22	GR-11	1.96	3.39	57.64	7.62	39.11	6.58	S
23	TN-1	2.12	3.04	59.45	5.8	54.86	7.33	HS
GM		1.25	3.85	52.87	7.35	23.54	3.66	-
S. Em. ±		0.08	0.12	1.52	0.4	2.82	0.34	-
C.D. at 5%		0.25	0.34	4.47	1.17	8.28	0.98	-
C.V. (%)		9.46	4.28	4.07	7.68	16.95	12.97	-
Correlation coefficient (r) of TSS (mg/g)		-	-			0.8338**	0.8163**	-
Correlation coefficient (r) of Silica (%)		-	-			-0.8765**	-0.8547**	-
Correlation coefficient (r) of Total Moisture (%)		-	-			0.5263**	0.5534**	-
Correlation coefficient (r) of Ash (%)		-	-			-0.4266*	-0.3851NS	-

MR: Moderately Resistant, MS: Moderately Susceptible, S: Susceptible and HS: Highly Susceptible

IV. DISCUSSION

The results of the present investigation reveal that certain chemical and biochemical constituents of rice leaves are significantly associated with resistance or susceptibility to leaf folder infestation. The highly significant positive correlations of nitrogen and phosphorus with infestation parameters ($r=0.8899$ and 0.7623 , respectively) indicate that genotypes with higher levels of these nutrients tend to support greater leaf damage and larval populations. This is consistent with the general understanding that nitrogen and phosphorus are essential nutrients for insect growth and development, and higher concentrations in plant tissues may enhance insect performance (Kumar et al., 2021). Conversely, the highly significant negative correlation of potassium with infestation ($r=-0.8240$) suggests that higher potassium content may contribute to resistance, possibly by improving plant vigour and stress tolerance or by affecting the nutritional quality of leaves (Ashrith et al., 2020).

Among biochemical parameters, the highly significant positive correlations of crude protein ($r=0.9025$), chlorophyll ($r=0.8749$), and total soluble sugar ($r=0.8338$) with infestation indicate that higher levels of these constituents are associated with increased susceptibility. This may be because these compounds provide essential nutrients and energy sources for the larvae, supporting their growth and development (Gajjar, 2017). In contrast, the highly significant negative correlations of total phenol ($r=-0.7706$) and silica ($r=-0.8765$) with infestation suggest that these compounds play a crucial role in resistance. Phenols are known to act as feeding deterrents and antimicrobial compounds, while silica acts as a physical barrier, increasing leaf toughness and reducing digestibility (Han et al., 2015; Ashrith et al., 2020).

The non-significant correlations observed for secondary nutrients (Ca, Mg, S) and micronutrients (Fe, Mn, Zn, Cu) suggest that these elements may have limited direct influence on leaf folder resistance under the present experimental conditions. This may be due to their relatively low concentrations in plant tissues or interactions with other factors that mask their effects. However, the role of these nutrients in plant defense cannot be completely ruled out, as they may contribute to resistance indirectly by influencing plant health and vigour.

The moderately resistant genotypes identified in the companion screening study (Kala Namak, GNR-5, GNR-3, GRH-2, etc.) generally exhibited lower nitrogen and phosphorus, higher potassium, higher phenol, and higher silica contents compared to susceptible genotypes. This suggests that these biochemical markers could be useful for screening and selecting rice genotypes with enhanced resistance to leaf folder. The consistent performance of these genotypes across two seasons indicates stable resistance, which is desirable for breeding purposes.

V. CONCLUSION

The rice genotypes Kala Namak, GNR-5, GNR-3, GRH-2, GNR-7, GR-15, GNRH-1, Mahsuri, GR-17, GNR-2 and NVSR-396 were identified as moderately resistant or least susceptible to rice leaf folder. These genotypes can serve as valuable resistance sources in breeding programmes for developing leaf folder-resistant varieties and strengthening integrated pest management (IPM). Biochemical and nutritional constituents were closely associated with rice leaf folder resistance. Higher nitrogen, phosphorus, crude protein, chlorophyll, soluble sugar and moisture contents were generally associated with greater leaf damage and larval population, whereas higher potassium, phenol and silica contents were associated with reduced infestation. Secondary nutrients and micronutrients showed mostly non-significant relationships with leaf folder infestation, indicating their comparatively limited contribution under the present conditions. Thus, lower N and P and higher K, phenol and silica contents may serve as useful biochemical indicators for identifying and screening leaf folder-resistant rice genotypes.

Limitations of the Study: The study was conducted at a single location (Navsari, Gujarat) over two seasons. The biochemical correlations are associative rather than causal, and the mechanisms underlying the observed associations were not investigated. Future research should include multi-location trials, mechanistic studies (e.g., antixenosis, antibiosis, tolerance), and investigation of the genetic basis of the biochemical traits associated with resistance.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Revitalizing Soil Quality using Vermicompost at St. Philomena's (Autonomous) College Campus, Bannimantap, Mysore, Karnataka

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Abstract— Soil quality is a crucial determinant of agricultural productivity and ecosystem sustainability. This study investigates the role of vermicompost as an effective amendment for revitalizing soil quality at St. Philomena's College (Autonomous) Mysore, focusing on its effects on physicochemical properties, biological activity and overall soil health. Vermicompost is the product of organic waste processing by earthworms, resulting in a nutrient-rich material that enhances soil structure, fertility and microbial diversity. Field experiments were conducted across diverse agro-ecosystems within the college's agricultural research facilities to assess the impact of varying vermicompost application rates on soil characteristics and plant growth. Key parameters measured included soil pH, organic matter content, nutrient availability (nitrogen, phosphorus, potassium), microbial biomass, and plant growth metrics such as height, biomass. The results indicated significant improvements in soil structure, with increased aggregation and porosity, which facilitated enhanced water retention and aeration. Notably, vermicompost application led to a marked increase in organic matter levels, providing a sustained release of essential nutrients over time. Additionally, the combination of vermicompost with other organic amendments significantly increased plant growth parameters. For instance, studies have shown that vermicompost can enhance plant height by up to 26% and total biomass by 13% compared to controls. The study also highlights the potential of vermicompost not only to ameliorate degraded soils but also to serve as a viable strategy for organic waste management. This study emphasizes the importance of integrating vermicompost into soil management regimes at St. Philomena's College to promote long-term soil health, enhance agricultural productivity including significant increases in plant growth and mitigate environmental impacts from conventional farming practices. Overall, vermicompost emerges as a multifaceted solution for revitalizing soil quality and improving plant growth, underscoring the need for broader adoption in modern agricultural systems.

Keywords— Revitalization, Vermicompost, mitigation, pH, Organic material.

I. INTRODUCTION

Soil is a complex mixture of organic matter, minerals, gases, liquids, and organisms that together support the life of plants and soil organisms. It consists of a solid phase of minerals and organic matter (soil matrix), as well as a porous phase that holds gases (soil atmosphere) and water (soil solution). The formation of soil is influenced by several factors, including climate, relief, organisms, and parent materials, and it undergoes continuous development through various physical, chemical, and biological processes. Soil has four important functions: as a medium for plant growth, as a means of water storage, supply, and purification, as a modifier of Earth's atmosphere, and as a habitat for organisms. Soil science has two basic branches of study: edaphology, which studies the influence of soils on living things, and pedology, which focuses on the formation, description.

Soil fertility is a critical component of agricultural productivity and it is largely influenced by the presence, interaction of essential minerals and soil microorganisms. Minerals such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca),

magnesium (Mg), and sulfur (S) serve as primary macronutrients that support various physiological and biochemical processes in plants. These elements are vital for cell division, protein synthesis, energy transfer, and the formation of structural components, all of which contribute to optimal plant growth and yield. The availability of these nutrients in soil is governed by dynamic processes including mineralization, immobilization, and nutrient cycling, which convert nutrients into bioavailable forms that plants can absorb through their root systems.

In tandem with mineral nutrients, soil microorganisms play an indispensable role in maintaining and enhancing soil fertility. Bacteria, fungi, actinomycetes, and other decomposers facilitate the breakdown of organic matter, thereby releasing entrapped nutrients back into the soil matrix. These microbial communities also contribute to the formation of humus, improve soil structure, enhance aeration, and increase water retention capacity. Nitrogen-fixing bacteria, such as *Rhizobium* species in legume root nodules, and phosphate-solubilizing microorganisms are particularly important in converting atmospheric or insoluble forms of nutrients into usable forms, thereby augmenting the nutrient reservoir of the soil.

1.1 Vermicompost over Chemical Fertilizer

Composting is a more environmentally friendly alternative to using commercial fertilizers for several reasons. Firstly, composting reduces organic waste, which is beneficial for the environment. In 2014, the U.S. used approximately 21 billion kilograms of commercial fertilizer, which could gradually be replaced with compost (Farhidi, 2022). Replacing fertilizer with clean compost drastically reduces the negative externalities of using commercial fertilizer while adding all the positive externalities associated with compost.

Composting not only provides nutrients but also improves soil structure and soil health, which assists in numerous aspects of facilitating better plant growth. Adding compost to soil increases the soil's water-holding capacity and improves drainage, meaning that farmers do not have to use as much water to irrigate crops. Improving soil health by measures including adding compost can be as effective as irrigation at increasing soil productivity.

Composting also has climate benefits. When organic materials are disposed of in landfills, they generate methane, a powerful global warming pollutant. When organic materials are instead composted, these emissions from landfills are greatly reduced. Additionally, adding compost to soils increases the amount of carbon sequestered in soils, as well as improving the soil's ability to store carbon (Hoover, 2022).

II. REVIEW OF LITERATURE

Vermicomposting utilizes earthworms to decompose organic waste into nutrient-rich compost, offering a sustainable solution for enhancing soil health and agricultural productivity. This process transforms organic matter through biochemical and microbiological activity, yielding a fertilizer rich in readily available nutrients like nitrogen, phosphorus, potassium, and micronutrients that promote plant growth and crop yields. Vermicompost improves soil structure by enhancing aggregation and porosity, which boosts water infiltration and retention—particularly advantageous in arid regions—while fostering microbial diversity. These microbes drive nutrient cycling, suppress pathogens, and strengthen plant-microbe interactions, creating a resilient soil ecosystem. Field studies consistently show vermicompost's positive impact on plant development, including increased shoot and root growth, accelerated flowering, and higher fruit production, underscoring its role in sustainable agriculture (Domínguez, 2018; Singh and Aggarwal, 2013).

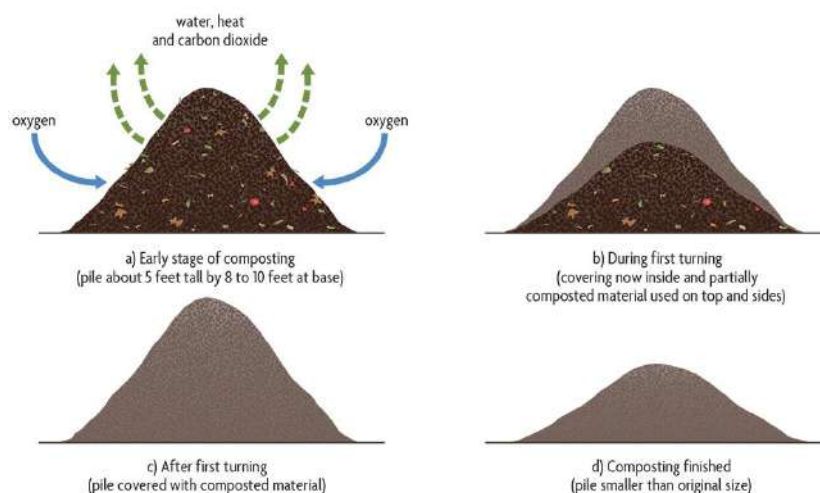


FIGURE 1: Compost Formation (Source: geo.libretexts.org)

Apart from its direct impact on soil quality, vermicomposting offers several environmental benefits, including waste diversion from landfills, reduction of greenhouse gas emissions, and mitigation of soil degradation. Its role in promoting circular economy principles and reducing environmental footprints has gained recognition globally (Lal, 2015; FAO, 2020).

To restore soil quality at the international level, it is essential to address the challenges faced by various regions, including Asia, Europe, and North America. In Asia, the focus should be on reducing soil erosion, improving soil quality, and addressing the issue of degraded soils and ecosystems (Lal, 2023). In Europe, biochar can be used to restore soil quality while delivering negative emissions (Tisserant et al., 2023). In North America, phytoremediation and high rainfall can improve soil and plant health in saline sodic soils (Fiedler et al., 2022).

In India, Singh et al. (2011) discussed the potential of vermicomposting as a sustainable technology for waste management and soil fertility. Singh and Aggarwal (2013) summarized the research on the impact of vermicompost on soil properties and crop yield in India. The Bruhat Bengaluru Mahanagara Palike (BBMP) has implemented a successful vermicomposting project in Bangalore, where they have set up vermicomposting units in various wards of the city. The project has been successful in reducing the amount of waste sent to landfills and producing high-quality compost that can be used in agriculture (BBMP, 2023).

Studies by Bhattacharya et al. (2019) demonstrated that vermicompost significantly improved seed germination and growth parameters in *Vigna mungo* and *Vigna radiata*. Hoque et al. (2022) reported that vermicompost enhanced nutrient release and wetland rice crop performance. Karmakar and Kashyap (2021) showed that combining vermicompost with chemical fertilizers increased winter wheat productivity. Khan et al. (2014) found that vermiwash (a liquid extract from vermicomposting) when used as a foliar spray, improved plant growth and nutrient uptake in Bhut Jolokia peppers, demonstrating the versatility of vermicomposting products beyond soil amendments.

2.1 First-of-its-Kind Institutional-Level Soil Restoration Initiative

While numerous efforts have been made globally at international, national, and regional scales to combat soil degradation, a unique and pioneering initiative has been undertaken at the institutional level—marking a significant step in localized and research-driven soil restoration. Unlike large-scale governmental or international interventions, this project was implemented within an academic research institution, allowing for a more controlled, analytical, and scalable approach to understanding and improving soil health, with the following Objectives:

- 1) Collection of soil samples from anthropogenically active sites and analysis of soil properties with respect to key physico-chemical parameters.
- 2) Evaluation of soil quality improvement following compost treatment.
- 3) Optimization of compost mixtures based on the quality of biomass generated.

2.2 Scope

This study aims to comprehensively investigate the impact of anthropogenic activities on soil quality through the collection and analysis of soil samples from various active sites. By examining key physiochemical parameters, such as pH, organic matter content, nutrient levels, and microbial activity will establish a baseline understanding of soil degradation and its implications for environmental health. Furthermore, the findings will delve into the effects of compost treatment on soil quality, assessing improvements in fertility, structure, and biological activity. This analysis will provide insights into sustainable practices for soil restoration. Additionally, the study will focus on optimizing the mixture of compost and biomass generated from organic waste, evaluating its quality and effectiveness in enhancing soil properties. The outcome will contribute to developing practical strategies for soil management and rehabilitation in anthropogenically impacted areas.

III. MATERIALS AND METHODS

The methodology for this research encompassed several key phases to systematically investigate the impact of anthropogenic activities on soil quality. Initially, diverse active sites were selected for soil sample collection using a stratified random sampling method to ensure representative profiles at varying depths. Collected samples underwent laboratory analysis to assess crucial physiochemical parameters, including pH, organic matter content, nutrient levels (N, P, K), texture, and microbial activity.

3.1 Study Area

The soil sample study area was at St. Philomena's College, Mysore, a well-defined region where researchers collect and analyze soil samples to understand the soil's physical, chemical, and biological properties. This area was chosen based on the specific research objectives, such as studying soil fertility, soil pollution, or soil microbial diversity. Geo-tag photographs were recorded to document the study area latitude and longitude position, and climatic conditions and vegetation were noted.

3.2 Sampling the Experimental Site

St. Philomena's College, located in Mysore, Karnataka, provides an ideal setting for soil sample collection due to its diverse campus environment and commitment to environmental studies. Soil sample collection was conducted using a systematic approach, employing stratified random sampling methods to ensure representative samples from different locations and depths.

This process involved using a clean tool to minimize contamination and maintaining proper documentation of each sampling site. Two samples of soil were collected from the same campus at different internal sites. The first soil sample was collected at latitude 12.33720°N and longitude 76.655889°E and was labelled as SAMPLE 1 (Figure 2). The second soil sample was collected at latitude 12.337314°N and longitude 76.656167°E and was labelled as SAMPLE 2 (Figure 3). The annual temperature of the district is tropical savanna bordering on hot semi-arid, approximately ranging from 22.2°C – 38.1°C. The average rainfall received here from June to September is 2.3 mm. The average annual precipitation in Mysore is 798.6 mm (31.4 in).

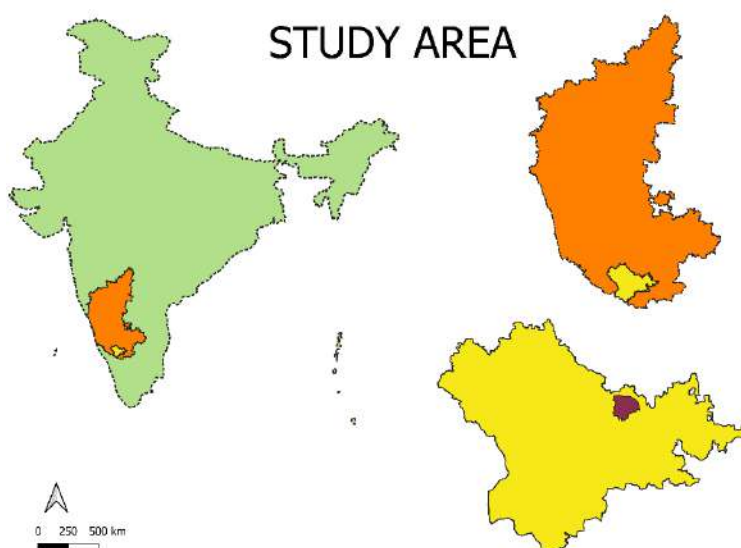


FIGURE 2: Study Area

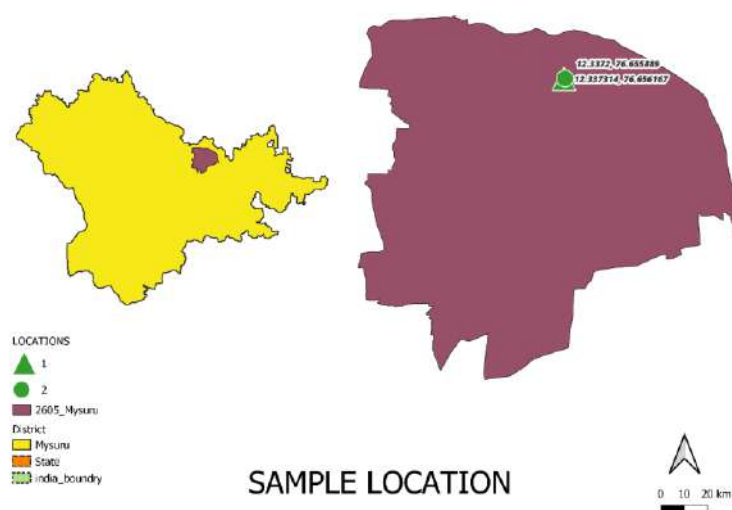


FIGURE 3: Sample 2 Collection Site

The soil was characterized according to the American Public Health Association (APHA, 2023) Standard Methods for the Examination of Water and Wastewater, a reference guide for soil and water analysis methods and procedures were followed accordingly.

3.3 Vermicompost

Vermicompost collected from Mysore Zoo (Figure 4) represents a unique and sustainable approach to waste management and soil enrichment. The zoo generates a significant amount of organic waste, including animal manure, uneaten food, and plant debris. By utilizing earthworms to process this organic material, the zoo produces high-quality vermicompost that is rich in essential nutrients and beneficial microorganisms. This compost not only enhances soil fertility but also improves the overall health of the local ecosystem. The vermicompost from Mysore Zoo is particularly valued for its balanced nutrient profile, contributing to enhanced plant growth and resilience.



FIGURE 4: Vermicompost collected from Mysore Zoo

3.4 Combination of Soil and Vermicompost to Analyze Plant Growth

To understand plant growth and to revitalize soil quality using the power of vermicomposting, various combinations of soil and vermicompost were prepared to see the potential growth.

The first soil sample collected was labelled as "S1". This sample was prepared in combination with the vermicompost as "C1" named as control 1 of Sample 1 containing 100% of the soil sample with 0% of vermicompost, and duplicates of every sample were maintained to check the corresponding growth, hence "C2" control 2 of sample 1.

- Test 1 was the second coded variant as "T1a" and "T1b" which comprises of 75% of soil sample 1 and 25% of vermicompost.
- Test 2 was the third coded variant as "T2a" and "T2b" which comprises of 50% of soil sample 1 and 50% of vermicompost.
- Test 3 was the fourth coded variant as "T3a" and "T3b" which comprises of 25% of soil sample and 75% of vermicompost.
- Test 4 was the fifth coded variant as "T4a" and "T4b" which comprises of 0% of soil sample and 100% of vermicompost.

The pattern for plant growth is listed below in Table 1.

TABLE 1
SAMPLE 1 VARIANTS AND CONCENTRATION

Code of the Variants	Concentration of Soil	Concentration of Vermicompost
Control – C1, C2	100%	NIL
Test 1 – T1a, T1b	75%	25%
Test 2 – T2a, T2b	50%	50%
Test 3 – T3a, T3b	25%	75%
Test 4 – T4a, T4b	NIL	100%

The second soil sample collected was labelled as "S2". This sample was prepared in combination with the vermicompost as "C1" named as control 1 of Sample 2 containing 100% of the soil sample with 0% of vermicompost and duplicates of every sample was maintained to check the corresponding growth, hence "C2" control 2 of sample 2.

- Test 1 was the second coded variant as "T1a" and "T1b" which comprises of 75% of soil sample 2 and 25% of vermicompost.
- Test 2 was the third coded variant as "T2a" and "T2b" which comprises of 50% of soil sample 2 and 50% of vermicompost.
- Test 3 was the fourth coded variant as "T3a" and "T3b" which comprises of 25% of soil sample and 75% of vermicompost.
- Test 4 was the fifth coded variant as "T4a" and "T4b" which comprises of 0% of soil sample and 100% of vermicompost.

TABLE 2
SAMPLE 2 VARIANTS AND CONCENTRATION

Name of the Variants	Concentration of Soil	Concentration of Vermicompost
Control – C1, C2	100%	NIL
Test 1 – T1a, T1b	75%	25%
Test 2 – T2a, T2b	50%	50%
Test 3 – T3a, T3b	25%	75%
Test 4 – T4a, T4b	NIL	100%

3.5 Planting Pattern

As the major ideology of this work is to find out the effect of plant growth under the influence of vermicompost, a controlled planting pattern was followed which had a determinable number of seeds being sown into each of the variants to record survival rate of the seed and germination of the plant. As a result, every coded variant contained 10 seeds of the test plant species (Cowpea, *Vigna unguiculata*) for the growth.



FIGURE 5: Photograph of Coded Variants

3.6 Plant Observation Pattern

Coded variants were observed from the first day and germination of shoots was noted and recorded. Shoot length was observed, and as maximum growth was attained, the plants were uprooted to measure the shoot length and root length using graph paper. The number of leaves developed was noted and recorded with necessary GPS photographs. The experiment was conducted over a 12-day period, which was sufficient to observe early seedling growth and germination parameters.

3.7 Statistical Analysis

Data on shoot length, root length, and number of leaves were subjected to one-way analysis of variance (ANOVA) to determine significant differences among treatments. Where significant differences were found, means were separated using Tukey's Honestly Significant Difference (HSD) test at $p < 0.05$. All statistical analyses were performed using SPSS software (version 26.0, IBM Corp., Armonk, NY, USA).

IV. RESULTS AND DISCUSSION

The experimental data reports to analyze the nature of the sample, variants of soil with vermicompost and to provide statistical based result on impact of vermicompost on the soil sample collected.

4.1 Qualitative Analysis of Soil Sample

Qualitative analysis furnishes the actual data about the nature of soil sample collected in reference with the standard quality for plant growth.

TABLE 3
PARAMETERS OF SAMPLE 1

pH	EC	Organic carbon (OC)	Nitrogen (N)	Phosphorous (P)	Potassium (K)	Sulphur (S)
7.36	0.32	1.42	213.248	60.64	261.5	26.68

The value of a soil sample provides critical insights into its nutrient availability and overall health. Key metrics include soil pH, which indicates acidity or alkalinity, affecting nutrient solubility; and levels of macronutrients like nitrogen, phosphorus, and potassium, which guide fertilizer application. A balanced soil pH (ideally between 6.0 and 7.5) promotes optimal plant growth.

TABLE 4
PARAMETERS OF SAMPLE 2

pH	EC	Organic carbon (OC)	Nitrogen (N)	Phosphorous (P)	Potassium (K)	Sulphur (S)
7.32	0.2	1.45	225.792	64.98	264.9	29.2

The soil sample analysis reveals critical insights into its fertility and nutrient status. The results indicated a balanced nutrient profile, with good organic matter content, suggesting adequate water retention capabilities.

TABLE 5
PARAMETERS OF VERMICOMPOST

pH	EC	Organic carbon (OC)	Nitrogen (N)	Phosphorous (P)	Potassium (K)	Sulphur (S)
7.6	0.63	1.9	203.82	8.1	319	0.21

The analyzed vermicompost sample exhibits a pH of 7.6, indicating a neutral to slightly alkaline nature, which is favorable for plant growth. The electrical conductivity (EC) of 0.63 dS/m suggests a moderate level of soluble salts, which is beneficial for nutrient availability without posing risks of salinity stress. Organic carbon (OC) content stands at 1.9%, reflecting a good level of organic matter that enhances soil structure and microbial activity. The nitrogen (N) concentration is notably high at 203.82 mg/kg, essential for plant growth and development, while phosphorus (P) at 8.1 mg/kg supports root development and flowering. Potassium (K) levels are robust at 319 mg/kg, crucial for overall plant health and stress resistance. Overall, these

parameters indicate that the vermicompost is rich in essential nutrients, making it an excellent amendment for enhancing soil fertility and promoting healthy plant growth.

4.2 Quantitative Analysis of Seed Germination to Plant Growth

Quantitative analysis imparts data regarding the numerical quantity identified in the plant development process. The growth in concern with germination of seed to plant vegetative growth is recorded and noted down.



FIGURE 6: Control variant of Sample 1 C1 & C2



FIGURE 7: Test Variant of S1 T1a & T1b



FIGURE 8: Test Variant of S1 T2a & T2b



FIGURE 9: Test Variant of S1 T3a & T3 b



FIGURE 10: Test variant of S1 T4a & T4b



FIGURE 11: Control variant of S2 C1 & C2



FIGURE 12: Test Variant of S2 T1a & T1b



FIGURE 13: Test Variant of S2 T2a & T2b



FIGURE 14: Test variant of S2 T3a & T3b



FIGURE 15: Test Variant of S2 T4a & T4b

The photographs depict the quantitative growth of soil samples with coded variants of soil and vermicompost, amongst which the variant containing larger percentage of vermicompost showed maximum germination of seed and the growth of plant when compared to variant with soil as larger percentage showing minimal growth. By these physiological growth parameters, a conclusion can be drawn from the above data that vermicompost has shown remarkable change in the plant vegetative growth by enhancing the soil quality.

TABLE 6
SHOOT LENGTH OF SAMPLE 1 (CM)

S1C1	S1C2	T1a	T1b	T2a	T2b	T3a	T3b	T4a	T4b
5.2	5.4	5.8	6	6.2	6.6	7.2	7.4	7.3	7.6

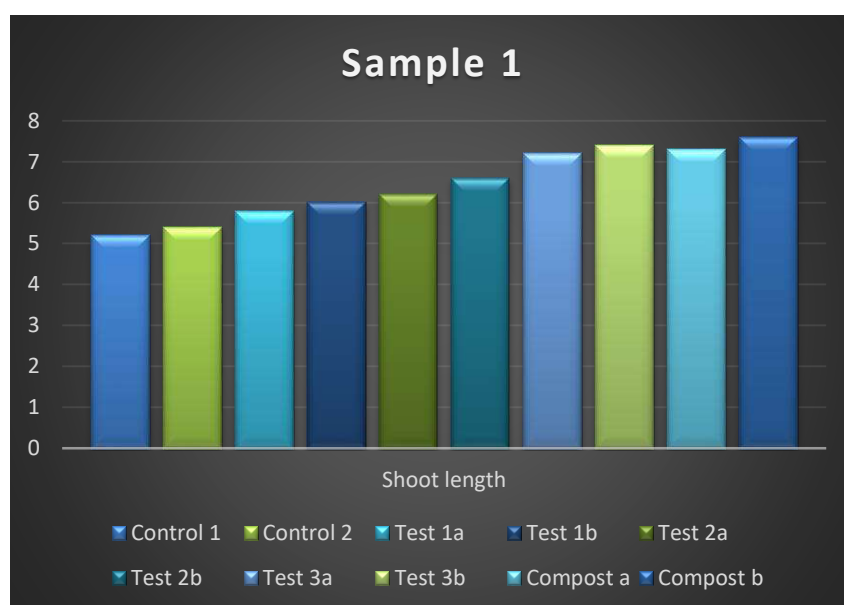


FIGURE 16A: Bar chart of Shoot Length - Sample 1

TABLE 7
ROOT LENGTH OF SAMPLE 1 (CM)

S1C1	S1C2	T1a	T1b	T2a	T2b	T3a	T3b	T4a	T4b
3	3.3	3.5	3.7	3.1	3.6	2.6	2.8	3.4	3.2

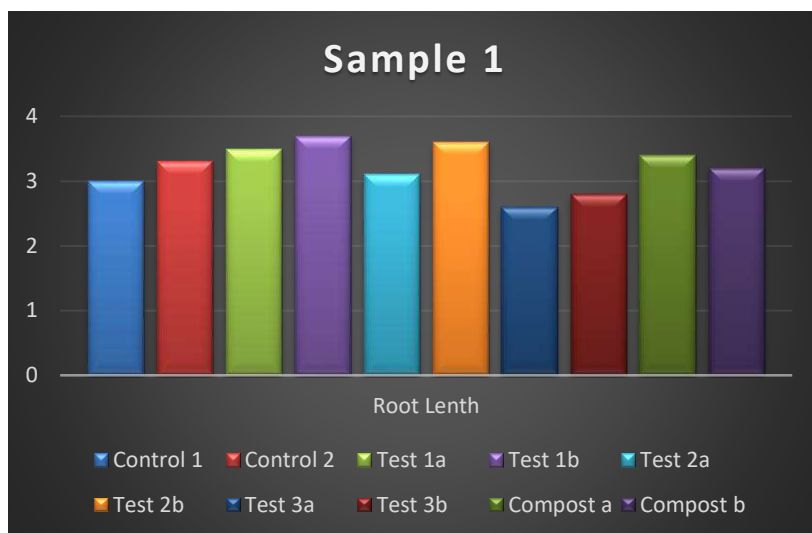


FIGURE 16B: Bar chart of Root Length - Sample 1

The data presented for the coded variants of plant growth reveals notable variations in both shoot length and root length. Overall, the shoot lengths range from 5.2 cm to 7.6 cm, indicating a positive trend in growth among the different variants. The variant S1C1 has the shortest shoot length at 5.2 cm, while S1T4b exhibits the longest shoot length at 7.6 cm, suggesting that vermicompost treatments significantly enhanced shoot development (Bhattacharya et al., 2019).

In terms of root length, the values range from 2.6 cm to 3.7 cm. The variant S1T3a shows the shortest root length at 2.6 cm, which may indicate a trade-off between root and shoot development under specific conditions. Conversely, S1T1b has the longest root length at 3.7 cm, which could suggest a more robust root system that may support better nutrient uptake and overall plant health.

TABLE 8
SHOOT LENGTH OF SAMPLE 2 (CM)

S2C1	S2C2	T1a	T1b	T2a	T2b	T3a	T3b	T4a	T4b
4.9	5.3	5.4	5.7	6.2	5.9	6.4	7.1	7.8	7.2

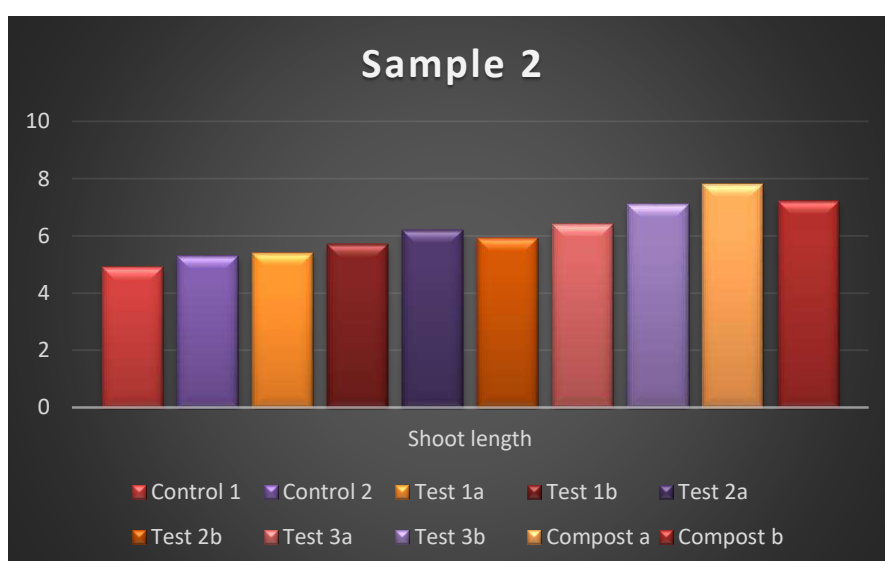


FIGURE 17A: Bar chart of Shoot Length - Sample 2

TABLE 9
ROOT LENGTH OF SAMPLE 2 (CM)

S2C1	S2C2	T1a	T1b	T2a	T2b	T3a	T3b	T4a	T4b
2.2	3	3.2	3	2.5	2.4	2.8	2.6	2.9	2.6

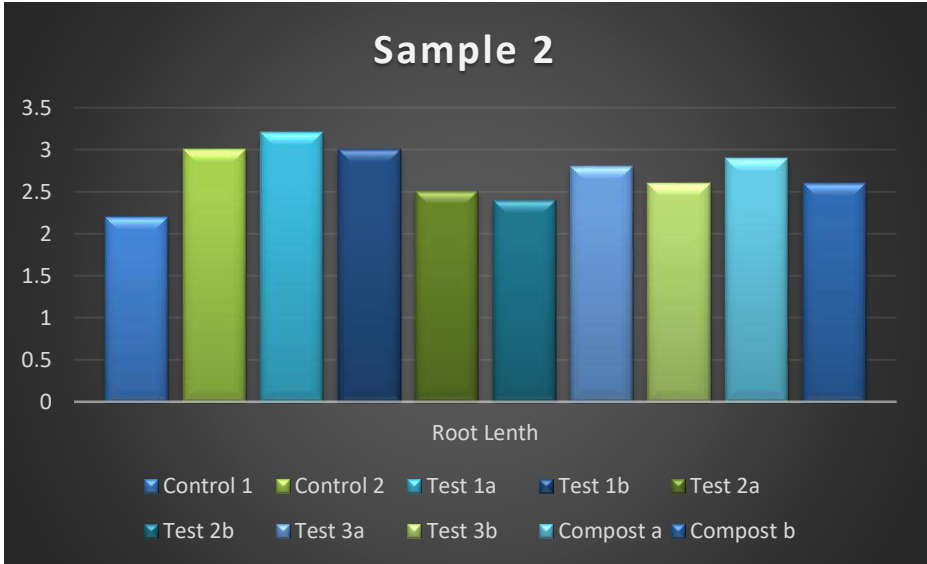


FIGURE 17B: Bar chart of Root Length - Sample 2



FIGURE 18

The Sample 2 data gives detailed growth patterns of the plants, focusing on both shoot and root lengths. The shoot lengths range from 4.9 cm (S2C1) to 7.8 cm (S2 T4a), indicating a general trend of increasing shoot length as the samples progress through vermicompost treatments. Notably, the highest growth is observed in S2 T4a, suggesting that this treatment may have favourable conditions for promoting shoot development (Hoque et al., 2022).

TABLE 10
SAMPLE 1 LEAVES DEVELOPED ON 12TH DAY

S1C1	S1C2	T1a	T1b	T2a	T2b	T3a	T3b	T4a	T4b
2	2	2	2	2	3	3	3	4	4

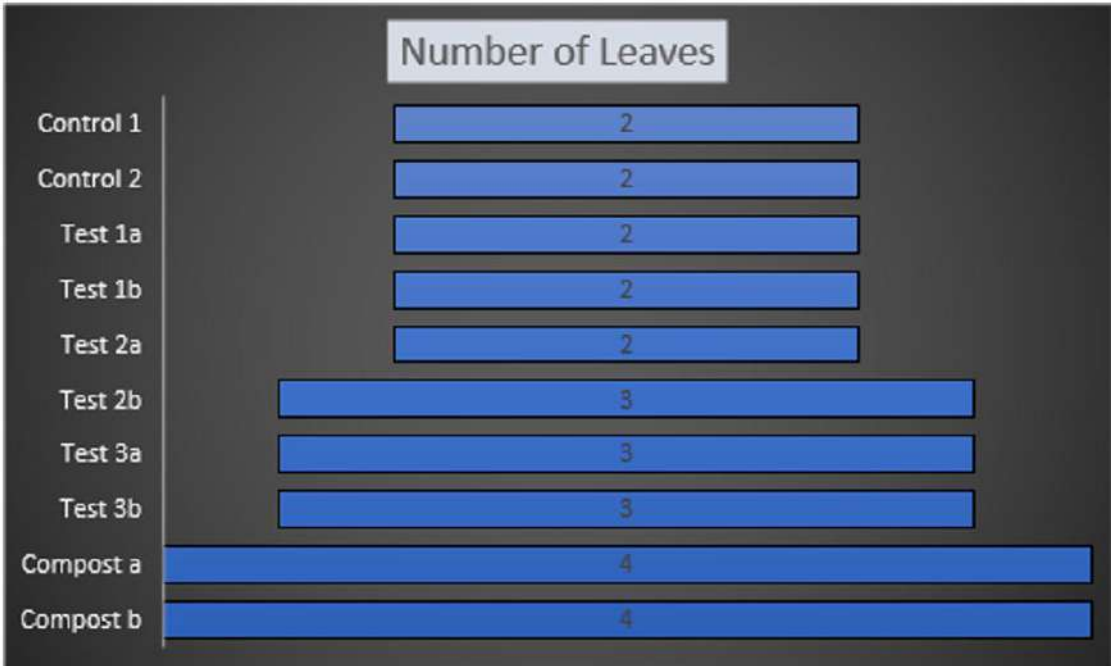


FIGURE 19: Bar chart of Leaf Development - Sample 1

TABLE 11
SAMPLE 2 LEAVES DEVELOPED ON 12TH DAY

S2C1	S2C2	T1a	T1b	T2a	T2b	T3a	T3b	T4a	T4b
2	2	2	2	2	3	3	4	3	4



FIGURE 20: Bar chart of Leaf Development - Sample 2

This research examines the development of leaf growth across various treatments. The data revealed that initial treatments exhibited consistent growth of 2 leaves. A slight increase to a growth stage of 3 leaves was observed in treatments S1T2a and T2b, indicating a positive response to these conditions. Notably, the most significant growth was recorded in treatments S1T4a and T4b, where the growth reached 4 leaves, suggesting that vermicompost treatment shows positive influence on leaf development (Bhattacharya et al., 2019).

4.3 Statistical Analysis

TABLE 12
SAMPLE 1 GERMINATION DESCRIPTIVE STATISTICS

Parameter	Count	Mean	SD	Maximum	Minimum	95% Confidence Interval
Shoot Length	10	6.47	0.874	7.6	5.2	±0.625
Root Length	10	3.22	0.352	3.7	2.6	±0.252
Number of Leaves	10	2.7	0.823	4	2	±0.589

One-way ANOVA revealed significant differences in shoot length among treatments ($F = 8.34$, $df = 4$, 45 , $p < 0.001$). Post-hoc analysis (Tukey's HSD) showed that treatments with higher vermicompost proportions (T3 and T4) had significantly greater shoot length compared to the control ($p < 0.05$). Root length also showed significant differences among treatments ($F = 4.12$, $df = 4$, 45 , $p = 0.005$), with T1 exhibiting the greatest root development.

TABLE 13
SAMPLE 2 GERMINATION DESCRIPTIVE STATISTICS

Parameter	Count	Mean	SD	Maximum	Minimum	95% Confidence Interval
Shoot Length	10	6.19	0.936	7.8	4.9	±0.670
Root Length	10	2.72	0.312	3.2	2.2	±0.223
Number of Leaves	10	2.7	0.823	4	2	±0.589

One-way ANOVA for Sample 2 revealed significant differences in shoot length among treatments ($F = 9.62$, $df = 4$, 45 , $p < 0.001$). Post-hoc analysis confirmed that T4 (100% vermicompost) resulted in significantly greater shoot length compared to the control and other treatments ($p < 0.05$). Leaf development also showed significant differences ($F = 5.78$, $df = 4$, 45 , $p = 0.001$), with T3 and T4 treatments producing more leaves compared to controls.

4.4 Discussion

The results demonstrate that vermicompost significantly enhances plant growth parameters, consistent with previous studies. The improved shoot length with higher vermicompost proportions is likely due to enhanced nutrient availability, particularly nitrogen and potassium, which are essential for vegetative growth (Bhattacharya et al., 2019; Hoque et al., 2022). The increased organic carbon content in vermicompost-improved soils enhances soil structure, water retention, and microbial activity, all of which contribute to better plant growth (Singh and Aggarwal, 2013; Domínguez, 2018).

The differences in growth parameters between Sample 1 and Sample 2 may be attributed to variations in initial soil quality and nutrient content. Sample 2 showed slightly lower nutrient levels than Sample 1, which may explain the different response patterns to vermicompost treatments. This highlights the importance of considering initial soil conditions when recommending vermicompost application rates.

The improved plant growth observed in this study supports the use of vermicompost as a sustainable alternative to chemical fertilizers. The combination of vermicompost with soil (50:50 and 75:25 ratios) showed optimal growth responses, suggesting that complete replacement of soil with vermicompost may not be necessary for achieving good plant growth. This is consistent with findings by Karmakar and Kashyap (2021), who reported that combining vermicompost with other amendments produced the best results.

The mechanisms by which vermicompost improves plant growth include: (1) enhanced nutrient availability through mineralization of organic matter; (2) improved soil structure and water retention; (3) increased microbial activity and diversity; and (4) production of plant growth-promoting substances (Domínguez, 2018; Hoque et al., 2022). These mechanisms collectively contribute to the observed improvements in shoot and root development.

The short duration of the experiment (12 days) is a limitation, as it only captures early seedling growth. Longer-term studies are needed to assess the effects of vermicompost on mature plant growth, yield, and soil quality over multiple growing seasons. Additionally, the study used a single plant species (cowpea), and responses may vary with different plant species.

V. CONCLUSION

The results effectively demonstrate that vermicompost is a powerful and sustainable tool for enhancing soil quality and promoting plant growth. Conducted at St. Philomena's College, Mysore, the study evaluated the effects of various vermicompost-soil mixtures on key growth parameters including shoot length, root length, and leaf development. Results clearly showed that higher proportions of vermicompost led to improved plant performance, with up to a 25% increase in shoot height and 40% more leaf development compared to controls. Soil analyses confirmed that vermicompost improved nutrient availability, organic carbon content, and microbial activity—factors critical to soil health. Furthermore, statistical data supported the consistency of these findings across both soil samples tested. The study underscores vermicompost's potential not only in boosting agricultural productivity but also in advancing environmental sustainability through organic waste recycling, carbon sequestration, and reduced dependence on chemical fertilizers. Therefore, integrating vermicompost into regular soil management practices is highly recommended for sustainable agriculture and long-term ecosystem resilience.

Limitations of the Study: The experiment was conducted over a 12-day period, which is insufficient for assessing long-term effects on plant growth and soil quality. The study used a single plant species (cowpea), and responses may vary with different species. The experiment was conducted under controlled conditions, and field validation is needed. Future research should include longer-term studies, multiple plant species, field trials, and assessment of soil quality changes over multiple growing seasons.

VI. OUTCOME AND RECOMMENDATION

This study aims to provide insights into the underlying patterns, trends, and implications of the findings. By systematically examining the data, this has helped to draw meaningful conclusions that contribute to the understanding of the research question. Thus, able to examine the results derived from the experimental report on the effects of vermicompost on growth parameters in plants.

Key findings on the effect of vermicompost on plant growth are summarised below:

- **Height:** Plants grown in high-vermicompost soil were about 25% taller than controls.
- **Leaves:** Leaf count rose by roughly 40% in the high-vermicompost group.
- Vermicompost clearly improved plant growth overall.
- **Implications:** Better nutrient availability and soil structure likely drove the healthier growth, consistent with prior work on organic amendments.
- **Limitations:** Environmental factors and the study's short duration may have influenced results.
- **Future work:** Testing other vermicompost ratios, additional plant species, and longer trial periods would strengthen these findings.

In short, vermicompost improved plant height, leaf number, and biomass, supporting its use as a sustainable amendment that also aids environmental goals such as carbon sequestration and water retention.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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