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Preface

We would like to present, with great pleasure, the inaugural volume-11, Issue-11, November 2025 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, Terrestric 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.

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Soil Science	Plant Science
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Power, Policy, and the Politics of Food in India

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Abstract— *Food, as a fundamental necessity for human survival, represents not only a basic right but also a critical responsibility of the state. This responsibility becomes even more significant in developing and poverty-stricken nations, where the state's dual obligation lies in supporting both the producers—primarily farmers—and the consumers, who often face food insecurity. Moreover, agriculture plays a pivotal role in shaping a country's overall economic health, influencing employment, income distribution, and trade balance. Agricultural policy, therefore, becomes a key instrument through which the state can drive inclusive growth and ensure food security. However, this paper seeks to analyze how private corporate interests, in collaboration with state mechanisms and influenced by global powers, are reshaping agricultural policy to serve market-oriented objectives. This reorientation often sidelines ethical and moral considerations of food justice, sustainability, and equity, ultimately compromising the broader economic and social goals of food security.*

***Keywords*— Agriculture, Food security, MSP, PDS, food politics.**

I. INTRODUCTION

After the discoveries of fire and the wheel, agriculture stands as one of humanity's most significant breakthroughs. Yet, it took humans a long time to truly master agriculture, the science of producing food, which ultimately gave them something unique in the natural world: food security. Humans became the only species capable of deliberately controlling food production.

However, we need to be cautious when using terms such as *human*, *food production*, or *food security*. This is because agriculture is often assumed to be a universal human practice, which is not the case. By *human*, we specifically mean *Homo sapiens*—the only surviving species among nearly nine different human species identified by science. And even within Homo sapiens, agriculture has never been universal. Many nomadic tribes, pastoral communities, and indigenous groups continue to live without practicing settled farming.

The advent of agriculture also marked a fundamental rupture in the natural relationship between humans and nature. In the natural world, the link between food and hunger is direct: when food is available, it is accessible to all. A forest filled with fruit-bearing trees sustains birds, primates, and other creatures who freely share in its bounty. In contrast, human societies regulate access to food through systems of ownership and commodification. A warehouse stocked with grains, fruits, and vegetables cannot be accessed by a hungry individual without the means to pay. Food may exist in abundance, but access to it is mediated—and restricted—by purchasing power.

This introduces a critical distinction: in natural ecosystems, availability equals accessibility. Among humans, hunger intersects not only with the production (supply side) but with economic entitlement (demand side). As Amartya Sen famously argued in *Poverty and Famines* (1981), famines often occur not due to an absence of food, but due to lack of accessibility. In other words, a biological need of hunger creates demand in all the animal species except the human beings. For humans just being hungry is not enough to create demand. It's the purchasing capacity which creates the demand. For humans who practice the agriculture hunger is more of a political economic activity than a biological one. This paper is not about the human population in general but that precise section of the population which practices agriculture.

Next comes the question of purchasing capacity. For a long time, human societies relied on barter, exchanging one commodity for another. The monetization of the economy, where goods (including food) began to be exchanged for money, took centuries to evolve. Once this system was firmly established, it brought about a permanent shift: the "demand" for any good was no longer defined simply by need, but by the purchasing power of the buyer. Agriculture, too, was shaped by this transformation.

Yet, there remains a common belief that food security can be ensured merely by increasing production. This perception has kept the focus largely on the supply side, while the demand side, people's ability to access food—remains neglected. The result is a paradoxical situation: hunger persists even in the midst of abundance. In nature, such a contradiction is unthinkable, you would never find animals starving in a forest rich with fruit. But in human societies, particularly in India, this paradox of "hunger amidst plenty" has become an everyday reality.

II. INDIA HUNGER AMIDST PLENTY

India provides a compelling case of this paradox. As of May 2025, India's central food grain stock was approximately 318.73 lakh tons of paddy and 3.16 lakh tons of coarse grains. It was also reported on last July that Central rice stocks have reached 37.48 MT, the highest in 20 years, that is over three times the buffer. However, at the same time India ranked 105th out of 127 countries in Global Hunger Index 2024. On one hand Food Corporation of India (FCI) reports overflowing grain stocks and on the other hand hunger persists across vast swathes of the country. The contradiction lies in the decoupling of production from consumption. A large section of the population remains food insecure, not due to a lack of production, but due to insufficient means to access the available food.

India's historical experience illustrates both the strengths and vulnerabilities of human food systems. Geographically blessed with fertile soils and riverine networks, the Indian subcontinent had a long tradition of food self-sufficiency. Medieval Indian rulers were acutely aware of the dual dimensions of food security, i.e. they had given equal importance to the food crop production and made it sure to be affordable for their subjects. For example, Alauddin Khalji (r. 1296–1316) implemented a dual strategy—creating grain storage systems (addressing supply) and instituting strict price controls (addressing affordability), thus stabilizing both sides of the food equation. Like any other parts of the planet India faces famines and drought time to time. Estimates suggest over 120 major famines occurred between 1900 BCE and 1765 CE. These were primarily triggered by climatic irregularities—droughts, floods, locusts—or wars that disrupted both agriculture and trade. Some of the kings and dynasties addressed natural calamities efficiently while some of them failed and faced the wrath of the subjects.

However, things changed dramatically after the advent of British colonial rule in 1756. Famines became more frequent, more severe, with more and more deaths. Between 1765 and 1943, at least twelve major famines were recorded, each claiming hundreds of thousands to millions of lives.

III. COLONIAL DISRUPTIONS OF SUPPLY AND DEMAND

The reasons for the spike in famine mortality under British rule lie in the simultaneous destruction of both supply and demand mechanisms:

- Supply Disruption: Indian agriculture was forcibly reoriented toward cash crops like indigo, cotton, opium, to serve imperial markets. The focus on monocultures reduced local food availability. The introduction of land revenue systems like the *Permanent Settlement* overburdened farmers, reducing incentives for food grain cultivation.

  The leading Indian economists, Shah and Khambata observed, the average income of an Indian was just enough either to feed two men in every three of the population, or give them all two in place of every three meals they need, on condition that they all consent to go naked, live out of doors all year round, have no amusement or recreation, and want nothing else but food, and that lowest, the coarsest, the least nutritious" (Shah and Khambata, " The Wealth and Taxable capacity of India, " 1924)

- Demand Destruction: Through heavy taxation, deindustrialization, and export-led policies, the British impoverished Indian peasants and urban laborers alike. Purchasing power eroded drastically.

  The report of the Bengal Director of Health for 1927-28 recorded that, "the present peasantry of Bengal are in a very large proportion taking to a dietary on which even rats could not live more than five weeks."

The British colonial rule started exploiting India from very early days of their rule but the situation was further exacerbated after the opening of the Suez Canal in 1869, which made grain exports to Europe logistically feasible and economically lucrative. As food grains were shipped overseas, local populations starved. Famines like the Orissa Famine (1866) and Great Famine (1876–78) became symbols of structural violence—famines not of scarcity, but of exclusion.

The Bengal Famine of 1943, which killed an estimated 3 million people, epitomized this grim legacy. Despite adequate food stocks, administrative apathy, market hoarding, and war-time inflation decimated the purchasing power of the poor.

Partition and Post-Colonial Inheritance

Colonial Post-independence India inherited a shattered agrarian economy. Colonial extraction, coupled with the traumatic partition, led to massive displacement, communal violence, and the loss of vital agricultural zones. The twin pillars of food security—production and accessibility, were both compromised.

In the mid-1960s, back-to-back droughts in Bihar and Uttar Pradesh triggered another food crisis. With food production crashing by 20%, the country was pushed to the brink of famine. India emerged as the biggest food importer of the world. The U.S. responded with food aid under the PL-480 agreement, but this dependence highlighted the vulnerability of India's food security system.

It was a turning point that compelled the India to adopt long-term strategies to ensure food sovereignty. Government intervention in foodgrain sector marketing began in a big way in the mid-1960s. It was meant to create a favourable incentive environment for the adoption of new technology based on high yielding varieties of wheat and rice, which were seen to possess vast potential for raising grain production. India was then facing a severe food shortage. The new technology provided a ray of hope to tackle the problems of food shortage and hunger. But it was just one part. In its second part of dealing the food security the government took several measures to benefited the consumers.

These included

1) Price assurance for the producers by the system of minimum support prices (MSP)
2) Maintaining buffer stocks
3) Making the stock available for the people in affordable price by distributing the at reasonable prices through the public distribution system (PDS).

This situation paved the way for the adoption of Green Revolution techniques. India experienced a dramatic surge in food production within a short span of time. From being one of the world's largest food importers, the country transformed into a grain-surplus nation, creating the impression that food security had been achieved at the national level. It was a success in terms of boosting food production, especially in regions like Punjab and Haryana. But it addressed only the supply side of the food problem. India's claim to food self-sufficiency, often celebrated in political rhetoric, rests on a narrow interpretation of food security—one that equates surplus production with universal access. In reality, food security entails both availability (supply side) and accessibility (demand side), which are ideologically and structurally distinct domains. The Green Revolution, while successful in increasing agricultural output, was fundamentally a capitalist, technology-intensive intervention that prioritized production without parallel investments in infrastructure or purchasing power enhancement for the poor.

However, this assumption soon began to crack, as reports of hunger, malnutrition, and starvation deaths—particularly among tribal and other marginalized populations—surfaced. The reason was straightforward: while the government focused on the supply side by boosting food production, the demand side, shaped by people's access to food, was left largely unaddressed due to various socio-political factors.

Foremost among these was the failure of land reforms, which left a vast population landless and, consequently, without income. Deprived of land ownership, they remained confined to roles as agricultural labourers, and in some cases, even bonded labourers. Without land, they had no claim over the produce of the Green Revolution.

The outcome was stark. Enormous quantities of food grains accumulated in public stocks—exceeding one-fourth of the annual production of rice and wheat—while, at the same time, one in every five Indians remained undernourished when measured against the minimum caloric requirements for a healthy, active life (World Bank, 2002). This stockpiling of food coincided with a rise in undernutrition, as both calorie intake and calorie deprivation worsened during the same period (Meenakshi & Vishwanathan, 2003).

While production is often driven by policy decisions, subsidies, and political will, demand is shaped by economic variables—infrastructure, employment, income levels, and market access. In a country like India, where vast rural and tribal regions lack basic transport and market connectivity, food distribution remains logistically challenging. Consequently, surplus grains remain concentrated in urban centers, inaccessible to large segments of the rural poor due to low purchasing capacity. Moreover, the ecological and socio-economic consequences of the Green Revolution—soil degradation, groundwater depletion, chemical contamination, and rising farmer debt—have rendered agriculture unsustainable in the long run. Because every factor, be it, soil degradation, groundwater depletion or chemical contamination leads to the increase in the input cost and eventually the less profit and less purchasing capacity. The dismantling of traditional farming systems and biodiversity further compounds the crisis. As costs of inputs rise and state procurement weakens, farming becomes unviable, prompting distress migration and agrarian exits.

Thus, while India may have achieved quantitative food surplus, it has not achieved qualitative food security. Hunger and malnutrition persist despite full godowns—a paradox resulting from the failure to integrate production with equitable access. This disjuncture underscores the need to reconceptualize food self-sufficiency beyond mere output, toward a rights-based, inclusive framework rooted in environmental sustainability and economic justice

The trajectory of India's food security framework highlights the persistent tension between state-led developmentalism and market-driven liberalization. The Green Revolution, which transformed India from a food-deficient to a food-surplus nation, was made possible largely through state interventions such as subsidies, price supports, the Minimum Support Price (MSP) mechanism, and public procurement systems. These measures were grounded in Keynesian principles, which emphasized the state's role in addressing market failures and ensuring food security through redistributive policies.

With the onset of neoliberal reforms in the 1990s, however, structural adjustment programs—shaped significantly by the influence of the IMF and World Bank—recast subsidies as fiscal liabilities rather than necessary safeguards. The irony lies in the fact that the very Western economies that had once promoted subsidy-driven agricultural modernization in India continue to shield their own farmers through extensive agricultural protectionism, even as they press for subsidy reductions in the Global South. This contradiction underscores the deep asymmetries embedded in global economic governance.

The 3Ps are essential to achieve the food security, namely the production, procurement and the price stability. India addressed the production issue with the green revolution. MSP was introduced to address the issue of procurement/storage and PDS was introduced in order to achieve goal of price stability regardless of bumper harvest or below-normal production, MSP was a guaranteed price mechanism for the producers, PDS for the reasonable prices for consumers and food supply at subsidised rates to vulnerable sections. The government has been carrying out procurement and storage (buffer stock) of foodgrains (rice and wheat) since the mid-1960s. These measures have been implemented through two important institutions, namely, the Commission on Agricultural Costs and Prices (CACP), which is entrusted with the task of suggesting MSP, and the Food Corporation of India, which carries out the task of procurement to ensure that producers get a price not below MSP and that foodgrains required for maintaining a reasonable level of buffer stock and for the public distribution system are in place.

Then comes the economic reforms of 1991. Till the beginning of economic reforms MSPs for foodgrains were based entirely on domestic factors, mainly on the cost of production of crops. Though CACP was required to take into consideration the international price situation, this aspect was never given any weight while arriving at the level of MSPs. The first attack on this well placed mechanism of food security came in form of devaluation of the rupee in June 1991. It not only raised the gap between MSP (domestic prices) and international prices it also increased the budget needed for the food security measures. Instead of much hyped rhetoric of providing support, the new economic policy measures proved to be devastating for the farming community. The foodgrain scene of the post-reforms period is the outcome of this shift in food policy to raise domestic prices through government intervention completely ignoring domestic demand and supply factors.

IV. CORPORATISATION AND INDIAN AGRICULTURE: FROM COLONIAL LEGACIES TO GLOBALISATION

Corporatisation of agriculture refers to the transformation of farming from a subsistence activity into a commercial enterprise organised and managed with a corporate outlook. It involves large-scale private investment, standardisation of production processes, infusion of advanced technologies, and emphasis on product quality and price competitiveness to meet both domestic and global demands (Singh, 2000). Historically, the corporatisation of Indian agriculture can be traced back to the colonial era, when the British introduced plantation-style farming focusing on cash crops such as indigo, jute, cotton, and tea. A key milestone was the establishment of the *Assam Tea Company* in London in 1839, which institutionalised tea cultivation and marked the beginnings of corporate involvement in agriculture (Chakrabarti, 2013). Mechanisation gradually replaced manual labour in plantations, giving agriculture a distinct corporate character in select regions. The second major phase emerged with the Green Revolution in the mid-1960s, which transformed agriculture through the adoption of High-Yielding Variety (HYV) seeds, chemical fertilisers, pesticides, and expansion of irrigation facilities (Frankel, 1971). Implemented first in the Kharif season of 1966 under the High-Yielding Varieties Programme (HYVP), this strategy was initially confined to wheat, rice, jowar, bajra, and maize (Swaminathan, 2006). While the Green Revolution significantly boosted productivity and modernised farming practices, it also entrenched corporatisation by encouraging large-scale, technology-driven production supported by state and private actors. Thus, the trajectory of corporatisation in Indian agriculture reflects both colonial legacies of commercial farming and post-independence strategies of technological modernisation. These developments laid the structural foundation for contemporary debates on contract farming, global market integration, and the socio-ecological consequences of corporate-led agriculture (Patnaik, 2007).

V. POST-GREEN REVOLUTION AND THE WTO ERA

The post-liberalisation phase of Indian agriculture, particularly after the 1990s, witnessed intensified debates around corporatisation under the influence of global trade regimes. The Uruguay Round of the General Agreement on Tariffs and Trade (GATT) and the subsequent establishment of the World Trade Organization (WTO) in 1995 opened agriculture to global capital flows and encouraged the entry of private foreign corporations into the sector (Shiva, 2000). Industrialised nations, backed by multinational agribusiness firms, demanded complete freedom of investment with provisions for 100 percent equity ownership, unrestricted repatriation of profits, and the right to acquire land, set up plantations, engage in fisheries, and undertake livestock rearing (Patnaik, 2007). Such policies effectively positioned corporations as the primary beneficiaries of liberalisation, with little obligation toward ensuring food security. As Senator George McGovern of the U.S. Senate aptly remarked, "food security in private hands is no food security at all," since corporations prioritise profit maximisation over equitable food distribution (McGovern, 1991).

Globalisation in the early 1990s further camouflaged the corporatisation of agriculture through jargon such as "competitiveness," "market access," and "aggregate measure of support," which masked the emergence of corporate monopolies, the dumping of subsidised products from the Global North, and the continuation of corporate subsidies (Shiva, 2005). These changes contributed to a structural agrarian crisis by pushing farm-gate prices downward while simultaneously escalating input costs. The withdrawal of state subsidies, coupled with deregulation of the seed and input sector, exacerbated farmers' indebtedness and deepened rural distress (Sainath, 2014). Recognising these challenges, the Government of India announced its first comprehensive National Agricultural Policy on July 28, 2000, which implicitly reinforced a framework for greater corporate participation and control in agriculture (Government of India, 2000). Thus, the WTO era marked a decisive stage in the corporatisation process, intertwining agriculture with global capital and deepening concerns over food sovereignty and farmer livelihoods. The policy emphasised private sector participation, promotion of agricultural competitiveness, and greater integration with global markets (Government of India, 2000). While it promised modernisation and investment, critics argue that the NAP facilitated a shift towards corporate control of agriculture at the expense of small and marginal farmers (Shiva, 2005). Concerns raised in this context included the replacement of smallholder farming with corporate agribusiness, threats to food security from profit-driven corporations, skewed subsidy structures benefiting developed countries, and rising farmer distress due to debt from escalating input costs (Patnaik, 2007; Sainath, 2014).

In response, various models of corporatisation were explored in India to balance investment with farmer protection. The Golden Triangle Model integrated the farmer, banker, and corporate entity into a tripartite arrangement, with contract farming and assured prices at its core. The concept of Special Agricultural Zones (SAZs), pioneered in Uttarakhand, aimed to replicate SEZ-style development for agriculture by conserving prime farmland, promoting region-specific cropping, and ensuring infrastructure support. In West Bengal, corporatisation initiatives addressed middlemen monopolies and introduced reforms under the APMC Act, allowing direct corporate procurement from farmers. Specific corporate-led marketing models also emerged: the Frito-Lay model of contract farming with input support and price assurance; the Reliance model with a three-tier Agri-retail infrastructure; Bengal Fresh, a public-private joint venture focusing on packaging, grading, and smallholder support; and cooperative-oriented approaches like the Confed Model and Swarojgar Model, which sought to protect farmers from distress sales.

And at the same time dismantling of the Universal Public Distribution System (PDS) into a Targeted PDS (TPDS) in 1997 marked a paradigmatic shift—from universal entitlements to means-tested welfare. While designed to increase efficiency and reduce fiscal expenditure, TPDS suffered from poor targeting, exclusion errors, and chronic under coverage, problems rooted in the lack of a reliable poverty identification mechanism. Despite numerous expert committees (e.g., Tendulkar, Rangarajan), India has failed to establish a consistent poverty yardstick, leading to the bureaucratization of hunger relief.

This twin retreat—weakening of price support on the supply side and narrowing of entitlements on the demand side—has resulted in a paradoxical situation: India ranks 117th on the Global Hunger Index, despite holding surplus food stocks in FCI godowns. This exposes the hollowness of a purely production-centric view of food self-sufficiency and calls for a rights-based, universal approach to food access.

VI. CONCLUSION

The corporatisation of agriculture in India—shaped by colonial legacies, the Green Revolution, and WTO-led liberalisation—has undeniably transformed the sector. While it has brought investment, technology, and global integration, it has also intensified inequalities, eroded smallholder resilience, and deepened food insecurity despite surplus production. The paradox of "hunger amidst plenty" underscores that food security cannot be reduced to production alone; it must integrate accessibility, equity, and sustainability.

Moving forward, a balanced model of agricultural governance is needed—one that prevents corporate monopolies while leveraging private sector efficiency.

Solutions must focus on:

Reviving the Universal PDS with stronger digital tracking to curb leakages, ensuring every citizen has guaranteed access to affordable food. Revisiting MSP and procurement policies, expanding them beyond rice and wheat to include pulses, millets, and oilseeds, thereby enhancing dietary diversity and farmer incomes. Regulating contract farming and FDI through farmer-centric laws that mandate fair pricing, transparent dispute resolution, and protection from corporate exploitation. Promoting cooperative and producer company models, which pool smallholder resources, enhance bargaining power, and democratise market access. Investing in agro-ecological and sustainable farming practices, reducing input dependency and restoring soil, water, and biodiversity. Strengthening rural non-farm employment and social safety nets, so that farmers are not forced to distress-sell or migrate under debt pressure. Decentralising food governance by empowering panchayats, self-help groups, and farmer-producer organisations (FPOs) to design localised, context-specific food security strategies. Ultimately, Indian agriculture must not be reduced to a site of corporate profit-making; it is the lifeline of rural livelihoods, cultural identity, and national food sovereignty. Policies must re-centre farmers, especially smallholders, women, and marginalised communities, ensuring that the politics of food align with the ethics of justice, sustainability, and universal human dignity.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Foliar Application of Boron can Increase Seed Formation, Seed Yield and Oil Content in Sunflower (cv. BARI Surjamukhi-3)

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***Abstract*—** *A field experiment was conducted at the experimental field of Soil Science Division, Bangladesh Agricultural Research Institute (BARI), Joydebpur, Gazipur-1701during winter season of 2022 – 2023. BARI Surjamukhi-3, a popular and promising dwarf variety of sunflower was used in this study as a test crop. The objectives were to know the effect of foliar spray of boron (B) on seed formation, seed yield and oil content in sunflower and to find out the optimum foliar dose of B for maximizing the seed yield. The experiment was conducted in a Randomized Complete Block Design (RCBD) having three replications. The fertilizer boric acid (H_3BO_3) containing 17% Boron (B) was applied at 20-25 and 40-45 days after sowing (DAS) as foliar mode. Five treatments comprised of different foliar doses of B were applied. T_1- control (spray with distilled water), T_2- 50 mg L^{-1} B, T_3- 100 mg L^{-1} B, T_4- 150 mg L^{-1} B and T_5-200 mg L^{-1} B. The foliar application of B significantly increased the seed formation, seed yield and yield contributing characters of sunflower. The treatment T_4 (150 mg L^{-1}B) produced the highest seed yield (2.25 t/ha) that was equal with the treatment T_5 (200 mg L^{-1}B). The minimum unfilled seed (19.00%) was recorded in T_4 (150 mg L^{-1}B), which was identical with the next higher dose T_5 (19.00%) treatment. Foliar application of B also significantly increased the oil content in sunflower seeds. The maximum oil content (39.99%) was recorded in T_5 (200 mg L^{-1}B), which was significantly higher over B control but identical to rest of the treatments. Thus, sunflower grown in B deficient Grey Terrace Soil of Gazipur (AEZ-28) found responsive to foliar application of B with regard to seed formation, seed yield and oil content.*

***Keywords*— Foliar application, Optimum dose of Boron, Seed sterility, Oil content, Reproductive growth.**

I. INTRODUCTION

Sunflower (*Helianthus annuus* L.) is considered as an essential oilseed crop, which grows well in Bangladesh during winter season. The oil of sunflower contains plenty of essential fatty acid such as linoliec and linolenic acid in comparison with rapeseed and mustard oil. But Rabi (winter) season is considered the best for producing sunflower in Bangladesh. The southern regions of Bangladesh is most suitable to grow sunflower after harvesting T. aman rice (BARI, 2023). The area and production of sunflower in 2020-2021 was 0.012 lakh ha and 0.014 lakh MT, respectively (DAE, 2022) and its cultivation and production are gradually increasing. Sunflower, has been recorded to be particularly sensitive to B deficiency and normally used as an indicator for the assessing available B in soils (Oyinlola, 2007). As B is essential for crop growth and can be applied according to crop demand, harmful effects also detected by the applying overdose in early phases of growth (Oyinlola, 2007 and Shorrocks, 1997). Foliar application may be required when the demands are higher than the boron supplied through the soil application. The doses of boron may affect either by positively and negatively the yield and the components in vegetative and reproductive stages of sunflower. The reproductive growth is much sensitive for boron than vegetative growth (Asad *et al*., 2003). Chatterjee and Nautiyal (2000) reported that the pollen viability and abortion of stamens and pistils, which contribute to poor seed set due to malformed capitulums and consequently low seed yield, due to B deficiency at flowering time. The demand of boron to sunflower varies depending on the stage of plant growth. The critical content of boron at the time of sunflower emergence is 20 mg kg^{-1} of soil (Asad, 2002). That is the reason why some farmers prefer foliar nutrition when applying micronutrients. Many scientists have described the effects of foliar application of boron on the growth and development of sunflower. Boron is an important element, which influenced yields of many crops like sunflower, cotton (Dodas, 2006). However, in depth research regarding the foliar application of B in sunflower for seed formation and its yield is scarce in Bangladesh. Therefore, the present study was carried out with following objectives: (i) to know the effect of foliar spray of boron (B) on seed formation, seed yield and oil content in sunflower and (ii) to find out the optimum foliar dose of B for maximizing the seed yield.

II. MATERIALS AND METHODS

The present investigation was carried out at the research field of Soil Science Division, Bangladesh Agricultural Research Institute (BARI), Joydebpur, Gazipur during winter season of 2022 - 2023. The study area was under the agro-ecological zone (AEZ)-28 known as Madhupur Tract, which represents Grey Terrace Soil (Aeric Albaquept). The experiment was laid out in a Randomized Complete Block Design (RCBD) having three replications. The unit plot size was maintained 2 m × 2 m. BARI Surjamukhi-3, a dwarf and promising variety of sunflower was used as test crop. Fertilizers were applied at the rate of 140-43-81-29-3 kg ha^{-1} of N-P-K-S-Zn in the form of urea, triple super phosphate (TSP), muriate of potash (MoP), gypsum and zinc sulphate, respectively. In addition, decomposed cowdung @ 5 t ha^{-1} was applied. The entire amount of cowdung and all P, K, S, and Zn were applied at the time of sowing as basal dose, while the rest N was applied in three splits (half at sowing and remaining half N was applied as top dress in two equal splits at 20-25 and 40-45 DAS). The seeds were treated with fungicide, vitavax before sowing.

Seeds were sown on 22 November, 2022 maintaining the spacing of 50 cm from row to row and 25 cm from plant to plant. Irrigation was applied for ensuring desirable soil moisture as per demand of sunflower. Intercultural operations were done as and when necessary.

2.1 Foliar application of boron:

There were five treatments for foliar spray of boron viz. T_1- control (spray with distilled water), T_2- 50 mg L^{-1} B, T_3- 100 mg L^{-1} B, T_4-150 mg L^{-1} B and T_5- 200 mg L^{-1}B. Boron in the form of boric acid (H_3BO_3) containing 17% B were sprayed two times at 20-25 and 40-45 days after sowing (DAS). A hand operated compressed air sprayer was used for foliar application. The spray volume was 10 liter per plot (2.5 Lm^{-2}). The foliar spray was done during morning (around 8:00A.M.).

2.2 Soil sample collection and analysis

Initial soil samples were collected from a depth of 0-15 cm and analyzed well ahead of sowing to know the fertility status of soil (Table 1) for determining the fertilizer requirement of crop. The soil pH measurement was done with a combined glass calomel electrode pH meter as described by Jackson, (1962). Organic carbon was determined by wet oxidation method (Walkley and Black, 1934). The total N was estimated by modified Kjeldahl method. The macro elements like K, Ca and Mg were determined by NH4OAC extractable method and the micro nutrients such as Cu, Fe, Mn and Zn were determined by DTPA extraction method using Atomic Absorption Spectrophotometer (Model SHIMADZU AA-7000). Boron was estimated by $CaCl_2$ extraction method. Phosphorus was measured determined by Bray and Kurtz method while S was estimated by turbidimetric method with $BaCl_2$.

TABLE 1
INITIAL PROPERTIES OF THE SOIL SAMPLES OF EXPERIMENTAL FIELD

Soil Properties	Texture	pH	OM	Ca	Mg	K	Total N	P	S	B	Cu	Fe	Mn	Zn
			(%)	meq $100g^{-1}$			%	ppm						
Result	Sandy clay loam	5.3	1.3	6	1.9	0.2	0.07	6	32	0.2	0.9	154	18	3.5
Critical level	-	Acidic	Low	2	0.5	0.1	Low	7	10	0.2	0.2	4	1	0.6

2.3 Initial soil fertility status

The soil of the research field was found acidic in reaction (pH 5.3). The texture was sandy clay loam.

2.4 Plant sample preparation and analysis

The plant samples from each plot were dried maintaining the temperature 65°C in an electric oven around 72 hours then ground to pass through a 20 mesh sieve and analyzed following standard procedures. Digestion of plant samples were done using H_2SO_4 for N and HNO_3-$HClO_4$ (3:1) for other nutrients determination. The grains were ground and N, P, K, Ca, Mg, S, B and Zn contents were determined according to method described by Jones and Case (2018). Atomic absorption spectrophotome was used for metal ion and spectrophotometer (Agiland Technologies, cary 60 UV-Vis) for anion analysis. The accumulatic nutrients in the plant was estimated by multiplying nutrient content by dry plant weight.

2.5 Nutrient uptake

Nutrient uptake was calculated using the formula suggested by Fegeria *et al.* (1997).

$$\text{Nutrient uptake (kg ha}^{-1}\text{)} = \frac{\text{Nutrient\%}\times\text{Dry weight (kg h}a^{-1}\text{)}}{100} \quad (1)$$

2.6 Data collection and statistical analysis

The heads of sunflower were harvested during maturity. Five plants were randomly selected from each and every treatment for collecting necessary data such as dry matter, head diameter, number of seed, number of unfilled seed, seed weight, seed yield (t ha^{-1}), B and oil content. All the data were statistically analyzed using STATISTIX-10 and treatment means were separated by multiple comparison test using LSD.

III. RESULTS AND DISCUSSION

Foliar application of B contributed significantly to the yield components, seed yield and oil content in sunflower (**Table 2**). The highest head diameter was observed in T_5 (17.18 cm) that was statistically identical with the T_4 (17.15) and followed by T_3 (15.50) and they were significantly higher over rest of the treatments where the control treatment showed the lowest diameter (12.03 cm). Number of seeds $head^{-1}$ was the highest in T_4 (604.25) treatment which was similar with T_5 (604.14) and the lowest was recorded in T_1 (384.35) and they were statistically dissimilar. The number of unfilled seeds $head^{-1}$ was recorded the highest in boron control (145.97), which was significantly higher over all other treatments. The number of unfilled seeds reduced gradually with increasing dose of B up to 150 mgL^{-1} and remained static for the next higher dose (T_5). The less number of unfilled seeds were recorded in the T_5 (114.80) treatment which was exactly similar with T_4. Al-Amery *et al.* (2011) mentioned similar results in their findings. The hundred seed weight was recorded the maximum in T_4 treatment (7.40g) which was identical with T_5 (7.15g) and both of them were significantly higher over rest of the treatments. The lowest hundred seed weight (4.45 g) was recorded in boron control, which was significantly lower than boron treated plants. The highest seed yield $plant^{-1}$ was produced by the treatment T_5 was (40.01 g $plant^{-1}$) that was similar with T_4 (40.00) followed by T_3 (33.27 g $plant^{-1}$) but the control treatment produced the lowest yield (21.00 g $plant^{-1}$). Mekki (2015), Brighenti and Castro (2008), Sharker and Mohammed (2011) and Al–Amery *et al.* (2011) observed that the higher dose of foliar application of B increased head diameter, number of seeds $head^{-1}$ and seed yield $plant^{-1}$ of sunflower. Bhattacharyya *et al.* (2015) explored the highest sunflower yield and maximum B efficiency with foliar spray of B. Saeed *et al.* (2015) showed that the yield components of sunflower significantly affected with foliar application of boron.

In case of yield (t ha^{-1}) significant differences were observed among the treatments. The highest seed yield (2.25 t ha^{-1}) was recorded with the T_4 treatment where 150 mgL^{-1} of B were applied which was statistically identical with T_5 (2.25) treatment (Table 2). Sunflower yield was significantly higher with boron foliar application in the study of Prabhakar *et al.*, (2021). The unfilled seed percentage was highest in control (37.98) treatment where malformed capitulum were identified but the lowest in T_4 and T_5 treatment (19.00 %), which might have contributed to higher yield in boron sprayed plants. The seed yield might have increased with foliar application of B due to prolonged photosynthetic capacity during flowering period and enhanced seed formation and also for the greater partitioning from increased biomass. Al-Amery *et al.* (2011) expressed that application of B resulted in increased seed yield partly may be due to decreased seed sterility. The reproductive growth required higher amount of B than vegetative stage of growth. So sufficient amount of B might have resulted enhanced growth (Asad *et al.*, 2003). The oil content in seed varied from 36.40 to 39.99%. Similarly, oil yield significantly ranged from 7.71 to 16.92 g/plant. The highest oil content (39.99%) and oil yield (16.92g $plant^{-1}$)) was observed in T_5 treatment, which was statistically identical with T_4 in both the cases. The increase in seed yield and percent oil content in BARI Surjamukhi-3 may be due to collective contribution of yield traits and vigorous seed formation resulted in foliar B application. The significant increase in oil yield might be influenced with the increase in oil content by foliar application of B up to150 mgL^{-1}. Renukadevi and Savithri (2003) mentioned that application of B had brought out a tremendous enhancement in the oil yield of sunflower.

TABLE 2
EFFECT OF FOLIAR APPLICATION OF B ON THE YIELD COMPONENTS, SEED YIELD AND OIL CONTENT IN SUNFLOWER DURING WINTER, 2022 – 2023

Treatment	Head diameter (cm)	No. of seeds $head^{-1}$	No. of unfilled seeds $head^{-1}$	Seed yield (g $plant^{-1}$)	Weight of 100 seed (g)	Yield (t ha^{-1})	Unfilled seed (%)	Oil %	Oil Yield (g/plant)
T_1: Control	12.03c	384.35d	145.97a	21.00d	4.45d	2.10d	37.98a	36.4	7.71d
T_2 :50 mgL^{-1}B	14.23b	459.30c	133.19b	27.30c	5.37c	2.15c	29.00b	37.95a	10.60c
T_3:100 mgL^{-1}B	15.50b	532.05b	127.69b	33.22b	6.36b	2.19b	24.00c	38.75a	13.82b
T_4:150 mgL^{-1}B	17.15a	604.25a	114.81c	40.00a	7.40a	2.25a	19.00d	39.98	16.85a
T_5:200 mgL^{-1}B	17.18a	604.14a	114.80c	40.01a	7.15a	2.25a	19.00d	39.99	16.92a
STC	**	**	**	**	**	**	**	NS	**
CV(%)	5.32	5.6	5.88	7.54	5.54	5.49	5.7	4.49	10.74

STC means significance test code, ** indicates significant at 1% level, * indicates significant at 5% level, NS indicates not significant

The stover of sunflower plant after the harvest of seed is regarded as biomass yield. However, the biomass yield also varied significantly due to foliar application of B (Table 3). The highest biomass (3.31 t ha^{-1}) was recorded in T_5 treatment that was statistically and numerically similar with the T_4 (3.30). The control treatment showed the lowest stover (1.79 t ha^{-1}). Al-Amery *et al*. (2011) mentioned that the B application increased dry matter of sunflower. The maximum boron conc. was recorded in T_5 treatment (79.00 ppm) resembling with T_4 (78.42 ppm) and followed by T_3 and T_2. But T_4 and T_3 were statistically dissimilar. The control treatment had the lowest amount (59.00 ppm). Boron uptake (kg ha^{-1}) was significantly varied among the treatments. The highest amount was recorded in T_5 (0.2616 kg ha^{-1}) which was statistically identical with T_4 (0.2587) and that were followed by T_3 (0.2016 kg ha^{-1}) and T_2 (0.1530 kg ha^{-1}). The control treatment was identified with lowest amount (0.1054 kg ha^{-1}). Bhattacharyya *et al*. (2015) revealed the yield maximization followed by the uptake of the plant with foliar application of B.

TABLE 3
BIOMASS YIELD, CONTENT AND UPTAKE OF B IN SUNFLOWER PLANT

Treatment	Biomass yield (t ha^{-1})	B conc. (ppm)	B uptake by plant (kg ha^{-1})
T_1: Control	1.79c	59.00d	0.1054d
T_2 :50 mgL^{-1}B	2.28bc	67.00c	0.1530c
T_3:100 mgL^{-1}B	2.79ab	72.33b	0.2016b
T_4:150 mgL^{-1}B	3.30a	78.42a	0.2587a
T_5:200 mgL^{-1}B	3.31a	79.00a	0.2616a
STC	**	**	**
CV(%)	6.63	4.76	4.78

Conc. means concentration

The seed dry yield, nutrient content and uptake of N, P, K, Zn and B, were presented in Tables 4 and 5. The sufficient amount of variation observed among the treatments for seed yield (kg ha^{-1}). The highest seed yield was recorded in T_4 (1569.33 kg ha^{-1}) treatment. Similar result was observed in T_5 treatment and followed by T_3 (1511.83 kg ha^{-1}) and T_2 (1456.50 kg ha^{-1}) treatment. The T_1 treatment was identified as the lowest one (1396.33 kg ha^{-1}). The application of B increased seed yield according to the findings of Ahmed *et al*. (2011), Jyothi *et al*. (2018) and Al-Amery *et al*. (2011).

The amount of boron concentration (ppm) was identified the highest in T_5 (46.00 ppm) that was similar with T_4 (44.67 ppm) and followed by T_3 and T_2 but the lowest was in T_1 (26.33), the control treatment. Significant differences among the treatments were showed in case of B uptake by seed (kg ha^{-1}). The T_5 treatment exhibited the maximum amount (0.0722 kg ha^{-1}) that was identical with T_4 (0.0701 kg ha^{-1}) and followed by T_3 (0.0585 kg ha^{-1}) and T_2 (0.0466 kg ha^{-1}) treatments. The minimum amount was obtained from the control treatment (0.0367 kg ha^{-1}).

TABLE 4
SEED DRY YIELD, CONTENT AND UPTAKE OF B AND ZN IN SUNFLOWER SEED

Treatment	Seed yield (kg ha^{-1})	B conc. (ppm)	Zn conc. (ppm)	B uptake by Seed (kg ha^{-1})	Zn uptake by Seed (kg ha^{-1})
T_1: Control	1396.33d	26.30d	65.74b	0.0367d	0.092c
T_2 :50 mgL^{-1}B	1456.50c	32.00c	72.99a	0.0466c	0.106b
T_3:100 mgL^{-1}B	1511.83b	38.67b	75.36a	0.0585b	0.114ab
T_4:150 mgL^{-1}B	1569.33a	44.67a	78.12a	0.0701a	0.123a
T_5:200 mgL^{-1}B	1569.33a	46.00a	76.45a	0.0722a	0.120a
STC	**	**	**	**	**
CV(%)	6.14	7.85	4.16	7.79	4.33

TABLE 5
N, P AND K CONTENT AND UPTAKE IN SUNFLOWER SEED

Treatments	N con. (%)	P con. (%)	K con. (%)	N uptake by seed (kg ha-^{1})	P uptake by seed (kg ha-^{1})	K uptake by seed (kg ha-^{1})
T_1: Control	3.42	0.55	1.38b	47.81b	7.63c	19.31b
T_2 :50 mgL^{-1}B	3.48	0.57	1.50b	50.69b	8.25bc	21.89b
T_3:100 mgL^{-1}B	3.61	0.58	1.71a	54.63a	8.82ab	25.86a
T_4:150 mgL^{-1}B	3.62	0.61	1.69a	56.77a	9.52a	26.58a
T_5:200 mgL^{-1}B	3.63	0.6	1.72a	57.02a	9.47a	26.94a
STC	NS	NS	*	**	**	**
CV(%)	2.84	6.12	6.19	3.39	6.35	6.52

Root dry weight, B conc. (ppm), and B uptake by root (kg ha^{-1}) have been described in Table 6. Adequate variation was recorded among the treatments for root dry weight. The highest root dry weight was recorded in T_5 (497.00 kg ha^{-1}) which was identical with T_4 (496.33kg ha^{-1}) and followed by T_3 (414.00 kg ha^{-1}) and T_2 (331.33 kg ha^{-1}). The control treatment showed the minimum value (246.00 kg ha^{-1}). Boron content in the form of ppm was significantly visible. The T_5 (40.66 ppm) identified the maximum concentration that resembled with T_4 (38.84 ppm) and followed by T_3 and T_2. The control treatment expressed the lowest amount (20.33 ppm).

TABLE 6
ROOT DRY WEIGHT, CONTENT AND UPTAKE OF B IN SUNFLOWER ROOT

Treatment	Root dry weight (kg ha^{-1})	B con. (ppm)	B uptake by root (kg ha^{-1})
T_1: Control	246.00d	20.33c	0.0050d
T_2 :50 mgL^{-1}	331.33c	26.00bc	0.0086c
T_3:100 mgL^{-1}	414.00b	32.00b	0.0132b
T_4:150 mgL^{-1}	496.33a	38.84a	0.0192a
T_5:200 mgL^{-1}B	497.00a	40.66a	0.0202a
STC	**	**	**
CV(%)	5.32	11.01	10.58

The boron uptake by root (kg ha^{-1}) revealed remarkable variation among the treatments. The highest amount was recorded in T_5 (0.0202 kg ha^{-1}) which was identical with T_4 (0.0192 kg ha^{-1}) and followed by T_3 (0.0132 kg ha^{-1}) and T_2 (0.0086 kg ha^{-1}) treatment. T_1 (0.0050 kg ha^{-1}) treatment identified with the lowest amount. Asad *et al*. (2003) expressed enhancement growth with boron foliar application but the little dependence of the concentration in root environment in sunflower.

The Zn concentration of fruit increased by the application of B to a certain level finally decreased its concentration with higher rate of B application. Percent Zn varied from 65.74 to76.45 ppm that also resulted in the maximum Zn uptake for the T_4 treatment (0.123 kg ha^{-1}). The lowest Zn uptake was recorded as 0.092 kg ha^{-1}.

The effect of B on the concentration of Nitrogen (N), Phosphorus (P), and Potassium (K) expressed that added B increased the concentration of P in sunflower seed, but the increment was not sufficient (Table 2). The concentration as well as uptake of nutrients such as N, P, K were influenced in bitter gourd upto certain level in the studies of Banu *et al*. (2024). The minimum N (3.42%) and P concentrations (0.55%) were found in control treatment while the maximum N concentration (3.63%) was found in T_5 and the maximum P (0.61%) was found in T_4 treatment. The N uptake by seed reached to the peak in T_5 (57.02 kg ha^{-1}) treatment which was identical with T_4 (56.77 kg ha^{-1}). The P conc. (%) was found to lie in between 0.55% and 0.61% that also reflected in P uptake by seed kg ha^{-1} limiting between 7.63 kg ha^{-1} and 9.52 kg ha^{-1}. The K conc. (%) was the highest in T_5 (1.72%) treatment. The K uptake by seed was the top in T_5 treatment (26.94 kg ha^{-1}) which however was identical with T_4 (26.58 kg ha^{-1}) and T_3 treatments. The present study revealed N P, K, Zn and B content showed synergistic relationship with B application in soil up to a certain level.

IV. CONCLUSION

Foliar application of B two times at 20-25 and 40-45 days after sowing of seeds, i.e. in vegetative and pre-flowering stage, respectively significantly contributed to increase seed formation, seed yield, biomass yield, oil content in sunflower (BARI Surjamukhi-3). Boron application in the form of foliar mode also decreased seed sterility and increased the B concentration and uptake by the plants. Boron @ 150 mg L^{-1} as foliar application containing the volume of 10 liters per plot (2.5 Lm^{-2}) appeared as the best dose for the cultivation of sunflower in Grey Terrace Soil under AEZ 28 and similar soils in Bangladesh.

NOVELTY STATEMENT

The present findings indicated that up to a certain level of B application to soil, N P, K, Zn and B content showed synergistic effect. This type of research was conducted first time in Bangladesh

AUTHOR'S CONTRIBUTION

Most. Bilkis Banu: Conceptualization and methodology of the study. Supervision, soil chemical analysis collection of data and analysis using Statistics10. Writing results and discussions, reference collection ect.

Habib Mohammad Naser: Conceptualization and supervision, providing logistic supports.

Mohammad Quamrul Islam Matin: Editing, proofreading, plagiarism, review collection.

Mohammed Harun or Rashid: Supervision, data collection, editing.

Rabiul Islam: Supervision, data collection, editing.

Mohammad Motasim Billah: Data collection, editing.

Md. Mahmudur Rahman: Review collection, editing.

Atikur Rahaman: Data collection and review collection.

CONFLICT OF INTEREST

The authors have declared no conflict of interest.

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Genetic Improvement of Bali Cattle through Artificial Insemination with Frozen Banteng (Bos javanicus) Semen: Part I – Performance of Resulting Calves (Work in Progress)

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***Abstract*—** *The performance of Bali cattle has been declining. To preserve their genetic quality and productivity, appropriate measures must be taken, such as revitalizing Bali cattle by breeding them with Banteng semen. This study aimed to evaluate the performance of offspring resulting from artificial insemination using frozen Banteng semen in Bali cattle. Ten Bali cows underwent synchronization twice using the PGF2α protocol. The cows were then monitored for signs of estrus 24 hours after the second injection, and breeding occurred 8-12 hours after confirming heat. Artificial insemination was performed with frozen Banteng semen from Taman Safari, Bogor, Indonesia. Insemination was conducted three times during estrus until ovulation was achieved. Pregnancy was diagnosed 20 days post-insemination. The dam's weight was recorded at the time of artificial insemination, and the calf's weight was tracked at birth and then weekly for 10 weeks using a specialized livestock scale. The birth weights recorded were 18.33±2.42 kg for female calves and 20.25±2.71 kg for male calves, with no significant difference in birth weights between the sexes (P>0.05). This study found that the average daily weight gain was 0.29 kg for female calves and 0.37 kg for male calves, indicating no significant growth difference between the sexes and higher than average for Bali calves born with Bali bull semen. The study concluded that Bali calves born through artificial insemination with frozen Banteng semen exhibited greater birth weight and body weight growth than average Bali calves.*

Keywords*— *Bali cattle, Banteng, frozen semen, artificial insemination.

I. INTRODUCTION

The Banteng (*Bos javanicus*) holds a protected status in Indonesia, as per Ministerial Regulation P.106/MENLHK/SETJEN/KUM.1/12/2018 (Permen 2018), and is classified as endangered on the International Union for Conservation of Nature (IUCN) Red List. Additionally, the Director General of KSDAE Decision No. 180/IV-KKH/2015 designates the Banteng as a priority species in the country. The Javanese Banteng is the ancestor of Bali cattle, which are bred in several regions of Indonesia. The domestication of the Javanese Banteng began around 3500 BC and was distributed to several regions in Indonesia [1].

Bali cattle, an indigenous breed of beef cattle in Indonesia, are found throughout the nation. These cattle were domesticated from the Banteng. Adapted to tropical climates, Bali cattle thrive and yield high-quality carcasses [2;3]. They have a relatively high fertility rate [4] low calf mortality rate [5] and can sustain themselves on low-quality feed [6]. The Central Statistics Agency [7] reported in its Agricultural Census that Bali cattle were the most raised beef cattle by Agricultural Households (RTUP) in 2023. Bali cattle accounted for 38.6% of the total beef cattle raised in this area. These cattle are predominantly raised in South Sulawesi, West Nusa Tenggara (NTB), East Nusa Tenggara (NTT), and Bali. South Sulawesi hosts the largest population, comprising 18% of the total population.

The performance of Bali cattle has declined. Prasodjo et al. [8] reported that the average birth weight of male calves was 18.9 ± 1.4 kg, and that of female calves was 17.9 ± 1.6 kg. In 2020, Gemuh [9] reported that the birth weights of female and male Bali cattle calves were 14.50 and 16.40 kg, respectively. Said et al. [10], also reported that the average birth weight of Bali cattle calves ranged from 15.69 ± 1.70 kg (Lombok) to 13.49 ± 1.89 kg (Sumbawa, West Nusa Tenggara). All three data points indicated a decline in the birth weight performance of Bali cattle.

Artificial insemination is the most widely used reproductive technology in livestock, including cattle. Banteng calves produced by artificial insemination at Taman Safari Bogor can reach 25-27 kg. To maintain the genetic quality and productivity of Bali cattle, appropriate efforts must be made, including the revitalization of Bali cattle by breeding them with Banteng semen. This study aimed to evaluate the performance of offspring resulting from artificial insemination with frozen Banteng semen in Bali cattle.

II. MATERIAL AND METHODS

All procedure of this research performs by veterinarians at the Taman Safari Indonesia (TSI) Bogor, west Java and TSI Prigen, East Java, Indonesia. The research conducted from 2023 to 2024 at TSI Prigen, East Java. Prigen Safari Park is located at an altitude of around 800 meters above sea level.

2.1 Animals:

Ten Bali cows were obtained from the Bali Cattle Breeding and Forage Center (BPTU-HMT) in Denpasar, Bali. The criteria for the Bali cow were age 3-5 years, a body weight of approximately 270 kg, having given birth 1-2 times, a healthy body and reproductive system, and a normal cycle with a Body Condition Score (BCS) of 3 (Scale 1-5). The cows were transferred from the BPTU-HMT to TSI Prigen in East Java and acclimatized for one month prior to the study. The cows were housed in separate enclosures measuring 2.5 by 4 meters, where they were given green fodder and concentrate at rates of 10% and 1% of their body weight, respectively. They had unlimited access to drinking water.

2.2 Frozen Banteng Semen

The frozen semen used belonged to TSI, Bogor, which was frozen in Andromed® extender with a sperm motility value after thawing of 30-35% [11].

2.3 Estrus Syncronization

The estrus of Bali cows was synchronised using the $PGF_2\alpha$ protocol twice. This process involved administering a 5 ml dose of $PGF_2\alpha$ (Lutalyse) on day 0, followed by a second intramuscular injection of the same dosage 11 days later [12]. The cows were then observed for signs of estrus 24 hours after the second injection, and breeding took place 8-12 hours after confirming estrus. The response to estrus and the time taken for each cow to show estrus were documented by checking for estrus signs at intervals of 24, 48, 72, and 96 hours.

2.4 Artificial Insemination

The insemination timing or sperm deposition was performed when the dominant follicle measures between 1.2 and 1.4 cm [11;12], and this is linked to uterine changes. Artificial insemination utilized frozen Banteng semen from TSI, with each straw containing 25×10^6 sperm. The post-thaw motility (PTM) was 30%, equating to approximately 7.5×10^6 motile sperm [11]. Insemination was conducted three times during estruses until ovulation was achieved [12]. Equipment designed for AI in cattle was used for the insemination process.

2.5 Pregnancy diagnosis

Pregnancy diagnosis was made 20 days after insemination with transrectal ultrasound to determine the presence of the embryo in the amniotic sac and re-examination with ultrasound and rectal palpation on day 60 to ensure continuation of pregnancy [14].

2.6 Assessing Dam and Calves' Performance

The dam's weight is recorded at the time of artificial insemination, while the calf's weight is tracked at birth and then weekly for a duration of 10 weeks using a specialized livestock scale.

2.7 Statistical Analysis

An Excel t-test was employed to examine dam weights, the length of gestation, calf birth weights, and their daily weight gain. The results are shown as the mean ± standard error of the mean (SEM).

III. RESULT AND DISCUSSION

In this study, the weights of the female subjects varied between 259 and 295 kg, with no significant difference observed between those that birthed male or female calves (p>0.05). All 10 Balinese cows that were synchronized responded to estruses. Among them, seven cows (70%) became pregnant and successfully gave birth to healthy calves, comprising four males (57%) and three females (42%). The birth weights recorded were 18.33±2.42 kg for female calves and 20.25±2.71 kg for male calves, with no significant difference in birth weights between the sexes (P>0.05).

TABLE 1
THE PROFILE OF DAM WEIGHT AND CALVES BIRTH WEIGHT OF BALI COW INSEMINATE WITH FROZEN BANTENG SEMEN

Variable	Calves sex		p-value
	Male	Female	
Dam weight (kg)	272 ±4,01	278.33±4.06	0.64
Calves birth weight (kg)	20.25±2.71	18.33±2.42	0.65

According to earlier reports, data from 2020 indicates that the birth weight of Balinese calves varied between 14.50 and 16.40 kg [9] and from 13.49 ± 1.89 kg to 15.69 ± 1.70 kg [10]. In this study, Balinese calves inseminated with frozen Banteng semen had birth weights ranging from 18.33 ± 2.42 to 20.25 ± 2.71 kg, showing an increase in birth weight. This is also higher than the 17.9 ± 1.6 kg to 18.9 ± 1.4 kg reported by Prasojo et al. [8] The findings of this research provide optimism for restoring Balinese cattle to their former performance levels.

The average weekly weight gain showed no difference between male and female calves (P>0.05). The average weight gain between males and females was 2.05–2.58 kg (Figure 1; Table 2). Weight gain varies. From the first to the eighth week, the weight gain ranged from 0 to 3.50 kg. From the ninth and tenth weeks, the height gain ranged from 3 to 6 kg (Table 2).

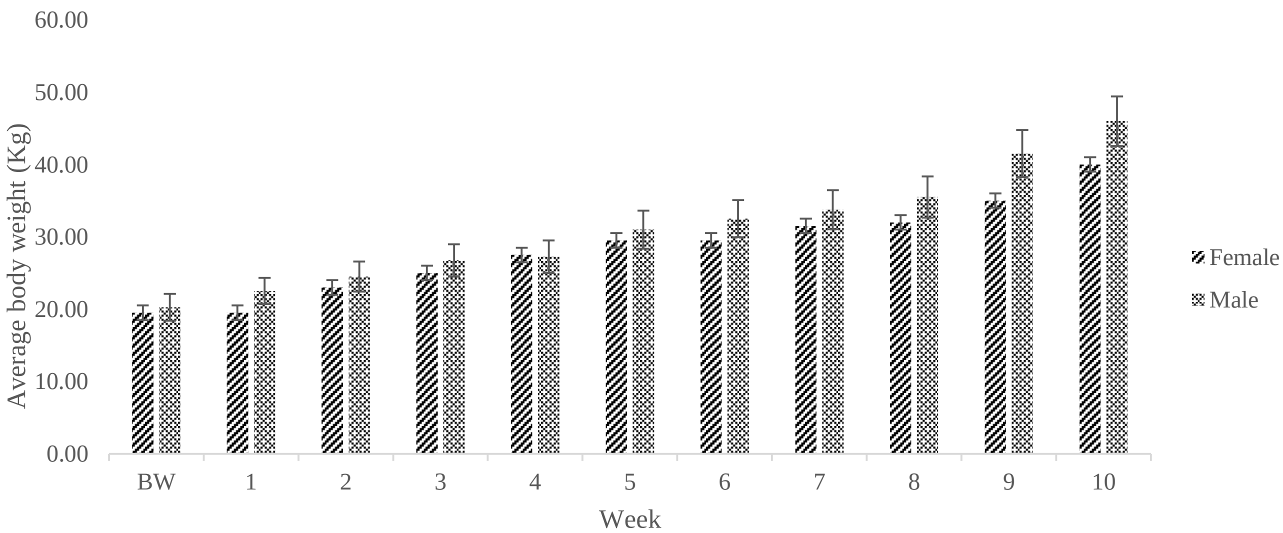

FIGURE 1: Weight gain in Balinese calves from crossbreeding with Banteng

According to Chadijah [15], the daily weight increase for female Bali cattle calves is between 0.15 and 0.21 kg, while other reported that male calves gain between 0.245 and 0.256 kg per day [16]. Both studies concluded that male calves experience greater weight gain compared to female calves. Gemuh [9] reported growth of Bali calves per day between 0.29 to 0.30 kg. However, this research found that the average daily weight gain was 0.29 kg for female calves and 0.37 kg for male calves, indicating no significant growth difference between the sexes (Table 2).

TABLE 2
COMPARISON OF WEIGHT GAIN IN MALE AND FEMALE CALVES OF BALI CATTLE BRED USING BANTENG FROZEN SEMEN

Calves sex	Delta Average gain (kg/week)										Average	p-value
	1	2	3	4	5	6	7	8	9	10	±SE	
Female	0	4	2	3	2	0	2	0.5	3	5	2.05±1.26	0.48
Male	2.3	2	2.3	1	3.8	2	1.3	1.8	6	5	2.58±1.29	

According to previous studies, the gestation period for female calve ranges from 258 to 307 days, while for males it is between 257 and 306 days [17]. Other research indicates a duration of 255 to 295 days for females and 256 to 295 days for males' calves, with an average gestation period of 283.9 to 284.9 days [8]. The gestation period for Bali cattle inseminated with frozen Banteng semen ranged from 293.67±2.01 to 295.75±1.12 days (Table 1), with no observed difference between male and female calves.

TABLE 3
GESTATION PERIOD IN BALINESE CATTLE AFTER INSEMINATION WITH FROZEN BANTENG SEMEN

Gestation length	Calves sex		p-value
	Male	Female	
Minimum (Days)	294	289	
Maximum (Days)	297	296	
Average ±SEM	295.75±1.12	293.67±2.01	0.47

This study's data is limited by the small number of female participants, and the assessment of body weight gain was conducted only up to the 10th week. Additional research is necessary to extend the evaluation until weaning and even until the calves reach puberty, so that improvements in performance can be more clearly observed compared to Bali cattle inseminated with Bali bulls. Ongoing studies are exploring the enhancement of Bali cattle using frozen Banteng semen. Despite the limited number of female cattle, results from these insemination efforts suggest possible improvements in both birth weight and overall body weight gain.

IV. CONCLUSION

The study concluded that Bali calves born through artificial insemination with frozen Banteng semen exhibited greater birth weight and body weight growth compared to the average Bali calves.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest with the results of this study.

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Evaluation of Biological Attributes on *Trichogramma chilonis* and *Trichogramma japonicum* on different Factitious Hosts under Laboratory Conditions

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Abstract— *The laboratory experiment was conducted during 2024 to study the different biological parameters of Trichogramma chilonis and Trichogramma japonicum on the factitious hosts Corcyra cephalonica and Cadra cautella. The present study revealed that 94.44 to 96.67 percent egg parasitization was recorded on C. cephalonica, which was found to be statistically at par with C. cautella eggs (93.33 to 96.67%). In the case of T.chilonis, percent parasitization ranged from 90.00 to 93.33% on both C. cephalonica and C. cautella eggs.*

A shorter development period of T. chilonis was observed (7.67 days) when reared on the eggs of C. cautella, which was found at par with the eggs of C. cephalonica (8.00 days). In the case of T. japonicum, the development period ranged from 8.33 to 8.67 days when reared on both factitious hosts. Adult longevity was higher when T. chilonis and T. japonicum were reared on C. cautella eggs compared to C. cephalonica eggs.

Fecundity was not affected by the number of eggs or host species, as results were statistically at par. In the case of T. chilonis and T. japonicum, maximum female parasitoid recovery was noticed from the parasitized eggs of C. cautella, which was at par with C. cephalonica. The number of host eggs showed significant differences in percent adult emergence of both parasitoids. The highest percent adult emergence of T. chilonis and T. japonicum was reported when one gravid female parasitoid was exposed to 10 eggs/card, and the results were significantly different from the other two treatments (20 eggs/card and 30 eggs/card).

Keywords— C. cephalonica, C. cautella, T. chilonis, T. japonicum.

I. INTRODUCTION

Trichogrammatids are polyphagous egg parasitoid wasps distributed globally and play a crucial role in biological pest control, especially against lepidopteran pests, by parasitizing the eggs of other insects, thereby supporting ecological balance and sustainable agricultural practices (Jalai et al., 2016; Mahankuda and Sawai, 2020). They are widely used in biological control strategies, especially in inundative releases. Over 200 insect species are parasitized by various strains of trichogrammatids (Tanwar et al., 2006).

Various methods involving the use of chemicals and breeding strategies have helped enhance the efficacy of these parasitoids as bioagents in the eco-friendly management of many crops. *Trichogramma* wasps are commonly reared on factitious hosts such as *Ephestia kuehniella*, *Sitotroga cerealella*, and *Corcyra cephalonica* to facilitate mass production for biological control applications. These artificial hosts enable controlled rearing conditions, ensuring a consistent supply of parasitoids (Knutson, 2000).

However, it is important to note that prolonged rearing on factitious hosts can lead to host preference shifts, potentially affecting the parasitoid's efficiency on target pests under field conditions. Therefore, monitoring and managing host use in laboratory settings is crucial for maintaining the effectiveness of *Trichogramma* wasps in biological control programmes.

The present study was carried out to evaluate the efficiency of *T. chilonis* and *T. japonicum* on different factitious hosts (*Corcyra cephalonica* and *Cadra cautella*) in the laboratory by assessing their biological attributes, i.e., percent parasitism, adult longevity, development period, fecundity, percent adult emergence, and sex ratio.

II. MATERIALS AND METHODS

The experiment was conducted in a Factorial Completely Randomized Design (FCRD) with twelve treatments, three factors, and three replications at the Biocontrol Laboratory, Department of Entomology, Dr. YSRHU-HRS, Ambajipeta, during 2024, to study the biological attributes of egg parasitoids *T. chilonis* and *T. japonicum* on the factitious hosts *C. cephalonica* and *C. cautella* eggs. Both parasitoids and factitious host egg cultures were reared at the Biocontrol Laboratory of Dr. YSRHU-HRS, Ambajipeta.

Twelve treatments were separated into different groups, i.e., 10 eggs/card, 20 eggs/card, and 30 eggs/card, respectively, for three replications. Similarly, other groups were made as per the requirement of the treatments. The desired-sized empty cards were smeared with gum, and host eggs were stuck on each card. These cards were then kept in glass tubes (15 × 2.5 cm). The host eggs were exposed to one gravid female parasitoid. The following observations were recorded.

2.1 Treatment Details:

2.1.1 Number of eggs parasitized:

Under laboratory conditions, 10, 20, and 30 eggs of *C. cephalonica* and *C. cautella* were exposed for parasitization by *T. chilonis* and *T. japonicum*. Parasitized eggs were recorded by counting the blackened eggs (Singh et al., 1998). The data recorded were converted into percentages, and percent egg parasitization was calculated.

Total Treatments: 12

Replications/Treatment: 3

Total Glass Tubes (15 × 2.5 cm): 36 glass tubes

T1: One female of *T. chilonis* / 10 eggs of *C. cephalonica*
T2: One female of *T. japonicum* / 10 eggs of *C. cephalonica*
T3: One female of *T. chilonis* / 10 eggs of *C. cautella*
T4: One female of *T. japonicum* / 10 eggs of *C. cautella*
T5: One female of *T. chilonis* / 20 eggs of *C. cephalonica*
T6: One female of *T. japonicum* / 20 eggs of *C. cephalonica*
T7: One female of *T. chilonis* / 20 eggs of *C. cautella*
T8: One female of *T. japonicum* / 20 eggs of *C. cautella*
T9: One female of *T. chilonis* / 30 eggs of *C. cephalonica*
T10: One female of *T. japonicum* / 30 eggs of *C. cephalonica*
T11: One female of *T. chilonis* / 30 eggs of *C. cautella*
T12: One female of *T. japonicum* / 30 eggs of *C. cautella*

2.1.2 Development period of *T. chilonis* and *T. japonicum* on different host eggs:

The duration between exposure of *C. cephalonica* and *C. cautella* host eggs to parasitoid females and adult emergence of *T. chilonis* / *T. japonicum* was recorded under laboratory conditions.

2.1.3 Adult longevity (in days):

Five newly emerged adult parasitoids per treatment were kept in small glass vials (7.5 × 1.21 cm) with a streak of honey on the inner wall and a strip of eggs. Adult longevity was determined from the day of emergence until death.

2.1.4 Fecundity:

The number of host eggs parasitized by the gravid female was counted, and fecundity was determined as per the method described by Miura and Kobayashi (1995). The number of eggs parasitized by a single female per day was used to express fecundity.

2.1.5 Sex ratio:

Emerged adults were categorized into male and female under a microscope based on morphological characters:

- **Female:** Antennae clubbed with few short hairs on flagellum.
- **Male:** Antennal hairs tapering and moderately long.

2.2 Percent adult emergence:

Out of total parasitized host eggs, the number of parasitoids emerged was counted based on emergence holes, and percent adult emergence was determined:

$$\text{Percent adult emergence} = \frac{\text{Number of black eggs with emergence hole}}{\text{Number of parasitized host eggs}} \times 100 \quad (1)$$

2.3 Statistical Analysis:

Data were analyzed using a three-factorial Completely Randomized Design (CRD) in OPSTAT software.

III. RESULTS AND DISCUSSION

3.1 Percent egg parasitization:

The data presented in Table 1 show that for *T. chilonis*, percent parasitization ranged from 94.44 to 96.67% on *C. cephalonica*, which was found at par with *C. cautella* (93.33 to 96.67%). For *T. japonicum*, percent parasitization ranged from 90.00 to 93.33% on both hosts.

Maximum parasitization occurred when parasitoids were exposed to 10 eggs/card, followed by 20 and 30 eggs/card. These findings agree with Kumari et al. (2020), who reported the highest percent parasitism of *T. chilonis* (89.33%) in *C. cephalonica* and 88.33% in *H. armigera*.

TABLE 1
PERCENT PARASITIZATION BY *T. CHILONIS* AND *T. JAPONICUM* ON DIFFERENT HOST EGGS

Parasitoid	10 eggs		20 eggs		30 eggs	
	C.cephalonica	*C.cautella*	*C.cephalonica*	*C.cautella*	*C.cephalonica*	*C.cautella*
T.chilonis	96.67	96.67	95	93.33	94.44	93.33
	-83.86	-83.86	-79.55	-77.71	-79.35	-75.36
T.japonicum	93.33	90	91.67	93.33	90	92.22
	-77.71	-75	-73.79	-75.24	-71.73	-76.72

	Factor 'A' (No. of eggs)	Factor 'B' (Host)	Factor ' C' (Parasitoid)	Interaction (AxBxC)
'F' test	NS	NS	NS	NS
SE(m)±	2.695	2.2	2.2	5.39
CD (p=0.05)	--	--	--	--

3.2 Development period:

Data in Table 2 show that the development period of *T. chilonis* was shorter (7.67 days) on *C. cautella* eggs and statistically at par with *C. cephalonica* (8.00 days). For *T. japonicum*, the development period ranged from 8.33 to 8.67 days on both hosts. These findings align with Dileep (2012), Funde et al. (2020), and Rathi and Ram (2000), who reported similar development durations on *C. cephalonica*.

TABLE 2
DEVELOPMENT PERIOD OF *T. CHILONIS* AND *T. JAPONICUM* ON DIFFERENT HOST EGGS

Parasitoid	10 eggs		20 eggs		30 eggs	
	C.cephalonica	***C.cautella***	***C.cephalonica***	***C.cautella***	***C.cephalonica***	***C.cautella***
T.chilonis	8	7.67	8.33	8	8.33	8
	-2.99	-2.94	-3.05	-3	-3.05	-2.99
T.japonicum	8.67	8.67	8.33	8.67	8.67	8.33
	-3.11	-3.11	-3.05	-3.11	-3.11	-3.05

	Factor 'A'	Factor 'B'	Factor ' C'	Interaction
	(No. of eggs)	(Host)	(Parasitoid)	(AxBxC)
'F' test	NS	NS	Sig	NS
SE(m)±	0.031	0.025	0.025	0.061
CD (p=0.05)	--	--	0.073	--

3.3 Adult longevity

As shown in Table 3, *T. chilonis* exhibited the highest adult longevity (8.67 days) when reared on *C. cautella*, significantly different from *C. cephalonica* (7.33 days). Similarly, *T. japonicum* adults lived longer (8.67 days) on *C. cautella* than on *C. cephalonica* (7.67 days). These findings support the observations of Shirazi (2006) and Funde et al. (2020).

TABLE 3
ADULT LONGEVITY OF *T. CHILONIS* AND *T. JAPONICUM* ON THE DIFFERENT HOST EGGS

Parasitoid	10 eggs		20 eggs		30 eggs	
	C.cephalonica	***C.cautella***	***C.cephalonica***	***C.cautella***	***C.cephalonica***	***C.cautella***
T.chilonis	7.33	8	7.67	8.67	8	8.67
	-2.89	-2.99	-2.94	-3.11	-2.99	-3.11
T.japonicum	7.67	8.33	8.33	8.67	8.33	8.33
	-2.94	-3.05	93.05)	-3.11	-3.05	-3.05

	Factor 'A'	Factor 'B'	Factor ' C'	Interaction
	(No. of eggs)	(Host)	(Parasitoid)	(AxBxC)
'F' test	NS	Sig	NS	NS
SE(m)±	0.035	0.028	0.028	0.07
CD (p=0.05)	--	0.083	--	--

3.4 Fecundity

Data in Table 4 reveal no significant differences among hosts regarding fecundity. *T. chilonis* parasitized 5.67–6.67 eggs per female, while *T. japonicum* parasitized 4.67–6.67 eggs. Fecundity was unaffected by host or egg number. Similar findings were reported by Funde et al. (2020) and Shirazi (2006).

TABLE 4
FECUNDITY OF *T. CHILONIS* AND *T. JAPONICUM* ON DIFFERENT HOST EGGS

Parasitoid	Fecundity /Per day/female					
	10 eggs		20 eggs		30 eggs	
	C.cephalonica	*C.cautella*	*C.cephalonica*	*C.cautella*	*C.cephalonica*	*C.cautella*
T.chilonis	6.67	6.33	6.33	5.67	6.33	5.33
	-2.77	-2.69	-2.7	-2.57	-2.7	-2.49
T.japonicum	5.67	5.67	4.67	5.33	6.67	5.67
	-2.57	-2.57	-2.37	-2.51	-2.77	-2.56

	Factor 'A' (No. of eggs)	Factor 'B' (Host)	Factor ' C' (Parasitoid)	Interaction (AxBxC)
'F' test	NS	NS	NS	NS
SE(m)±	0.075	0.061	0.061	0.15
CD (p=0.05)	--	--	--	--

3.5 Sex ratio

Data in Table 5 show that *T. chilonis* produced the highest female ratio from *C. cautella* (1:1.80), at par with *C. cephalonica* (1:1.78). *T. japonicum* showed a similar trend with *C. cautella* (1:1.73) and *C. cephalonica* (1:1.52). Comparable results were observed by Funde et al. (2020).

TABLE 5
SEX RATIO OF *T. CHILONIS* AND *T. JAPONICUM* ON DIFFERENT HOST EGGS

Parasitoid	10 eggs		20 eggs		30 eggs	
	C.cephalonica	*C.cautella*	*C.cephalonica*	*C.cautella*	*C.cephalonica*	*C.cautella*
T.chilonis	01:01.8	01:01.8	01:01.7	01:01.8	01:01.3	01:01.4
T.japonicum	01:01.2	01:01.6	01:01.5	01:01.7	01:01.0	01:01.3

	Factor 'A' (No. of eggs)	Factor 'B' (Host)	Factor ' C' (Parasitoid)	Interaction (AxBxC)
'F' test	NS	NS	NS	NS
SE(m)±	0.132	0.108	0.108	0.263
CD (p=0.05)	--	--	--	--

3.6 Percent adult emergence

Table 6 indicates that when 10 host eggs were offered, adult emergence of *T. chilonis* was 96.67% on both hosts. For *T. japonicum*, adult emergence was 96.30% on *C. cautella* and 89.63% on *C. cephalonica*. Significant differences were observed between treatments. When 20 and 30 eggs/female were provided, adult emergence ranged between 84.45–91.80% in both parasitoids. These findings align with Rathi and Ram (2000) and Funde et al. (2020).

TABLE 6
PERCENT ADULT OF *T. CHILONIS* AND *T. JAPONICUM* ON DIFFERENT HOST EGGS

Parasitoid	10 eggs		20 eggs		30 eggs	
	C.cephalonica	*C.cautella*	*C.cephalonica*	*C.cautella*	*C.cephalonica*	*C.cautella*
T.chilonis	96.67	96.67	84.45	89.45	91.8	89.28
	-83.86	-83.85	-67.2	-71.05	-73.41	-70.88
T.japonicum	89.63	96.3	89.06	89.28	91.4	89.12
	-74.65	-83.51	-70.69	-70.89	-73	-70.74

	Factor 'A' (No. of eggs)	Factor 'B' (Host)	Factor ' C' (Parasitoid)	Interaction (AxBxC)
'F' test	sig	NS	NS	NS
SE(m)±	2.022	1.651	1.651	4.043
CD (p=0.05)	5.902	--	--	--

IV. CONCLUSION

From the results of the present study, it is concluded that maximum female parasitoid recovery and shorter development periods of *T. chilonis* and *T. japonicum* were observed from parasitized eggs of both *C. cautella* and *C. cephalonica*. The highest percent adult emergence for both species was recorded when one gravid female parasitoid was exposed to 10 eggs/card, significantly different from the 20- and 30-egg treatments.

These findings are of great importance for utilizing the almond moth (*C. cautella*) along with the commonly used factitious host *C. cephalonica* in the preparation of trichocards in biocontrol laboratories.

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Building Resilience of Communities Living in Degraded Forests, Savannahs and Wetlands Through Ecosystem based Adaptation (EbA) Approach: Case study of Kayonza District

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***Abstract*—** *This article presents the role of Ecosystem–based Adaptation (EbA) approach to restore degraded forests, savannahs and wetlands and highlights priority options and select urgent and immediate EbA activities regarding adaptation planning processes addressing ecosystems to solve the problems associated with climate change, where this approach will use biodiversity and ecosystem services as part of an overall adaptation strategy to help people and communities adapt to the negative effects of climate change at local level through wetlands, savannahs and forests restoration.*

In general, the EbA approach will constitutes a decisive step in its search to respond to immediate and urgent needs for adaptation to negative effects of climate change in Kayonza District.

Keywords*— *Ecosystem-Based Adaptation, EbA, climate change adaptation, community resilience, degraded forests, savannah restoration, wetland restoration, Kayonza District, Rwanda, biodiversity, ecosystem services.

I. INTRODUCTION

Rwanda is currently highly vulnerable to climate change as it is strongly relient on rain-fed agriculture both for rural livelihoods. It depends on hydropower for half of its electricity generation. Rwanda has experienced a temperature increase of 1.4oC since 1970, higher than the global average and can expect an increase in temperature of up to 2.5oC by the 2050oC from 1970 (Green Growth and Climate Resilience, 2011 Kigali).

Kayonza District being located in Eastern Province of Rwanda, the region affected by drought with livelihoods essentially based on rain-fed agriculture, it is obviously vulnerable to negative effects of climate change. The agricultural use depends almost exclusively on the quality of the rainy season, which makes the area particularly vulnerable to climate change; the increased frequency of drought periods, floods and erosion presently observed considerably decreases the food availability in the area. The biomass represents the main source of energy for households and craft industries. The big pressure on firewood for energy needs and natural resources does not favour the protection of forests, savannahs and wetlands (Kayonza District Development Plan (2013-2018).

1.1 Definitions:

- **Climate change** is a change in climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods (UNFCCC, 1992).
- **Adaptation** can be used to refer to additional activities needed to prepare for climate change. This typically involves specific interventions (larger storm drains or new crop varieties) but can also involve broader social or economic strategies (e.g. irrigation system) (Green Growth and Climate Resilience, 2011 Kigali).
- **Climate resilience** can be used to describe a broader agenda than adaptation. It captures activities which build the ability to deal with climate variability-both today and in the future. Climate resilience building activities include many

existing development investment including those in the agriculture, food security, health, land management and infrastructure sectors (Green Growth and Climate Resilience, 2011 Kigali).

- Ecosystem-based approaches to adaptation are the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change. Ecosystem–based approaches for adaptation may include sustainable management, conservation and restoration of ecosystems as part of an overall adaptation strategy that takes into account the multiple social, economic and cultural co-benefits for local communities (GEF, 2012: operational guidelines on ecosystem-based approaches to adaptation, Washington, D.C).
- **Mitigation** refers to efforts to limit or absorb gas emissions which contribute to climate change. Greenhouse gases can be removed from the atmosphere by plants (called carbon sequestration), (Green Growth and Climate Resilience, 2011 Kigali).
- **Vulnerability:** The climate change vulnerability is similar to degree from which the ecological, social and economic systems are susceptible to be affected by disastrous effects of climate change, according to its sensitivity and capacity to face, therefore to adapt (UNFCCC, 1992).

II. VULNERABILITY OF CLIMATE CHANGE IN KAYONZA DISTRICT

The present strong dependency on natural resources in Kayonza makes economic activities directly dependent on climate conditions. In addition, because of overuse of natural resources, the ecosystems are more and more affected. These only two factors explain the vulnerability of Kayonza in a context of climate insecurity. Here, the vulnerability is similar to degree from which the ecological, social and economic systems are susceptible to be affected by disastrous effects of climate change, according to its sensitivity and capacity to face, therefore to adapt. The subjacent causes are not taken into account, the magnitude of risks, the extent of social and environmental problems and the emergencies linked to natural disasters and climate change risk to be underestimated (Report from Agriculture and Natural Resources Unit, 2016).

The analysis of vulnerability in Kayonza has simultaneously tackled biophysical vulnerability, which can be measured in relation to the extension of the periods of vegetation growth, the duration and frequency of dry and rainy periods, risks of floods, erosion and risks of drought, and social vulnerability, which can be measured by the level of education, income, poverty and diversification of the means of existence.

The qualitative approach in the evaluation of vulnerabilities has made it possible to identify a larger range of the vulnerabilities of areas, populations and sectors, even those that are not directly linked to climate but which actually hamper development.

The evaluation of the past and present vulnerability with the aim of building resilience of Kayonza’s adaptation capacity to climate change by the choice of urgent and immediate adaptation measures, at local level.

2.1 Negative effects of climate change:

In Kayonza, negative effects linked with disturbances of climate system affected the natural resources. In fact, a correlation exists between the increase in temperature and the humidity of the soil; the lowering of lake water levels and water flows, drying up of sources, agricultural productivity and appearance of paludism. A prolonged drought seriously affected Kayonza, such disasters are mostly provoked by climate change (NAPA, Rwanda, 2006).

2.2 Occurrence of extreme phenomena of drought and floods:

The same scenario of irregularities of rainfalls was observed. This provoked a famine in Kiyonza, which provoked an emergency intervention from the Government to the most vulnerable population of the area. Floods, droughts episodes constitute the major repetitive natural disasters for Rwanda associated with climate change (NAPA, Rwanda, 2006).

The most current risks are:

1) Prolonged seasonal drought, recurrent drought on two or three successive years as well as low precipitations have an important impact of leading to a loss lives, economic losses of among the affected population. The occurrence tendency of these events is very important and of high frequency.
2) Particularly intense rains coupled with short droughts (dry spells) alternating with low precipitations in rainy seasons also presents a recurring risk with localized impacts. The occurrence tendency of these events is considered as average but of high frequency.

2.3 Evaluation of vulnerability:

After identifying most frequent risks which are mainly droughts and heavy rains and high sensitivities to services rendered by ecosystems, means and modes of existence is now below localize most vulnerable regions and sectors.

TABLE 1
INVENTORY OF NEGATIVE EFFECTS OF CLIMATE CHANGE IN KAYONZA

Area	Phenomenon	Risk or immediate Consequence	Negative effect	Catastrophe registered
Kayonza District	Prolonged absence of precipitation.	Drought	Drop in Agricultural production and lack of water and food produces for the populations.	Famine and disseminated population.
				Water shortage, drying up of water sources, rivers, lakes
			Decrease of levels of lakes and rivers.	Drop in hydro electrical production.
			Lack of pasture for domesticated animals.	Disappearance of aquatic life (Hippopotamus…).
			Soil and forests degradation.	Decimated domesticated animals.
				Desertification tendency.
				Deforestation
	High precipitation.	Floods.	Destruction of biodiversity of humid zones	Environmental degradation and disappearance of rare species.
		Soil degradation & impoverishment	Destruction of plants in swampy and river zones.	Famines.
		Destruction of habitat.	Destruction of infrastructures in low zones.	Human loss.
				Erosion.
				Threatened human and animal lives.
		Wind	Destruction of biodiversity	Environmental degradation
				Erosion.
				Plant losses

Source: District Development Plan (2013-2018) for Kayonza District and report from Agriculture and natural Resources Unit, Kayonza District

The problems that are likely to be encountered by each sector such as forest and agricultural sector by causing: i) further reductions in the amount of arable land as a result of frequent soil erosion from floods; ii) deforestation, iii) reduced soil moisture content because of increased evaporation; and iv) crop losses owing to increased temperature and prolonged droughts.

In the environmental sector, climate change lead to ecosystem degradation and loss of biodiversity. For example, increased temperatures, droughts and floods cause animals to migrate as they search for environments that are more suitable. The water sector is also particularly vulnerable because prolonged droughts decrease the quantity and quality of water available.

The area is undergoing rapid utilization natural resources; this leads to an increasing of challenges associated with providing sustainable management of ecosystem. Aware that the communities lack necessary means to face the problems linked to climate change, EbA has been established to define the guidelines to restore wetlands, savannahs and forests.

2.4 What is the relationship between ecosystems and adaptation?

Ecosystems affect the climate, but climate change also affects ecosystems, their functions and the many benefits and services they provide to people, as well as the ability of ecosystems to regulate water flows and cycle nutrients.

Healthy ecosystems can play a major part in increasing resilience, helping people to adapt to climate change, and in reducing climate-related risk and vulnerability through the delivery of the range of services that play a significant role in maintaining human well-being.

- Ecosystem-based adaptation uses biodiversity and ecosystem services in an overall adaptation strategy. It includes the sustainable management, conservation and restoration of ecosystems to provide services that help people adapt to the adverse effects of climate change.
- Ecosystem-based adaptation can be cost-effective, generate social, economic and cultural co-benefits, and contribute to the conservation of biodiversity.

TABLE 2
PRINCIPLES FOR EFFECTIVE EBA

Principle	Requirements	Details
Promote resilient ecosystems	Modeling of projected climate change	EBA approaches cover a broad spectrum in land management, policy and project implementations.
	Revised systematic planning	
	Revision of protected area systems design	
Maintain ecosystem services	Valuation of ecosystem services	Maintaining ecosystem services is key – and, again, something that the field of conservation must develop better understanding of how to design and implement, and our ability to effectively measure benefits especially improve provided.
	Determine climate change impact scenarios	
	Identify options for managing ecosystems or managing use	
	Involve user communities in adaptation action	
	Trade-off analysis	
Support cross sectoral adaptation	Include approaches in national adaptation plans	New opportunities are opening up for partnerships and natural system solutions with many of societies sectors impacted by climate change. Reduce risks and disasters
	Incorporate ecosystem services in land/coastal management frameworks	
reduce risks and disasters	Restore key habitats that reduce vulnerability	There is growing interest in the security, public safety and disaster prevention communities -- we are seeing increasing awareness of climate impacts and for the potential of natural system solutions.
	Involve vulnerable communities in restoration efforts	
Complement infrastructure	Dam re-engineering – maintain ecological flows in rivers	Innovations and strategies like these, for complimenting infrastructure, are being tested now around the world.
	Dams, levees – Restoration of floodplains for flood attenuation	
Avoid maladaptation	Improve analysis of impacts from adaptation activities	Some engineered solutions can have significant negative impacts to natural systems
	Avoid inadvertent impacts on natural ecosystems and communities	

Source: UNEP, 2014: Ecosystem-based Adaptation: Framework, Guidelines and Training manuals

2.5 Ecosystem-based approaches to adaptation:

Natural ecosystems provide a wide range of goods and services, including resources such as water, soil, forests, and fisheries on which human lives and livelihoods depend. This dependency is more direct and natural resources more critical for survival in degraded areas, which makes role of ecosystems vital in operations developing country like Rwanda. It is recognized that attention needs to be given towards vulnerable ecosystems as well. However, projects that have reducing ecosystem vulnerability to climate change as a primary objective are best addressed in the context of global environmental benefits.

Management, conservation and restoration of ecosystems, that is informed with climate variability and expected climate change, can maintain and restore 'natural' infrastructure such as wetlands and forests, and savannahs whilst reducing biodiversity loss, and maintaining or enhancing ecosystem function. Furthermore, such approaches can improve the resilience of biodiversity and ecosystems to climate change so that they can continue to provide a full suite of ecosystem services. This is particularly important for sustaining natural resources on which vulnerable communities depend for their subsistence and livelihoods, and for providing alternative livelihoods in the face of climatic uncertainty. Such approaches should have a clear and robust monitoring system to track benefits to communities vulnerable to climate change ((GEF, 2012: Operational guidelines on ecosystem-based approaches to adaptation, Washington, D.C).

2.6 Guidelines for ecosystem based approaches to adaptation:

These guidelines are aimed at clarifying criteria for projects that intend to employ ecosystem-based approaches to adaptation and at providing practical, operational advice to implementing agencies, executing agencies and project proponents that seek funding. The guidelines below have benefitted from earlier work.

1. Identification of communities or development projects or programmes vulnerable to climate change
   - Using climate science and collection of local information on perceived changes in temperature, precipitation and local environments identify communities or development projects or programmes that are at risk.
2. Identification of ecosystems and related ecosystem services necessary for communities and development initiatives.
   - Identify goods and services that are essential for continued survival and well-being of vulnerable communities and operations of a development programme, in particular in the face of climate change impacts. Trace the source of such goods and services to ecosystems.
   - Identify key ecosystem services and relevant stakeholders through ecosystem service mapping.
3. Assessment of the status and vulnerability of the identified ecosystems.
   - Identify ecosystems of direct importance to vulnerable communities or development programmes, and determine their boundaries
   - With relevant measurements, studies and local knowledge determine the status of ecosystem health
   - Scope potential climatic and non-climatic threats that together may compromise ecosystem health and delivery of services
4. Using the assessments undertaken, establish linkages between humans and ecosystems
   - Under current climate conditions and future projections develop understanding of ecologically and socially relevant, as well as inter-linked, variables at suitable spatial and temporal scales.
   - Identify feedback linkages and loops between ecosystems and humans.
   - Establish direct linkages between climate change vulnerability of communities and development initiatives, and ecosystem health.
   - Develop an understanding of the key social processes between system components and the institutions that govern them.
   - Determine exposure, sensitivity and adaptive capacities of vulnerable groups and ecosystems to climate variability and future climatic change.
5. Development of ecosystem-based approaches for adaptation interventions based on scenario exercises, comprehensive assessments and comparison against an array of possible adaptation measures.
   - By using criteria developed through full and effective stakeholder participation (including those who manage and benefit from ecosystem goods and services), consider a suite of adaptation interventions that address community and/or development project vulnerability as well as the vulnerability of the ecosystems used in the (ecosystem-based) adaptation strategy.
   - Through cost benefit and feasibility analyses determine suitability of ecosystem-based approaches.
   - Consider possible trade-offs of implementing such ecosystem management alternatives at different temporal and spatial scales.
   - Establish multi-stakeholder teams including adaptation, resilience, disaster risk reduction, ecosystem service experts
   - Locate interventions within national and sub-national policies and strategies

6. Develop an action plan for implementation of ecosystem-based approaches to adaptation
7. Monitoring and evaluation system that assesses project effectiveness through indicators that measure ecosystem health, provision of ecosystem services to the vulnerable populations and reduction in the level of climate risks.
    - Include indicators that reflect ecosystem health
    - Include indicators that can measure ecosystem services delivered to vulnerable populations
    - Incorporate mechanisms to quantitatively or qualitatively assess vulnerability and resilience of the human communities after adoption of ecosystem-based adaptation measures.
    - Choose indicators that reflect resilience of all the components of the human-environment system and their inter-linkages.
    - Design monitoring systems that include both short- and long-term indicators, and operate at the most appropriate scale to assess project effectiveness and any changes in vulnerability.
    - Involve local communities in monitoring to enhance local adaptive capacity and monitoring efficiency
    - Through a participatory process, regularly monitor, and evaluate the adaptation benefits to communities, and adjust the adaptation actions as necessary.

2.7 Importance of Ecosystem based Adaptation

- EbA provides many benefits to communities, for example through the maintenance and enhancement of ecosystem services crucial for livelihoods and human well-being, such as clean water and food. Appropriately designed ecosystem management initiatives can also contribute to climate change mitigation by reducing emissions from ecosystem loss and degradation, and enhancing carbon sequestration.
- Ecosystem-based Adaptation involves a wide range of ecosystem management activities to increase resilience and reduce the vulnerability of people and the environment to climate change.
- To promote the resilience of livelihoods;
- To reduce the impacts of natural disasters such as storms and floods, on vulnerable people and ecosystems;
- To build the capacity of civil society and government institutions to support integrated approaches to adaptation;
- To increase awareness of the underlying causes of vulnerability (degraded ecosystems, poor governance, unequal access to resources and services, discrimination and other social injustices);
- To promote the sustainable management and conservation of biodiversity to maintain the benefits provided by ecosystems (e.g. provision of food and shelter).

2.8 Gaps and needs to EBA:

1. Lack of robust information on EBA options and measures in comparison to more traditional adaptation technologies (references)
2. Training tools, e.g. to support NAPA, and NAP implementation, targeted training at decision –making project level
3. Synthesis and sharing of practical learning

III. THE WAY FORWARD

3.1 Implementation of EbA in context of restoration of degraded forests, savannahs and wetlands in Kayonza:

Ecosystem-based Adaptation involves a wide range of ecosystem management activities to increase resilience and reduce the vulnerability of people and the environment to climate change, Such as

- sustainable agriculture,
- integrated water resource management,
- And sustainable forest management interventions that use nature to reduce vulnerability to climate change.

The key adaptation options proposed are the ones which should be integrated into the District development Plan and annual action plan:

- Promotion of non-rain-fed agriculture (irrigation system)
- Promote rain water harvest system
- Introduction of species resistant to drought
- Reinforce early warning and rapid intervention systems;
- Develop alternative sources of wood energy (biogas, gas, solar energy…)
- Rational utilization of wood energy (cooking stoves)
- Tree planting of forests, fruit and agroforestry (reforestation and afforestation)
- Restoration of wetlands
- Application of organic manure
- Promotion of non-agricultural activities;

3.2 Land degradation:

Agriculture has led to overexposure of most soils to soil erosion pressures. Thus, several factors of which the most important are the deforestatio, inappropriate farming practices and overgrazing have been responsible for various forms of Land degradation.

Proposed solutions

- Protection of steep slope farm land;
- Terracing and contouring of farms on gentle slopes
- Reforestation and Afforestation;

3.3 Sedimentation:

Extensive soil erosion in the region leads to severe sedimentation, which causes the silting of wetlands and lakes. A significant portion of this sediment load is transported downstream into lakes such as Kibare and Gishanda, resulting in declining water quality. This degradation not only affects aquatic ecosystems but also contributes to the proliferation of waterborne diseases and the creation of unfavorable conditions for aquatic life. The most prevalent waterborne diseases include malaria, diarrhoea, cholera, and bilharzia, which often reach epidemic levels during the rainy season. Malaria remains a major concern, as the parasites have increasingly developed resistance to commonly available and affordable treatments, and cases have recently been reported in previously non-endemic mountainous areas.

Proposed solutions

- Sediment retention structures;
- Rain harvesting and storage;
- Small water reservoirs;
- Terracing and contouring of farms on gentle slopes

3.4 Water pollution:

Resulting from a combination of siltation and poor waste management, degradation of catchment areas and inappropriate management of municipal and industrial wastes. Water pollution from use of pesticides and fertilizers as well as pollution from mining are still marginal but need careful monitoring.

Proposed solutions

- Sediment retention structures;

- Rain harvesting and storage;
- Small water reservoirs;
- Village infrastructure (drinking water boreholes, improvement of access roads and protection of natural springs);
- Wetlands rehabilitation;

3.5 Deforestation:

It has resulted in increasing shortage of timber, fuelwood, and other wood and non-wood products.

Proposed solutions

- Catchment or forest protection;
- Afforestation and reforestation
- Agroforestry

3.6 Other pressures on wetlands:

It also includes the extraction and mining of stones, clay, peat, and other construction materials, as well as sedimentation in valleys resulting from intense erosion on steeply sloping hills during the rainy season.

Proposed solution

- Wetlands rehabilitation

3.7 Loss of habitat for biodiversity:

The loss of habitats and biodiversity in the aquatic and terrestrial ecosystems are the consequence of conversion of forests, w etlands, range lands and other natural ecosystems into agricultural land, settlements and other activities

Proposed solution

- Wetlands rehabilitation;

3.8 Overfishing and/or inappropriate exploitation:

Overfishing and inappropriate exploitation threaten the fishing potential of lakes and are further exacerbated by the absence of a transboundary framework to regulate and monitor cross-border fishing activities. A major concern is the limited recognition of the potential of fisheries—both capture fishing and wetland-based fish farming—as important sources of affordable animal protein, household income, and recreation for local communities.

Proposed solutions

Aquaculture and stocking and restocking of inland satellite lakes for enhanced Fisheries Resources.

The interventions will include support to income generating activities benefiting the poor such as:

- Terracing and contouring of farms on gentle slopes;
- Horticulture and economic trees, forage and livestock development;
- Small scale Irrigation and drainage activities;
- Livestock development;
- Aquaculture, small scale fish processing, and cold storage facilities.

IV. RECOMMENDATIONS

4.1 Capacity building:

Strengthening technical capacity of local institutions and participating local communities to plan and implement EbA in Kayonza. To achieve this, Component 1 will: i) increase the technical capacity of environmental committees, local authorities, relevant private sector actors and user groups on EbA planning and implementation; iii) update and increase the availability of technical knowledge on EbA best-practices and complementary green technologies; iv) increase awareness and knowledge of local communities, and school students on EbA and climate change.

4.2 Ecosystem based Adaptation implementation:

- Training sessions at the local level should primarily be directed at: i) DEOs; ii) environmental committees; and iii) private sector actors, NGOs and CBOs.
- The training shall increase the technical capacity of the participants to prioritise, conceptualise, plan and implement EbA. Particularly, the training sessions will focus on the following technical aspects of EbA: i) selection of plant species that are resilient to droughts or floods; ii) selection of plant species that have stabilising effects on soil; selection of indigenous species in restoration activities and iii) planning of restoration activities to increase resilience of local communities to climate change in the ecosystems relevant to Kayonza District.
- Additionally, technical guidelines should be produced for the application of green technologies that promote the sustainability of the restoration activities (e.g. biogas, solar energy) and promote the use of climate resilient techniques in agriculture (e.g. organic composting and irrigation with treated wastewater). Furthermore, developing a map of priority ecosystems will facilitate the prioritisation of EbA interventions nationally.

Campaign to raise public awareness. This campaign shall target the local communities living in degraded forests, savannahs and wetlands to increase local awareness of the benefits of EbA. The increased public awareness of the predicted effects of climate change and the benefits of EbA should support the local up scaling of EbA implementation and increase human capacity to plan and implement EbA at local level.

V. CONCLUSION

This study demonstrates that the Ecosystem-Based Adaptation (EbA) approach plays a vital role in enhancing the resilience of communities living in degraded forests, savannahs, and wetlands of Kayonza District. By focusing on ecosystem restoration and sustainable management, EbA strengthens the natural capacity of the environment to buffer against the adverse impacts of climate change, including droughts, floods, and soil degradation. The findings reveal that healthy ecosystems are crucial for ensuring water availability, improving soil fertility, maintaining biodiversity, and supporting rural livelihoods.

Integrating EbA into local and district development plans is essential to promote sustainable adaptation practices. The study highlights key interventions such as reforestation, afforestation, wetland rehabilitation, rainwater harvesting, adoption of drought-resistant crops, organic farming, and the use of renewable energy. These measures not only reduce vulnerability but also contribute to long-term environmental sustainability and poverty reduction.

Furthermore, building local institutional capacity, strengthening policy implementation, and increasing community awareness are critical for the successful application of the EbA approach. Overall, the research concludes that Ecosystem-Based Adaptation provides an effective, inclusive, and cost-efficient pathway for restoring degraded ecosystems, enhancing climate resilience, and supporting sustainable development in Kayonza District and other similar ecological zones in Rwanda.

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Socio-Demographic Status of Onion Cultivators and Major Correlates of Onion Production: A Study from Pabna, Bangladesh

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Abstract— *Onion cultivation plays a vital role in the agricultural landscape of North-West Bangladesh, though Bangladesh experiences a great gap between national production and consumption. The main aim of the study is to show the socio-demographic status of onion producers in North-West Bangladesh (Pabna) along with key correlates of onion production. In order to gather primary data from a sample of 100 onion farmers who were randomly selected from four unions in the study area, a face-to-face interview method was used. Descriptive statistics was used to show the socio-demographic status and Spearman's rank-order correlation (Spearman's rho) was used to measure the strength and direction of the relationships between pairs of variables: (i) total seed cost and output in kg, (ii) Age of farmers and involvement years in Onion production, and (iii) output in kg and after harvesting cost. Most of the farmers were found experienced which also indicates a statistically significant strongly positive relationship between age and involved years of farmers ($\rho = .685, p<0.01$), though maximum farmers were found as having lower formal education with lower annual income. A statistically significant relationship was also fund between total seed cost and output though the relationship is weak ($\rho = .208, p<0.05$), underscoring that there are other factors also which can affect production. A significant moderate positive relationship was found between output and after harvesting cost ($\rho = .508, p<0.01$) which indicates that the more production, the more economic burden on the farmers. Despite facing various problems, 90% farmers wanted to continue production in future.*

Keywords*— *Onion production; Agriculture in Bangladesh; Statistical Analysis; Smallholder farmers; Supply chain in Agriculture.

I. INTRODUCTION

Bangladesh is an agro-based country. The country is endowed with many natural resources, including a variety of temperate zones and vast amount of productive land, making onion production a very promising industry for cultivation, marketing, processing, and export. This country is rich in natural resources and its weather is excellent for onion cultivation. Throughout the world, onion (*Allium cepa*) is a significant herbaceous bulb and spice crop, including Bangladesh. Onion is a major cash crop of Bangladesh and it is largely cultivated in Bangladesh [4]. It is a spice crop that is used as a spice in our food and salad. It also acts as medicine for many diseases since it contains calcium, carbohydrates, protein, vitamin C and E. In Bangladesh, we use onion every day and cannot think a day without onion.

Livelihoods of many people in the village are mainly based on onion, some are involved in onion cultivation and others are involved in onion trading which is profitable in most cases. Onion is produced in all area of Bangladesh and largely cultivated in profitable scale in the greater districts of Rajshahi, Dhaka, Faridpur, Dinajpur, Jessore, Pabna, Rangpur and Kushtia. Bapari *et al.* [5] conducted a study on onion production in Sujanagar and Santhia upazila of Pabna. They found that onion production is profitable and they found a profit of Tk. 26883.48 per bigha, though they found some problems in onion production like lack of storage facilities, limited access to quality seeds etc. Anjum and Barmon [2] explored a study on profitability and comparative advantage of onion in two districts named Jhenaidah and Kushtia. They also found that onion production is profitable in both districts with a BCR of 2.02 in Kushtia and 1.83 in Jhenaidah. Haque *et al* [8] directed a study in Magura Faridpur and Rajshahi and observed that onion is a highly profitable crop with a BCR of 1.85 and the profitability from onion is higher than the profit from other crops like cabbage, mustard, and groundnuts. Islan *et al.*[12] observed a study by categorizing farmers as small, medium, and large based on farm size and found that onion production was profitable for all farmers with an overall undiscounted BCR of 1.74. Islam et al.[11] conducted a study to analyze the value chain of onion and found onion production as profitable where a BCR of 1.55 was found. They also found that farmers add the highest value of 29.14% in the supply chain and receive the highest net marketing margin of 42.51%. Mila et al. [13] explored a study to show the onion supply chain and find out barriers faced by stakeholders before and during the COVID-19 pandemic. They found that onion production is viable with a BCR of 1.19.

According to BBS (2024) 2917 (000 M. tons) onion was produced in 514 (000 acres) area in Bangladesh in 2023-24 fiscal year which was 2547 (000 M. tons) in 503 (000 acres) just in immediate past fiscal year. Hossain, Abdullah and Parvez [10] did a time series analysis of onion production in Bangladesh using ARIMA (0,2,1) model and the model forecasted a steady increase in onion production from 2014 to 2023, from 1.24 million metric tons to 1.88 million metric tons. While onion output is growing daily, in a land-starved nation like Bangladesh, high population growth may make it impossible to offer local demand. There is a huge lack of onion compared to the total demand. As there is land constraint, it is not possible to increase the area under cultivation in order to enhance onion production; however, there is a chance to do so by improving current production methods and adopting advanced technology. Baree [6] conducted a study on technical efficiency of onion in Santhia upazila of Pabna district and showed that the yield of onions per hectare will increase by 0.0718 percent, 0.3026 percent, and 0.0442 percent, respectively, if the labor force, land areas, and capital costs are all increased by 1%. They found mean technical efficiency 83% which indicates that, with the present level of material and technology, onion farmers are producing 17% less output than the maximum possible. But, at the same time, he found that as the education of farmers rises the effect of technological inefficiency grows because most of the educated farmers not only depend on agriculture for their livelihood but also have other income sources. Hossain *et al.* [9] observed that Bangladesh annually produces 1.7 million tonnes of onions, yet the demand stands at 2.2 million tonnes, highlighting a considerable shortfall between production and consumption. Bangladesh depends on onion imports from neighboring countries (i.e., India, Myanmar) to meet its domestic demand as proposed by Ahmed and team [3]. This trade dependency significantly rinsings the country's foreign currency reserves, emphasizing the urgent need to enhance domestic onion production and reduce import reliance [1]. Pabna is well-known for onion production. Among the 64 districts of Bangladesh, highest amount of onion is produced in Pabna. Bapari *et al.* [5] did a study on onion production in Sujanagar and Santhia upazila of Pabna and Baree [6] conducted a study only in Santhia upazila. Again, Islan *et al.* [12] conducted a study in Durgapur, Sadarpur, Sujanagar of Bangladesh and Haque *et al.*[8] directed a study in Magura Faridpur and Rajshahi about onion production. But there is no study solely in Sujanagar of Pabna. It has been passed so many years since there is no study in Sujanagar. So, our concern is about Sujanagar upazila. This study will help people to know about the socio-demographic status of onion cultivators and interrelation among various variables of onion production in Sujanagar upazila of Pabna district. The main objectives of the study are:

1) To show the socio-demographic status of onion farmers in Sujanagar upazila of Pabna;
2) To determine the interplay between seed cost and output, age and involved year of farmers in onion farming and output and after harvesting cost.

II. METHODOLOGY

2.1 Selection of the Study Area:

On the basis of high concentration of onion cultivation and production, Pabna district is considered as one of the leading onion producing zone in Bangladesh. So, among the 64 districts of Bangladesh we have selected Pabna district as our study area. There are 9 sub-districts in pabna district. We have collected our data from Sujanagar of Pabna district. Sujanagar upazila has ten unions and Manikhat, Satbaria, Hatkhali and Raninagar have been chosen randomly from the union. Among the union of Manikhat union data have been collected from Manikhat, Dashpara, Toilkundu, Bonkola, Khetupara, Bil khetupara, Chor Gojaria and Ulat village. In case of Satbaria union data have been collected from Ramchandrapur village. From Hatkhali union data have been collected from Hatkhali and Soidpur villages. And in case of Raninagar union data have been collected from Raninagar village.

2.2 Study Period:

With the aid of pre-designed and pre-tested interviews, data have been obtained using the survey method during November 2022 to April 2023. To achieve the goals of the study, the obtained data will be edited, summed up, tabulated, and analyzed. The author personally visited the area on multiple occasions to gather additional data.

2.3 Sampling Size:

Total number of onion cultivator in the sampling villages is around 5000. To meet our objectives, we have collected data from 100 onion cultivators. Not only 100 cultivators but also middlemen, dealers, stockiest, wholesalers, retailers, and final users or customers in Pabna district are also population of the survey. Various information have been collected from middlemen, dealers, stockist, wholesalers, retailers, and final users or customers in Pabna district.

2.4 Preparation of Survey Schedule:

Before collecting data from survey method it is mandatory to set a questionnaire for interview or communication. According to the objectives of the study one set of formal questionnaire or interview schedules was prepared for farmers and an informal schedule was set for middlemen, dealers, stockist, wholesalers, retailers, and final users or customers. Through the interview schedule, information on the volume of sales, places where sales and purchases are made, production costs, marketing costs, sales prices, and purchase prices, who to buy from and who to sell to, the amount of post-harvest loss suffered by farmers and middlemen, problems faced by supply chain stakeholders, and their potential recommendations will be gathered. After the necessary corrections, modifications, and adjustments, all of the schedules were pre-tested and then completed.

2.5 Data Analysis:

To show socio-demographic status, Microsoft Excel was used to analyze collected data and statistical software SPSS was used to determine the relationships between key correlates of onion production. As the data were not normally distributed and the relationships between each pair of variables were not strictly linear, Spearman's rho was used to examine the direction of the monotonic relationships between three pairs of variables: (i) Total Seed Cost and Output, (ii) Farmer Age and Involved years in Onion Production, and (iii) Output and After Harvesting Cost. The rho (ρ) can range from -1 to +1, and the closer the values to +1, the stronger the relationship.

III. RESULTS AND DISCUSSION

3.1 Age of the Farmers:

Age distribution contributes a pivotal role for the improvement of farming activities as found by Blijham et al., [7]. Aged farmers normally possess higher production experience which helps to higher production. On the other hand, too much aged farmers become physically less strong and can have negative impact on production. Baree [6] found that as age increases by one percent, onion production decreases by 0.0090 percent. In this case, middle aged farmers are considered as best suitable for better yielding. In our study area, 42% of the respondents are middle aged which indicates that almost half of the farmers are experienced farmers (Figure 1). Only 20% respondents are young (age 20-35).

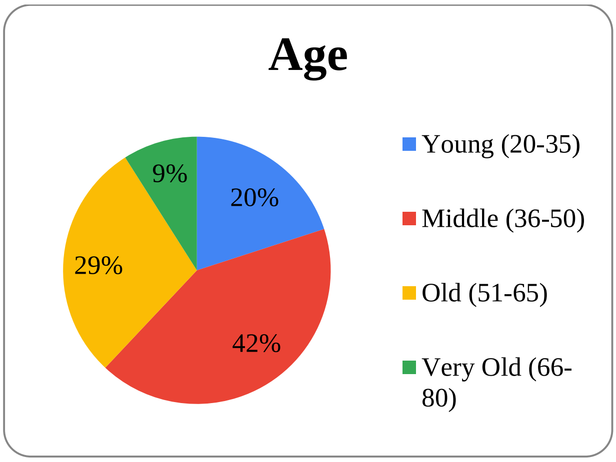

FIGURE 1: Age of the Respondents

3.2 Number of Year Involved in Onion Production of Farmers

The horizontal bar chart (Figure 2) illustrates the involvement of the farmers in onion production. 43% of the respondents are highly experienced (21-30), whereas 13% of the respondents have experience of 31-40 years. So, it can be said that more than half of the respondents are highly experience in onion production which is good sign for production.

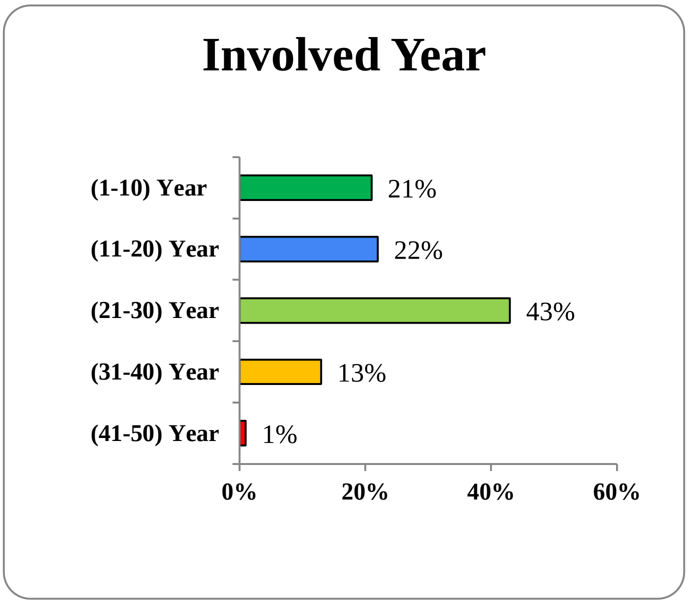

FIGURE 2: Involved in Onion Production (in years)

3.3 Education Level of the Farmers:

Though the application of education can increase production, in reality, the more educated a person is, the higher inclination of aversion from agricultural production. In the study area, 56% of the respondents have primary education (0-5 in numbers) indicating that most of the farmers are lower educated. A total of 14% farmers have higher education.

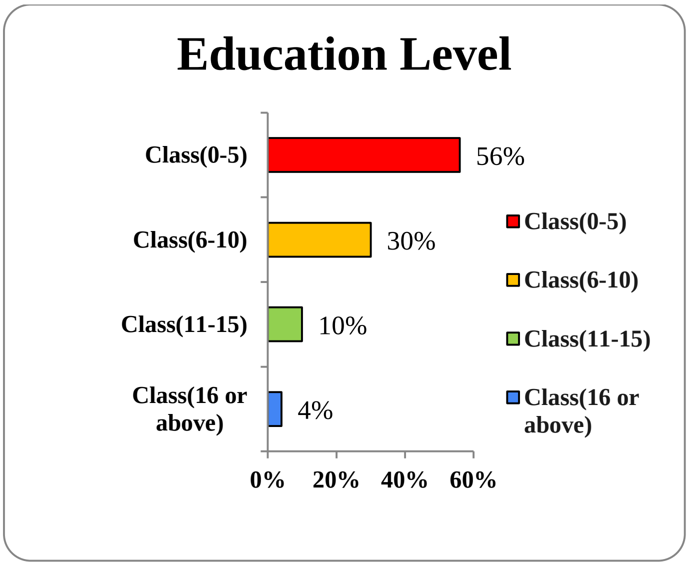

FIGURE 3: Education of the Respondents (in years)

3.4 Status of Owning Land of the Farmers:

In the study area, two types of farmers were found, one who have their own land and another who do not have. The farmers who do not have their own land cultivate land by rent which increases their production cost. Almost 56% of the total farmers have their own and whereas 44% do not have (Figure 4).

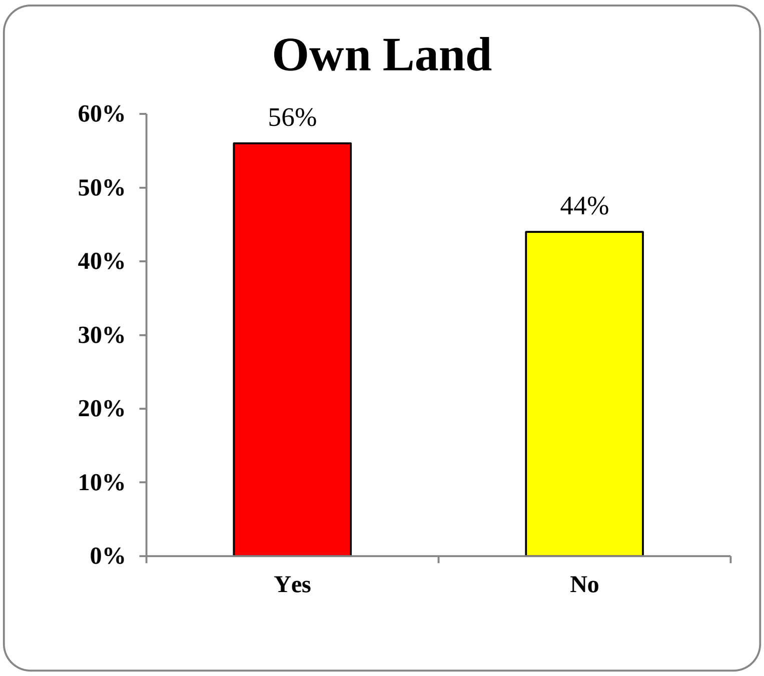

FIGURE 4: Status of Owning Land

3.5 Annual Household Income of the Farmers

Annual income may have positive impact on production because farmers having higher seeds can afford high quality of seeds, skilled labor, modern technology etc. In the study area, 48% farmers have annual income of Tk. one lac to two lacs (Figure 5). It is the lowest annual income in the study area. Only 8% farmers have annual income of above Tk. 5 lacs.

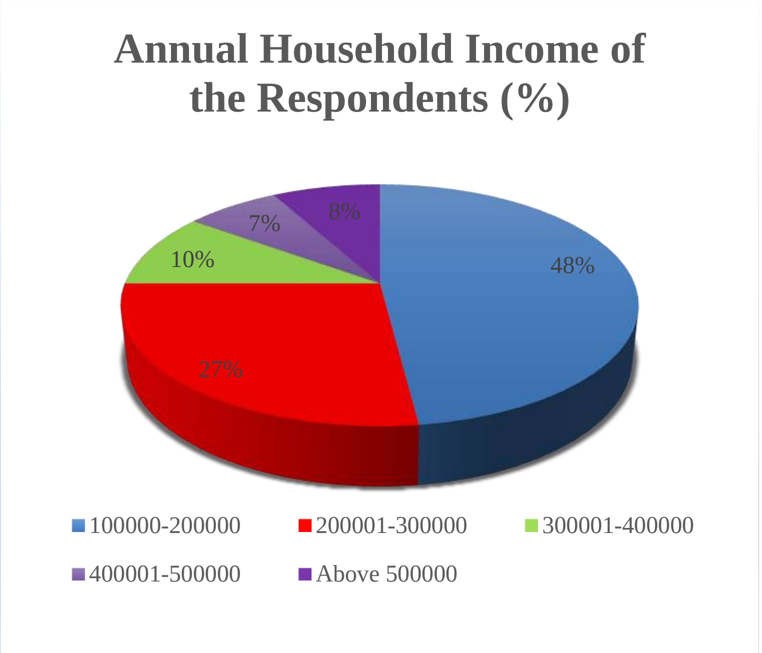

FIGURE 5: Annual Household Income of the Respondents (in tk.)

3.6 Types of Onion Seed Used:

There are various types of onion available named King, Hybrid, Deshi, Cross King, Queen, Sultan King, Khan Hybrid and so on. A diversification was seen in the use of onion seed in the study area. The most used onion seeds are King, Deshi and Cross King. They are used by 36%, 37% and 29% farmers respectively.

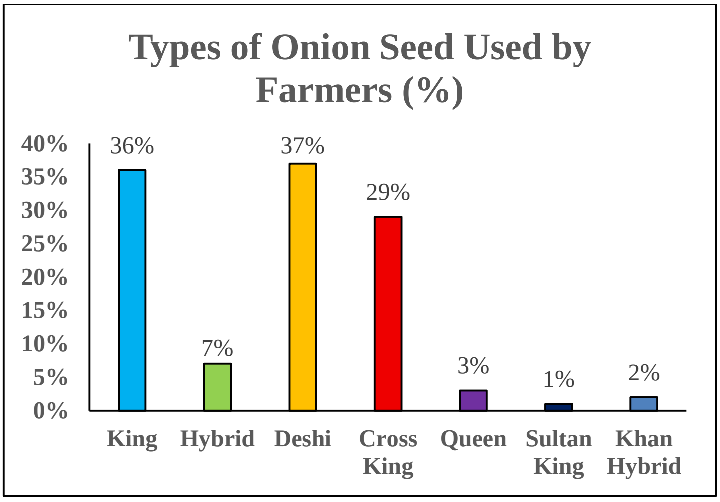

FIGURE 6: Types of Onion Seed Used by Farmer

3.7 Correlations between Total Seed Cost and Output

Spearman's rank order correlation was used to find out the relationship between total seed cost and output. Before calculation, visual representation was used to examine the linearity between these two variables and found non-linear relationship. At the same time, both of the variables were found not to be normally distributed. The table 1 shows that there exists a weak positive relationship between total seed cost and output and the relationship is statistically significant, ρ = .208, *p*<.05, two-tailed. The relationship indicates that as total seed cost increases, output also tends to increase but there are other factors also which can affect production.

TABLE 1
SPEARMAN'S RHO RESULTS

Variable		Total Seed Cost	Output
Total Seed Cost	Correlation Coefficient	1	.208*
	Sig. (2-tailed)	.	0.038
	N	100	100
Output	Correlation Coefficient	.208*	1
	Sig. (2-tailed)	0.038	.
	N	100	100

. Correlation is significant at the 0.05 level (2-tailed)

3.8 Correlations between Age and Involved Year in Onion

To determine the relationship between age and involved year, Spearman's rank order correlation was also used as the variables are not normally distributed and there exists non-linear relationship between them. Table 2 shows the rank order correlation was found strongly positive and statistically significant, ρ = .685, *p*<.01, two-tailed. This indicates that as age of the respondents, the involved year or experience also increases.

TABLE 2
SPEARMAN'S RHO RESULTS

Variable		Age	Involved Year in Onion
Age	Correlation Coefficient	1	.685**
	Sig. (2-tailed)		0
	N	100	100
Involved Year in Onion	Correlation Coefficient	.685**	1
	Sig. (2-tailed)	0	
	N	100	100

****. Correlation is significant at the 0.01 level (2-tailed)***

3.9 Correlations between output and Cost After Harvesting

Along with various types of costs, production requires cost after harvesting. A Spearman's rank order correlation was also used to determine the relationship between output and cost after harvesting as these variables were also fit for the test. A statistically significant moderate positive relationship (ρ=.508) was found between these two variables, indicating that as output increases, cost after harvesting also increases. This result underscores the pecuniary burden of supervising larger harvests.

TABLE 3
SPEARMAN'S RHO RESULTS

Variable		Output	Cost After Harvesting
Output	Correlation Coefficient	1	.508**
	Sig. (2-tailed)		0
	N	100	100
Cost After Harvesting	Correlation Coefficient	.508**	1
	Sig. (2-tailed)	0	
	N	100	100

*****. Correlation is significant at the 0.01 level (2-tailed)***

3.10 Problems Faced by Onion Farmers

During and after production, farmers face various problems like labor shortage, high wage of labor, high cost of various types of materials etc. As figure 7 shows the most facing problem is high price of fertilizers and pesticides (60%). As without these, production is not possible, higher price of them lead to increase the production cost. Additional wage is another major problem faced by farmers as there is labor shortage this problem arises. Most of the problems are money related problems which is a major constraint to production. Low quality of seeds is another problem which is faced by 13% of the farmers. Sometimes, low quality of seeds is mixed with good quality seeds which affect production badly.

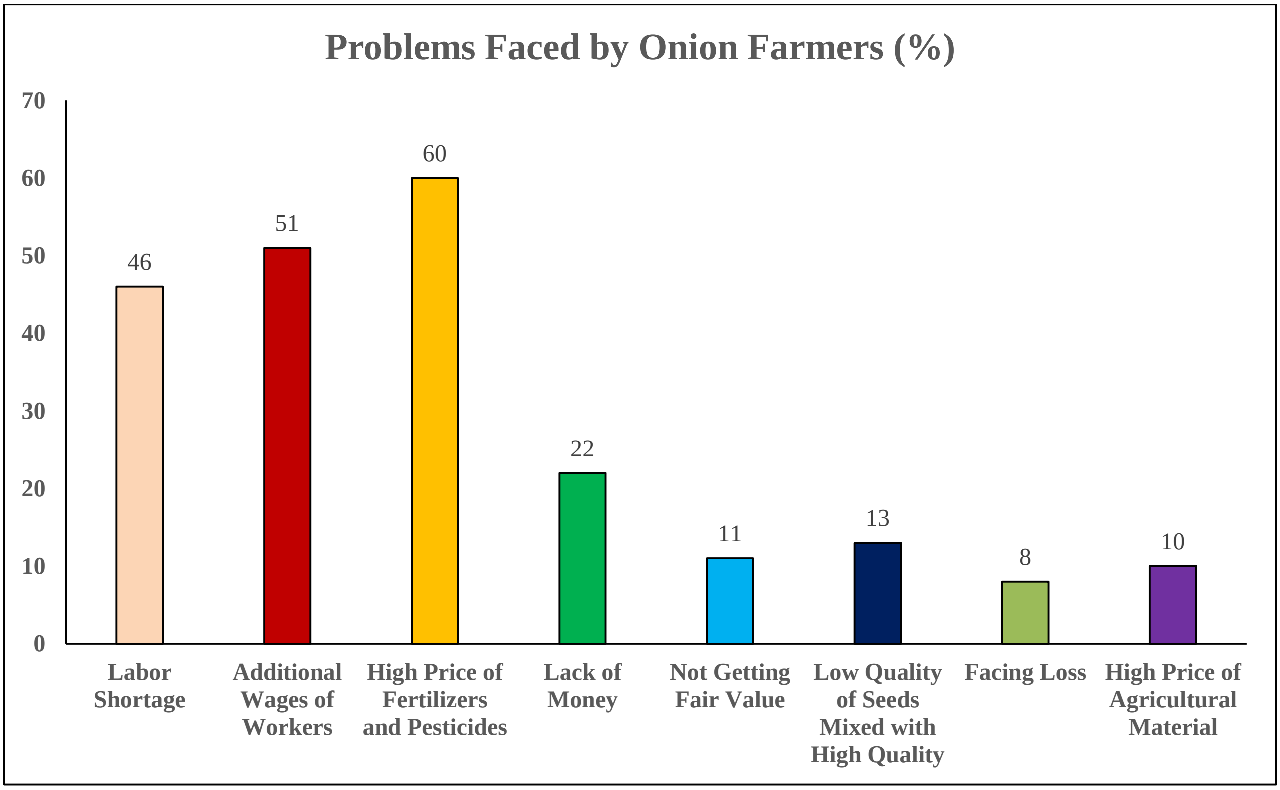

FIGURE 7: Problems Faced by Onion Farmers

3.11 After Harvesting Problems Faced by Farmers:

Harvesting or collecting the products is not the last stage of production. After harvesting, there are so many stages like sorting, storing, transporting etc. before reaching to customers. The common problem faced by farmers is decomposition of onion. As during harvesting period, the price of onion drastically falls the farmers tend to not to sell and face decomposition of onion. 74% of farmers said that they face the problem of decomposition. Additionally, there is storage problem too which may lead to decomposition. Another big problem faced by farmers is uses of fan as more fan is needed to store onion. Lack of vehicles and shortage of women labor are also problem though they are faced by a few.

TABLE 4
AFTER HARVESTING PROBLEMS FACED BY FARMERS

Problems	Percentage of Farmers
Fan has to be used	34
Decomposition of onion	74
Storage problem	40
Lack of Vehicles	7
Shortage of women labor to cut leaf	3

Source: Field Survey, 2023

3.12 Want to Continue Onion Production or Not:

As the farmers face various types of problems in onion production from the beginning of production process to the reaching of the product to the hand of customers or retailer seller, a question was asked whether they want to continue to produce onion in future or not. The result is shown in below figure (Figure 8). 90% of the farmers said that they want to continue onion production in future and the rest 10% said they do not want. The result indicates that onion production might be profitable in spite of having various types problems.

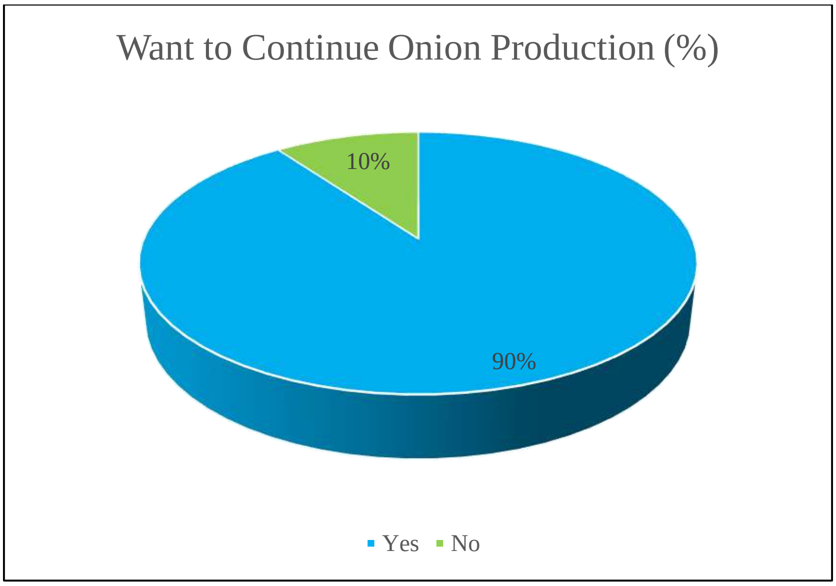

FIGURE 8: Whether Want to Continue Onion Production or Not

3.13 Suggestions by Farmers to Improve Onion Cultivation

Farmers were asked to share suggestions according to their production experience which can increase onion production or encourage farmers to be engaged in onion production. From various types of suggestions five suggestions are given below (Table 5). 66% of the farmers shared that import of onion should be stopped because import of onion leads to decrease the price of price which contribute to lower profit. 55% of the farmers said that price of pesticide has to be reduced. A fixed price of onion, establishing training institutions and loan on low interest rate were also suggested.

TABLE 5
SUGGESTIONS BY FARMERS TO IMPROVE ONION CULTIVATION

Suggestions	Percentage of Farmers
No import	66
Price of pesticide has to be reduced	55
A fixed price has to be set	35
Training institutions have to be established	28
Loan has to be given on low interest rates	20

Source: Field Survey, 2023

IV. CONCLUSION

The study was divided in two parts- socio-demographic status of onion producers and key correlates of onion production. Socio-demographic status like age, education, family member, annual income, involvement of years can affect any kind of agricultural production. Though education is not directly applied or educated people in Bangladesh rarely come in farming profession, age, family member, involvement years directly can affect farming. The socio-demographic results reveal that the farmers are well experienced but not that much educated and most of the farmers are not financially stable. Mainly three pairs of key correlates were tested using spearman's correlation test and all of them found statistically significant. There was a weak but positive relationship found between total seed cost and output ($\rho = .208$), a strong positive relationship was found between age and involved years ($\rho = .685$) and a moderate positive relationship was found between output and cost after harvesting ($\rho = .508$). The farmers face various types of problem from the beginning of the production to the selling of the product. Yet 90% of the farmers expressed their opinion that they want to produce onion in future, indicating the profitability of onion. Farmers were concerned about high import of onion. Government and the concerned authority should come forward and take proper initiative regarding this matter.

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Evaluating Agricultural Policy and Performance in Liberia (2004-2024): Implications for Policy in Post-Civil War Liberia

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Abstract— *This paper synthesizes a comprehensive review examining two decades of agricultural policy formulation, implementation, and performance in post-conflict Liberia (2004-2024). Following extensive civil conflict (1989-2003), Liberia's agricultural sector employing approximately 70% of the population and contributing nearly 40% to GDP faced unprecedented reconstruction challenges. The analysis reveals significant policy-performance gaps, characterized by ambitious frameworks undermined by weak implementation capacity, inadequate funding, poor infrastructure, and governance challenges. While progress has been achieved in policy formulation and institutional rebuilding, agricultural productivity remains low, food insecurity persists at 41%, and rural poverty continues to affect 54% of agricultural households. This synthesis contributes to the discourse on post-conflict agricultural development by identifying critical success factors and persistent constraints in fragile state contexts.*

Keywords— Agricultural policy, post-conflict reconstruction, food security, smallholder farmers, Liberia, policy implementation, institutional capacity.

I. INTRODUCTION

Liberia emerged from fourteen years of devastating civil war (1989-2003) with its agricultural sector in ruins. By 2003, agricultural production had collapsed to approximately 30% of pre-war levels, infrastructure was destroyed, human capital was depleted, and rural livelihoods were severely compromised (World Bank, 2007; Jaye, 2003). The conflict resulted in widespread displacement, disruption of farming systems, destruction of rural infrastructure, and erosion of institutional capacity (Levitt, 2005). Food insecurity was pervasive, affecting over 60% of the population, and traditional coping mechanisms had been exhausted (WFP, 2005). The post-conflict literature emphasizes that agricultural recovery is central to broader reconstruction efforts in war-affected societies (Brück & Schindler, 2009; Collier et al., 2003; Justino, 2012). Agricultural development in such contexts faces unique challenges distinct from development in stable environments, including weak state capacity, fragmented institutions, damaged infrastructure, displaced populations, and disrupted market systems (Stewart & Brown, 2009). The transition from emergency relief to sustainable development requires coherent policy frameworks, institutional rebuilding, and strategies to re-engage smallholder farmers who constitute the majority of producers in sub-Saharan Africa (Jayne et al., 2010; Barrett et al., 2010).

This paper employs a policy-process-performance analytical framework grounded in several theoretical perspectives. First, the state fragility literature highlights how post-conflict states suffer from weak institutional capacity and limited administrative capabilities that fundamentally constrain policy implementation (Hudson & Leftwich, 2014; Booth & Cammack, 2013). Second, the agricultural transformation literature emphasizes that smallholder productivity improvements require addressing multiple constraints simultaneously including access to inputs, extension services, markets, credit, and secure land tenure rather than isolated interventions (Christiaensen et al., 2011; Timmer, 2009; Hazell et al., 2010). Third, the political economy perspective recognizes that policy outcomes are shaped by the interaction between political and economic factors, including elite interests, resource allocation politics, and institutional incentives (Khan, 2010; Whitfield et al., 2015). Finally, the food security framework in post-conflict settings acknowledges that ensuring food security requires both production restoration and addressing access issues through functioning markets, infrastructure, and social protection (Maxwell & Slater, 2003; Messer & Cohen, 2007).

Contemporary African agricultural policy has evolved from structural adjustment programs emphasizing market liberalization (World Bank, 1981; Bates, 1981) toward more comprehensive approaches recognizing the need for public investments in infrastructure, research, and institutional development (World Bank, 2007; AGRA, 2013). The Comprehensive Africa Agriculture Development Programme (CAADP), launched in 2003, provided a continental framework emphasizing increased investment, productivity growth, and country-led processes (NEPAD, 2003), significantly influencing Liberia's policy trajectory.

This paper aims to: (1) analyze the evolution of agricultural policies from 2004 to 2024; (2) assess sectoral performance across key indicators; (3) examine policy-implementation relationships; (4) identify critical constraints to development; (5) evaluate the role of institutional capacity and governance; and (6) provide evidence-based recommendations. Understanding these dynamics is significant for theoretical contributions to post-conflict development literature, policy relevance for fragile states, practical lessons for development actors, and informing future policy directions.

II. METHODOLOGY

The study adopts a policy-process-performance analytical framework to evaluate the evolution and effectiveness of Liberia's agricultural policies from 2004 to 2024. This approach integrates theoretical perspectives on state fragility, agricultural transformation, political economy, and food security, providing a nuanced understanding of the challenges Liberia faces in the post-conflict context. The research synthesizes data from national government reports, international organizations like FAO and the World Bank, and secondary sources. Key policy documents, such as the Food and Agriculture Policy and Strategy (FAPS) and the Liberia Agricultural Sector Investment Program (LASIP), are analyzed to assess the development and implementation of agricultural policies over the two-decade period.

The study focuses on policy evolution, implementation outcomes, institutional capacity, and constraints in areas such as infrastructure, finance, and governance. It also compares Liberia's agricultural performance with neighboring countries like Sierra Leone, Ghana, and Côte d'Ivoire to provide a regional context for understanding post-conflict recovery. Data on agricultural production, food security, and poverty from the FAO, World Bank, and Liberia's Ministry of Agriculture are used to evaluate the impact of policy decisions and track key indicators from 2005 to 2024.

Map of Liberia

III. POLICY EVOLUTION (2004-2024)

3.1 Emergency Relief and Early Reconstruction (2004-2007):

The immediate post-conflict period focused on emergency food security, institutional rehabilitation, and land mine clearance (WFP, 2005; MOA, 2005; UNMIL, 2006). The Interim Poverty Reduction Strategy (2004-2006) identified agriculture as a priority sector for recovery. This phase was necessarily focused on stabilization and humanitarian response rather than long-term transformation.

3.2 Policy Framework Development (2007-2012):

The Ellen Johnson Sirleaf administration (2006-2018) ushered in comprehensive policy formulation. The Food and Agriculture Policy and Strategy (FAPS) 2008 articulated a vision for "increased agricultural productivity and incomes, food and nutritional security, and employment creation through a market-oriented, modernized, commercially viable and environmentally sustainable agricultural system" (MOA, 2008, p. 12). Key policy documents included:

- **National Food Security and Nutrition Strategy (2008):** Established a comprehensive approach encompassing availability, access, utilization, and stability dimensions
- **Liberia Agriculture Sector Investment Program (LASIP I) 2010-2015:** Aligned with CAADP, focusing on food security, value chain development, sustainable land management, and institutional strengthening (MOA, 2010)
- **Land Rights Act (2009):** Attempted to address tenure issues by recognizing customary land rights, though implementation faced challenges (RRI, 2012; Unruh, 2009)

However, implementation fell short of ambitions LASIP I achieved only 30% of planned funding, revealing the persistent policy-implementation gap (MOA, 2015).

3.3 Implementation Focus and Value Chain Development (2012-2018):

This period emphasized translating policies into programs. The Agricultural Transformation Agenda (2013) aimed to shift from subsistence to commercial orientation through mechanization, value addition, market development, and private sector partnerships. LASIP II (2014-2020) focused on rice and cassava value chains, tree crop revitalization, and infrastructure development (MOA, 2014).

The Pro-Poor Agenda for Prosperity and Development (PAPD) 2018-2023 committed to 8-10% annual agricultural GDP growth, reducing food insecurity below 35%, creating 50,000 agricultural jobs, and achieving rice self-sufficiency (MFDP, 2018). However, these targets remained largely unmet agricultural sector growth averaged 3-4%, and food insecurity remained above 40%.

3.4 Post-Ebola Recovery and Resilience Building (2018-2024):

The 2014-2016 Ebola epidemic severely disrupted agriculture, requiring recovery efforts. The National Agriculture Investment Plan (NAIP) 2019-2024 represented a comprehensive approach emphasizing productivity enhancement, value chain development, infrastructure, climate-smart agriculture, and institutional strengthening (MOA, 2019). The Climate-Smart Agriculture Strategy (2021) addressed adaptation and mitigation, while the Digital Agriculture Initiative (2020) introduced technological innovations. Despite increasingly sophisticated policy frameworks incorporating lessons learned and emerging challenges, fundamental implementation challenges persisted. By 2024, most NAIP targets remained unmet food insecurity had not declined to 30%, rice self-sufficiency remained below 40%, and agricultural GDP contribution fell short of the 45% target (FAO, 2023; World Bank, 2024).

IV. SECTOR PERFORMANCE AND OUTCOMES (2004-2024)

4.1 Production and Productivity:

4.1.1 Rice Production:

Rice is Liberia's staple food, with national consumption estimated at 350,000 metric tons annually (FAOStat, World Bank).

TABLE 1
TRENDS IN RICE PRODUCTION, AREA HARVESTED, YIELD, AND SELF-SUFFICIENCY IN LIBERIA (2005-2024)

Year	Production (MT)	Area (Ha)	Yield (MT/Ha)	Self-Suffiency (%)
2005	84,000	120,000	0.7	24%
2010	138,000	155,000	0.89	35%
2015	156,000	165,000	0.95	37%
2020	178,000	175,000	1.02	38%
2024	195,000	182,000	1.07	40%

Source: MOA Statistics, FAO Data

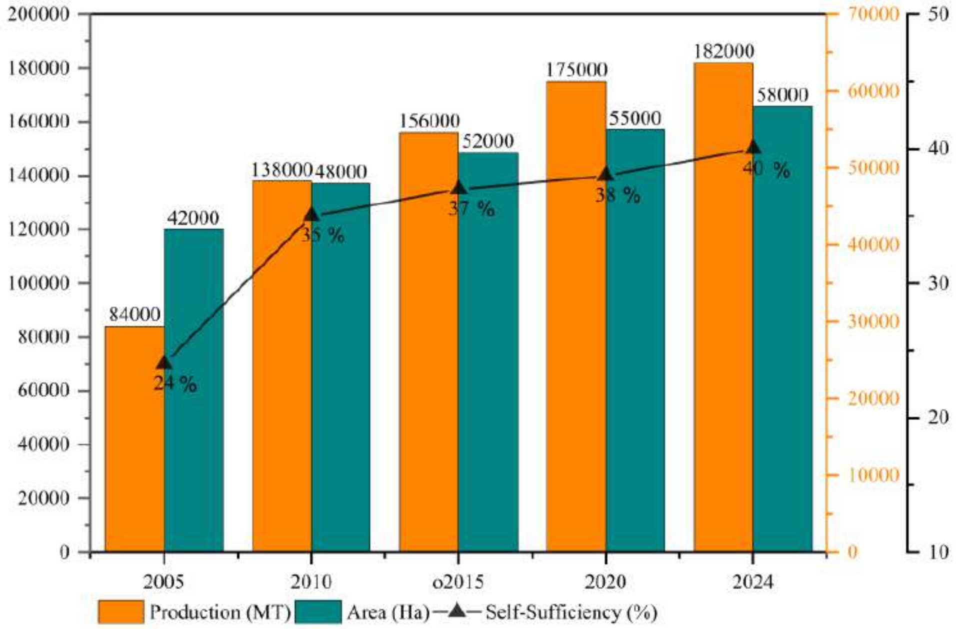


FIGURE 1: Rice Production 2025-2024

Rice production increased 132% from 2005 to 2024, yet self-sufficiency remained below 40%, necessitating substantial imports (approximately 250,000 MT annually). Yields improved modestly from 0.70 to 1.07 MT/Ha, well below the potential of 4-6 MT/Ha with improved varieties and management.

4.1.2 Cassava Production:

Cassava, the second most important staple, nearly doubled from 320,000 MT (2005) to 635,000 MT (2024), with yields improving from 7.6 to 10.9 MT/Ha, though below the potential of 15-25 MT/Ha.

TABLE 2
TRENDS IN CASSAVA PRODUCTION, AREA HARVESTED, AND YIELD IN LIBERIA (2005-2024)

Year	Production (MT)	Area (Ha)	Yield (MT/ Ha)
2005	320,000	42,000	7.6
2010	425,000	48,000	8.9
2015	510,000	52,000	9.8
2020	580,000	55,000	10.5
2024	635,000	58,000	10.9

Source: MOA Statistics, FAO Data

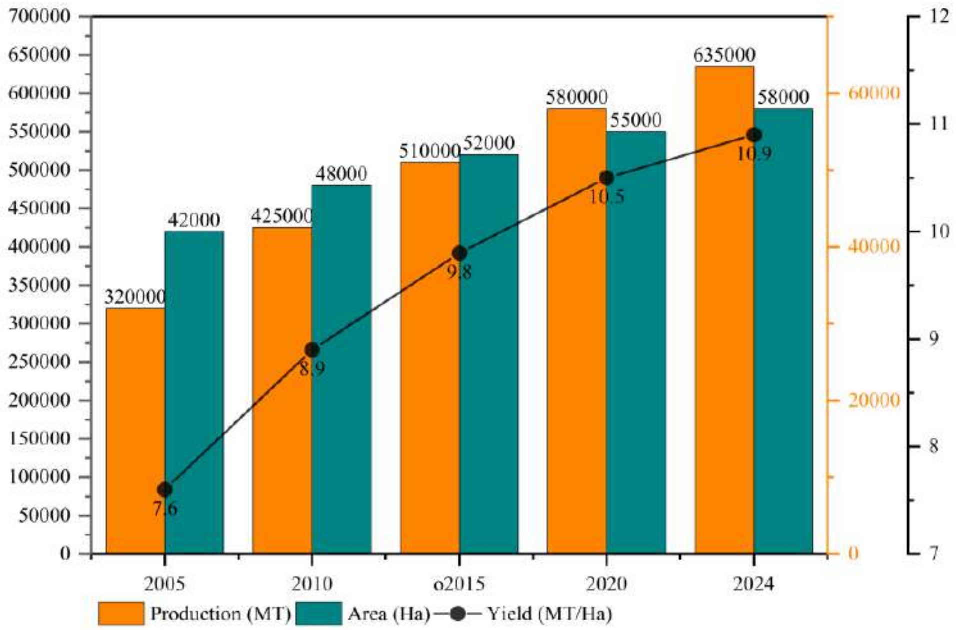


FIGURE 2: Cassava Production 2005 – 2024

4.2 Productivity Comparison with Regional Peers:

TABLE 3
COMPARISON OF KEY CROP YIELDS IN LIBERIA WITH SUB-SAHARAN AFRICAN AND GLOBAL AVERAGES (2024)

Crop	Liberia Yield	SSA Average	Global Average
Rice (MT/Ha)	1.07	2.3	4.6
Cassava (MT/Ha	10.9	12.8	13.1
Cocoa (MT/Ha)	0.35	0.55	0.47

Source: FAO Statistics 2024

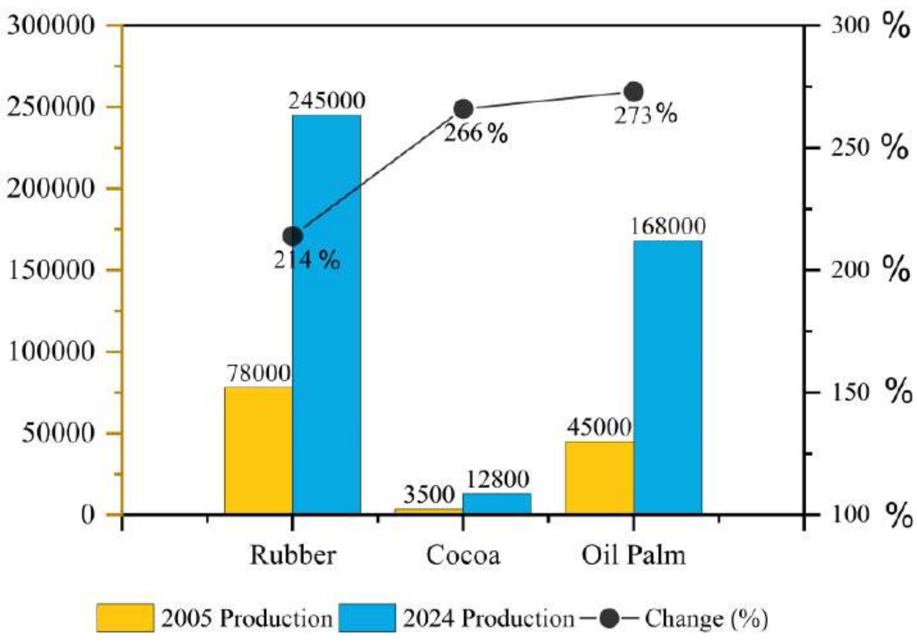


FIGURE 3: Productivity Comparison

4.3 Food Security and Nutrition:

TABLE 4
TRENDS IN FOOD SECURITY AND NUTRITION INDICATORS IN LIBERIA (2006-2024)

Indicator	2006	2012	2018	2024
Food Insecure Population (%)	62%	49%	44%	41%
Severely Food Insecure (%)	28%	18%	15%	13%
Stunting in Children <5 (%)	42%	35%	32%	28%
Wasting in Children <5 (%)	8%	6%	5%	4%
Dietary Diversity Score	3.2	4.1	4.5	4.8

Source: WFP, Liberia Demographic and Health Surveys, FAO

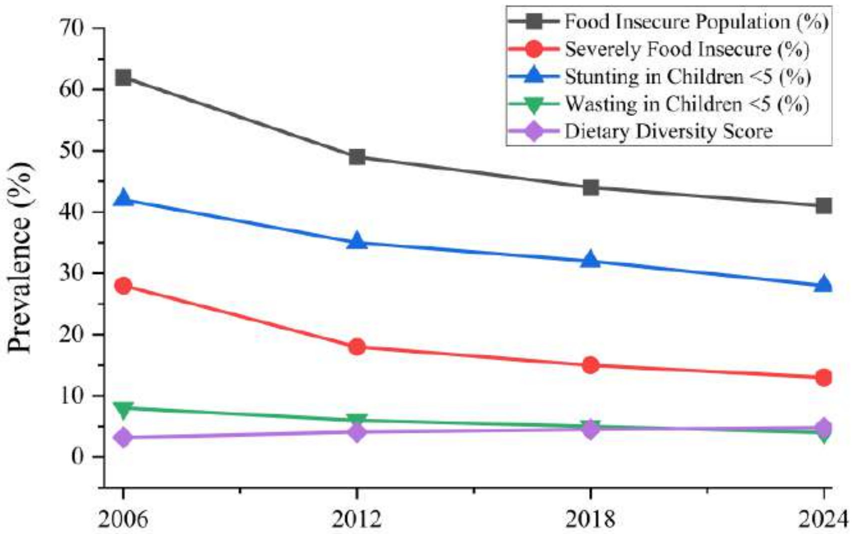


FIGURE 4: Food security

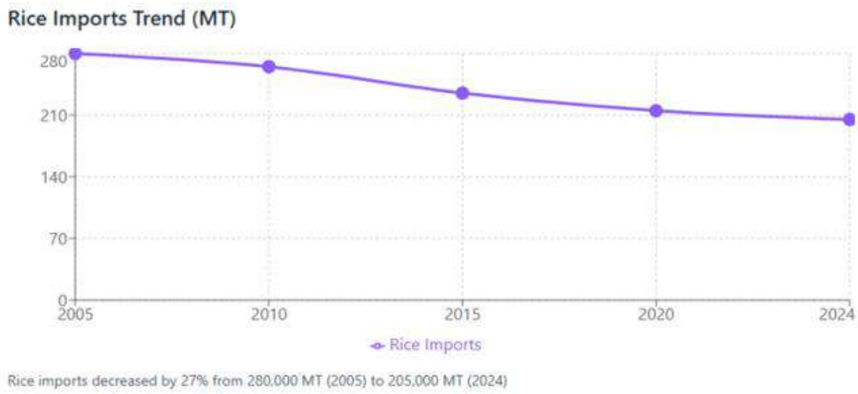
While food insecurity declined from 62% to 41%, over two million Liberians remain food insecure, with rural areas disproportionately affected. Nutrition indicators improved, though stunting rates remain high by international standards.

4.4 Food Import Dependency:

TABLE 5
LIBERIA'S FOOD IMPORT DEPENDENCY AND ASSOCIATED FINANCIAL COST (2005-2024)

Year	Rice Imports (MT)	Food Import Bill (USD Million)	% of Export Earnings
2005	280,000	95	28%
2010	265,000	156	32%
2015	235,000	182	36%
2020	215,000	168	34%
2024	205,000	195	31%

Source: Central Bank of Liberia, UN Comtrade



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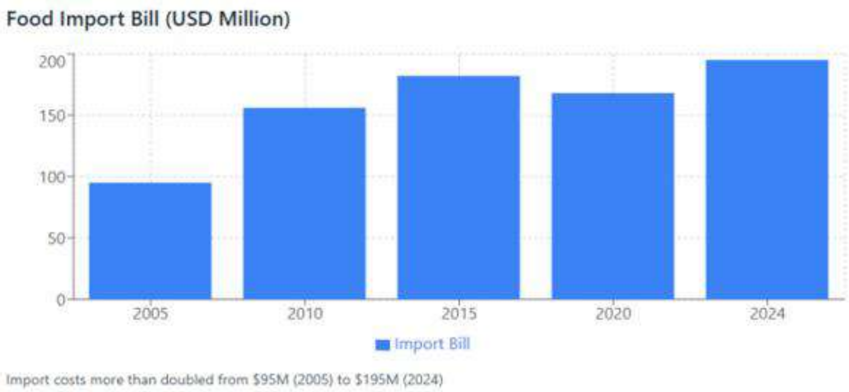

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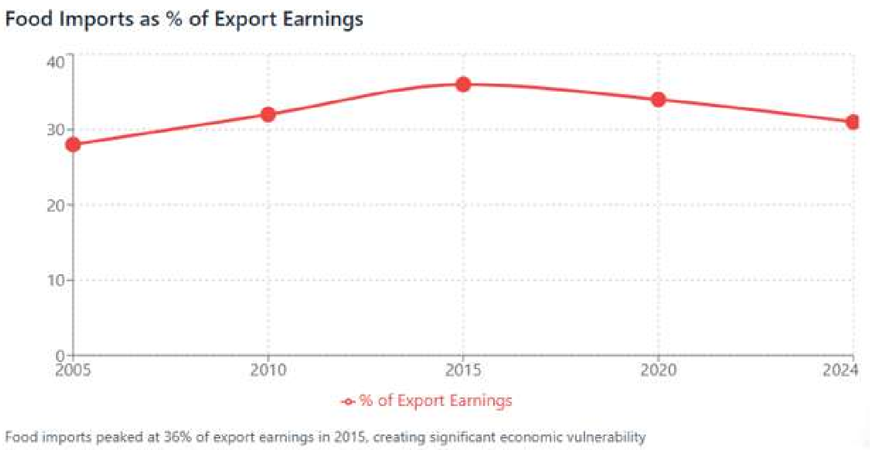

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FIGURE 5: Food Import Dependency

Liberia spends approximately USD 195 million annually on food imports, representing 31% of export earnings, creating vulnerability to international price shocks.

V. CRITICAL ANALYSIS: THE POLICY-IMPLEMENTATION GAP

The most striking feature is the persistent gap between policy ambitions and implementation realities. Liberia developed increasingly sophisticated frameworks such as the Food and Agriculture Policy and Strategy (FAPS), Liberia Agricultural Sector Investment Plan (LASIP), National Agriculture Investment Plan (NAIP) with clear objectives and strategies, yet implementation consistently fell short. LASIP I achieved only 30% of planned investments, while NAIP 2019-2024 targets for food security reduction, rice self-sufficiency, and GDP contribution remain unmet (MOA, 2015, 2019).

5.1 Institutional Capacity Constraints:

Post-conflict institutional rebuilding has been slow. The Ministry of Agriculture lacks adequate staff, technical expertise, operational resources, and coordination capacity. Extension services reach fewer than 15% of farming households. Research systems remain weak, with limited adaptive research and technology transfer. Coordination between MOA, other ministries, county administrations, and development partners is often ineffective (MOA, 2019; USAID, 2020).

5.2 Multiple Interrelated Constraints:

Agricultural performance is limited by:

a) **Technical Constraints:** Low adoption of improved varieties (18%), limited mechanization (<5% of farms), inadequate extension services, weak research-extension-farmer linkages

b) **Infrastructure Constraints:** Poor rural road networks, limited irrigation (2% of cultivated area), inadequate storage, unreliable electricity

c) **Market Constraints:** Thin markets, high transaction costs, limited market information, weak value chain coordination, competition from cheaper imports

d) **Financial Constraints:** Limited credit access (<10% of farmers), high interest rates (20-35%), lack of collateral due to land tenure issues

e) **Land Tenure Issues:** Insecurity of land rights, customary-statutory tensions, land conflicts, concerns about land grabbing with large-scale investments (Unruh, 2009; Eckert et al., 2013; Oakland Institute, 2012; Liberti, 2013)

f) **Climate and Environmental Challenges:** Increasing climate variability, deforestation, soil degradation, limited adaptation capacity.

g) **Political Economy Factors:** Implementation is affected by limited political prioritization of agriculture compared to urban-focused policies, elite capture of benefits, patronage politics, limited farmer organization and political voice, and tensions between large-scale investments and smallholder interests (Khan, 2010; Whitfield et al., 2015).

5.3 Comparative Regional Analysis:

a) **Rwanda:** Post-genocide transformation has been more successful through strong political commitment, rapid institutional rebuilding, consistent implementation, high public investment (>10% of budget), effective land reform, successful cooperatives, and strong extension services. Rwanda demonstrates the importance of political commitment and institutional capacity, though its centralized governance may not transfer directly to Liberia's decentralized context.

b) **Sierra Leone:** As a neighboring post-conflict state, Sierra Leone offers relevant comparisons. Both face similar challenges with comparable agricultural potential and policy frameworks (CAADP alignment). Sierra Leone shows slightly better rice productivity (1.3 vs 1.07 MT/Ha) and comparable food insecurity (38% vs 41%), confirming that post-conflict agricultural transformation is challenging even with appropriate policies.

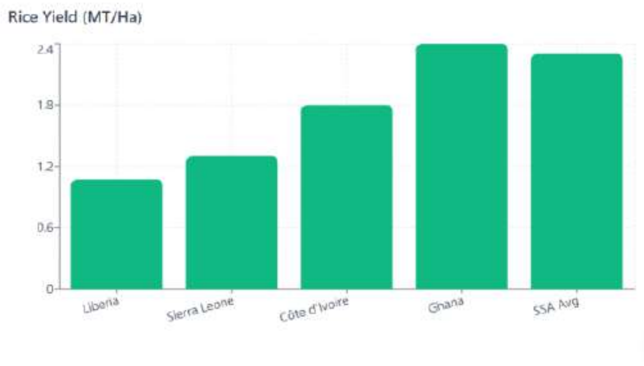
c) **Uganda:** Post-conflict recovery in northern Uganda demonstrates the importance of farmer organizations, consistent extension services, and private sector partnerships in driving productivity.

5.4 Regional Performance Indicators:

TABLE 6
COMPARATIVE ANALYSIS OF KEY AGRICULTURAL PERFORMANCE INDICATORS IN LIBERIA AND NEIGHBORING COUNTRIES (2024)

County	Rice Yield	Ag. GDP Growth	Food Insecurity	Rural Poverty	Ag. Budget
Liberia	1.07	3.50%	41%	54%	6.20%
Sierra Leone	1.3	3.80%	38%	51%	7.80%
Cote d'Ivoire	1.8	4.20%	28%	42%	8.50%
Ghana	2.4	5.10%	24%	38%	9.20%
SSA Average	2.3	3.20%	35%	47%	5.80%

Source: FAO, World Bank, AfDB Statistics 2024



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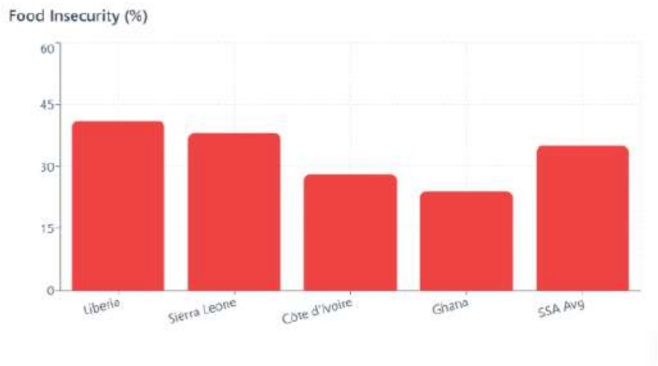

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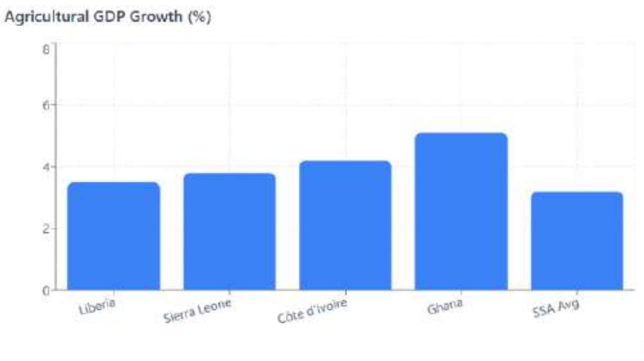

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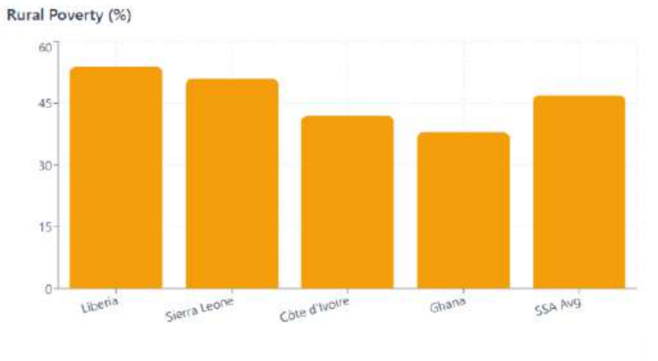

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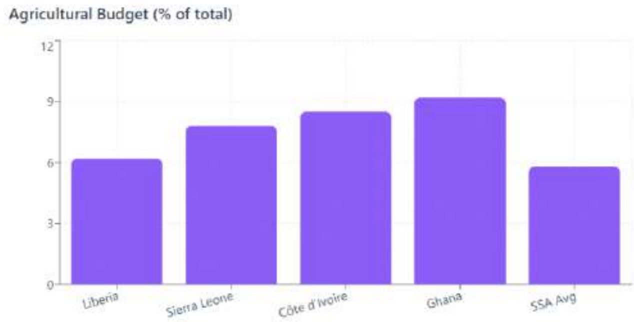

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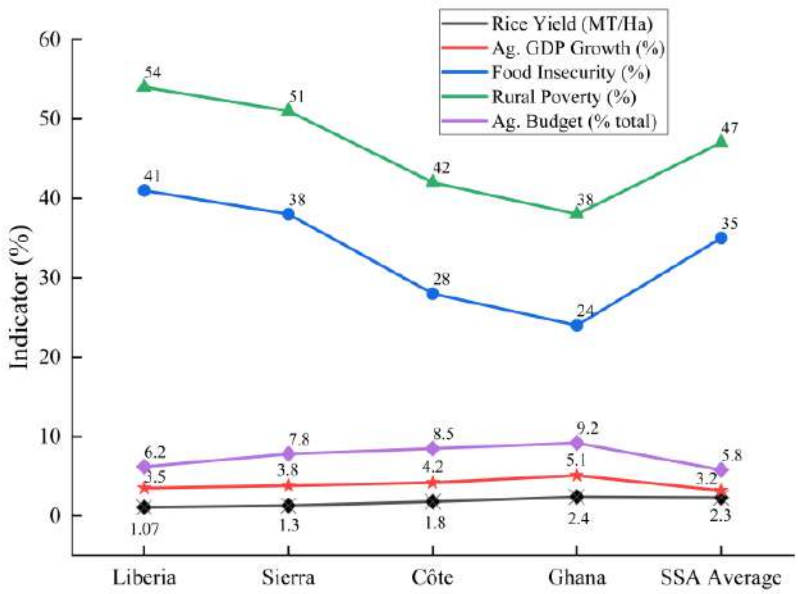

FIGURE 6: Regional Performance Indicators – Combined

Liberia's performance lags behind stable West African neighbors but is comparable to Sierra Leone, suggesting post-conflict status significantly affects outcomes, though policy choices and implementation quality also matter substantially (world bank).

5.5 Role of Development Partners:

Key partners include:

a) **Multilateral Organizations:** World Bank (infrastructure, institutional strengthening), FAO (food security, policy advisory), IFAD (smallholder development), AfDB (value chain development), WFP (food assistance, nutrition)

b) **Bilateral Donors:** USAID (Feed the Future, value chains), EU (food security, research), China (infrastructure, technology transfer), Sweden (smallholder empowerment), Japan (rice development, irrigation)

c) **International NGOs:** ACDI/VOCA (value chains), Mercy Corps (livelihoods, market systems), Action Against Hunger (food security), Welthungerhilfe (smallholder productivity)

International assistance is estimated at USD 80-120 million annually, providing crucial support for agricultural reconstruction.

5.5.1 Coordination and Effectiveness Challenges:

Despite substantial assistance, challenges persist: fragmentation across multiple donors with different priorities, limited government capacity to coordinate donors, sustainability concerns with heavy donor reliance, parallel systems bypassing government institutions, and geographic concentration leaving remote regions underserved.

Aid effectiveness shows mixed results. Positive contributions include maintaining programs during fiscal constraints, bringing technical expertise, supporting institutional rebuilding, and enabling infrastructure investments. Limitations include limited sustainability due to project-based approaches, uneven geographic coverage, insufficient capacity building focus, and inadequate integration with government systems.

5.6 Gender, Youth, and Social Inclusion:

Women constitute 60% of the agricultural workforce but face significant constraints. They have limited land ownership rights under customary systems, receive only 5% of agricultural credit and 10% of extension contacts, and bear disproportionate domestic responsibilities (MOA, 2019). Despite policy commitments to gender mainstreaming in NAIP 2019-2024, women's agricultural productivity is estimated 30-40% lower than men's due to resource access constraints rather than inherent differences.

5.6.1 Youth Engagement:

Youth (ages 15-35) represent 35% of the population but are underrepresented in agriculture due to low profitability, lack of prestige, hard physical labor, poor rural infrastructure, and land access difficulties. Recent policies emphasize youth engagement through entrepreneurship training, youth-focused credit facilities, and agribusiness incubation programs, though substantial challenges remain.

5.7 Climate Change and Environmental Sustainability:

Climate change poses significant threats with observed temperature increases (0.8°C since 1960), changing rainfall patterns, more frequent extreme weather, and increased pest pressure. Projections indicate 1.5-3.0°C temperature increase by 2050 with increased rainfall variability. Vulnerability is heightened by heavy dependence on rainfed agriculture (95% of production), limited irrigation, low adaptive capacity, and poor infrastructure (MOA, 2021).

5.7.1 Environmental Degradation:

Agricultural expansion contributes to deforestation (forest cover declined from 48% in 2000 to 41% in 2024), soil degradation, water resource contamination, and biodiversity loss. The Climate-Smart Agriculture Strategy (2021) emphasizes climate-resilient varieties, improved water management, agroforestry, and climate information services, though implementation capacity and farmer adoption remain limited.

5.8 Land Tenure and Concessions:

Liberia's land tenure is characterized by legal pluralism: approximately 70% customary land, 25% private land, and 5% public land. The Land Rights Act (2009) attempted to address tenure issues by recognizing customary rights, requiring community consent, and protecting women's rights (Republic of Liberia, 2009). However, implementation faces challenges including limited funding, resistance from customary authorities, complex procedures, and elite capture (Unruh, 2009; RRI, 2012).

5.8.1 Agricultural Concessions:

Approximately 30 large-scale concessions cover over 800,000 hectares, primarily for tree crops. Benefits include foreign investment, employment creation (35,000 direct jobs), technology transfer, and infrastructure development. However, concerns persist regarding land grabbing with inadequate community consultation, displacement of smallholders, inequitable benefit sharing, environmental impacts, labor rights issues, and limited smallholder integration (Oakland Institute, 2012; Liberti, 2013).

5.9 Technology and Innovation:

Adoption remains low: improved seeds (18%), fertilizer use (12%), mechanization (5%), irrigation (2%), compared to regional averages of 42%, 35%, 18%, and 12% respectively. Constraints include high input costs, limited credit access, inadequate supply chains, poor extension services, risk aversion, uncertain profitability, land tenure insecurity, and limited farmer knowledge.

5.10 Research and Extension:

The Central Agricultural Research Institute (CARI) has limited capacity with approximately 40 researchers, inadequate funding, aging infrastructure, and weak research-extension-farmer linkages. Extension services are severely constrained with only 240 agents for 370,000 households (1:1,540 ratio, far above the recommended 1:500). Digital agriculture initiatives including mobile-based extension, market information systems, and digital financial services are emerging but remain at pilot stage.

VI. DISCUSSION

Liberia's agricultural policy has undergone significant evolution since 2004, transitioning from emergency relief efforts to more structured development frameworks. The **Interim Poverty Reduction Strategy (2004-2006)** marked the beginning of this shift, prioritizing food security and humanitarian relief. The subsequent **Food and Agriculture Policy and Strategy (FAPS)** of 2008 aimed to enhance agricultural productivity and food security through commercialization and sustainability. Despite the ambition of these policies, their implementation has been hindered by inadequate funding, weak institutional capacity, and poor infrastructure.

The **Liberia Agricultural Sector Investment Program (LASIP)**, aligned with the **Comprehensive Africa Agriculture Development Programme (CAADP)**, sought to increase investment in the agricultural sector, yet results were underwhelming. **LASIP I** achieved only 30% of its planned investments, and **LASIP II** (2014-2020) also struggled to meet key targets, such as rice self-sufficiency and GDP growth from agriculture. By 2024, food insecurity remained above 40%, and rice self-sufficiency goals remained unmet, reflecting a persistent gap between policy formulation and execution.

6.1 Agricultural Performance and Productivity:

In terms of productivity, **rice production** increased by 132% from 2005 to 2024, but Liberia remains heavily dependent on rice imports, bringing in about **250,000 metric tons** annually. Despite improvements in yield from **0.7 MT/Ha** in 2005 to **1.07 MT/Ha** in 2024, these figures still fall well below the potential of **4-6 MT/Ha**, demonstrating challenges in productivity due to weak extension services and limited mechanization. Similarly, **cassava production** nearly doubled from **320,000 MT** in 2005 to **635,000 MT** in 2024, with yield improvements from **7.6 MT/Ha** to **10.9 MT/Ha**. However, these gains still fall short of the potential yield range of **15-25 MT/Ha**.

Liberian yields for rice and cassava remain lower than both regional and global averages, with rice yielding **1.07 MT/Ha** in Liberia compared to the **SSA average** of **2.3 MT/Ha** and the **global average** of **4.6 MT/Ha**. Cassava yields in Liberia are also behind regional and global norms, underscoring the persistent underperformance of Liberia’s agricultural sector.

6.2 Food Security and Institutional Constraints:

Although food insecurity has improved modestly, it remains a pressing issue. The **food-insecure population** decreased from **62%** in 2006 to **41%** in 2024, but over **two million Liberians** still face food insecurity. The country continues to depend heavily on food imports, with a food import bill of **USD 195 million** in 2024, which accounts for **31%** of Liberia’s export earnings. This dependency makes Liberia vulnerable to international price shocks and highlights the need for stronger domestic food production systems.

Institutionally, Liberia faces numerous challenges. The **Ministry of Agriculture (MOA)** is under-resourced, with insufficient technical expertise and infrastructure. Extension services reach less than **15%** of farming households, and agricultural research remains underfunded. The country also faces significant land tenure issues, with about **70%** of land governed by customary law, which makes land access uncertain, especially for women and smallholder farmers.

6.3 Climate Change and Environmental Sustainability:

Climate change exacerbates the challenges facing Liberia's agricultural sector. The country's agriculture is highly sensitive to climate variability, with approximately **95%** of agricultural production dependent on rainfall. Rising temperatures, increased rainfall variability, and more frequent extreme weather events such as floods and droughts make the sector increasingly vulnerable. The **Climate-Smart Agriculture Strategy (2021)** emphasizes the need for climate-resilient crops, improved water management, and agroforestry practices to adapt to these changes. However, the implementation of these strategies remains slow due to capacity constraints both at the government and farmer levels.

VII. CONCLUSION

This comprehensive paper reveals a complex picture of progress and persistent challenges in post-conflict Liberian agriculture. Over two decades, significant strides have been made in rebuilding the sector from civil war devastation, developing policy frameworks, and achieving modest improvements. However, critical gaps persist between policy ambitions and implementation outcomes, reflecting fundamental challenges in institutional capacity, resource mobilization, infrastructure, and governance.

The central lesson is that agricultural transformation in post-conflict settings requires more than well-designed policies. Success depends on sustained political commitment, institutional capacity building, comprehensive approaches addressing multiple constraints simultaneously, infrastructure investment, long-term perspectives recognizing that transformation requires decades, effective governance with transparency and accountability, coordinated action among multiple actors, and adaptive management learning from implementation.

Liberia's agricultural potential remains significant with favorable climate, adequate rainfall, diverse agroecological zones, and substantial arable land. The challenge is creating the institutional, infrastructural, and policy environment enabling farmers to realize this potential. International experience demonstrates that transformation is achievable even in challenging post-conflict contexts with sustained commitment, strategic investments, and effective implementation (as evidenced by Rwanda's post-genocide experience, though in a different political context).

For Liberia, the next decade will be critical. With appropriate strategies, adequate resources, effective implementation, and sustained commitment, significant progress toward food security, poverty reduction, and agricultural transformation is achievable. However, this requires moving from policy rhetoric to genuine implementation, from scattered interventions to coordinated programs, and from short-term projects to long-term institutional development.

The implications for post-civil war Liberia are clear: agricultural development is essential for national development but requires realistic strategies, adequate resources, strong institutions, and sustained effort. Success will depend not on policy document sophistication but on implementation effectiveness and the ability to address binding constraints facing farmers. These lessons are relevant not only for Liberia but for other post-conflict countries pursuing agricultural reconstruction, as the fundamental challenges of rebuilding institutions, mobilizing resources, strengthening capacity, and translating policy into outcomes are common across post-conflict settings.

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Efficiency of Microbial Concoction on the Reduction of Odor and Housefly Population in Quail Farming

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Abstract— *The study focused on evaluating the efficiency of the microbial concoction on reducing the odor distance (m), fly density (per m2), and the number of dead eggs and larval stage of flies in the pit. The result implies that on the day of application the fly population was 391 specks per square meter and decreased to 273 specks on the second day of application. Consequently, the dead egg and larval stage of flies has sudden increase on the second day of application from approx. 335 on the day of application to approx. 349 but decreases on the following days up to zero visibility on the pit. On the other hand, it was shown that there is a decreasing distance point on smelling the odor of the manure until the last application of the concoction. On the day of the first application the odor was smelled 7.7 meters and reduce to 4 meters on the last day of application. The distance was decreased but it has still the same odor until the finished of the experiment. Minimal dead earthworms were also visible on the first three days of the experiment. White spots were also seen from the second day of application until the 5th day of experimentation. The incorporation of odor erasing microbial concoction on the pits of the quail had positively shown its efficiency on the reduction of the fly population and eggs and larval stage. Hence, reduced the distance of smelling the odor.*

Considering its positive result, the manure pits should be place on covered for better experimentation or should be applied immediately on the litter beds for more conclusive results.

Keywords— ammonia, fly ash, manure, OEMC, quail.

I. INTRODUCTION

The Bureau of Animal Statistics (BAS, 2015) and its 2012 special report, reported that quail comes third in the production of poultry products following ducks and broiler as the secondary and primary source, respectively. Despite being only third, quail raising in the country is promising (BPI-NSPRDC, 2010). This can be started with a much lower capital investment as compared to chicken and ducks. Quail, locally known as pugo, is a small and tailless bird found in many parts of Asia. It belongs to the Phasianides family under the order of Galliformes. As commercial birds, quails require minimal space, time, and investment. Moreover, they are quick growers, and fast multipliers (Bolla and Randall, 2012). Also, they are richer in protein, phosphorous and vitamin A. Quails, unlike other fowl, are not delicate birds. These birds do not easily contract fowl diseases common to poultry, especially chickens (Mulemora, 2013). In addition, there is a growing demand on the meat and egg of quail at present.

Quail farming is very profitable like other farming ventures, such as chicken, turkey or duck farming business. Almost all types of weather conditions are suitable for starting quail farming business. Meat and eggs of quail are very tasty and nutritious. Having meeting the demand requires an intensive production. Thus, factors emerged in increasing the production just so to supply the demand of the population.

Having a larger scale of production in any animal of either livestock or poultry maximizes the production of manure. Hence, a serious consideration especially on its environmental impact. Some of these impacts are the strong odor and production of flies due to mishandling of manure produce by the animal). Manure handling practices and environmental conditions also affect chemical and physical properties of the manure, such as chemical composition, biodegradability, microbial populations, oxygen content, moisture and pH (Xin, et al., 2011). According to Ranadheera et. al. (2017), the strong odor is often a result of uncontrolled anaerobic decomposition of manure, feathers, waste feeds and bedding materials. And these odorous smells are a complex mixture of gases. It is important to maintain optimal conditions for production but should not impair human and the animal itself through emission of harmful gases. The high stocking density in the modern poultry barns may lead to reduced air quality with high concentrations of organic and inorganic dust, pathogens and other micro-organisms as well as harmful gases such as ammonia, nitrous oxide, carbon dioxide, hydrogen sulphide, and methane (Ellen, 2005; Gates et al., 2008).

Ammonia (NH3) is the primary basic gas in the atmosphere. Elevated concentrations of NH3 in poultry farms reduce feed intake and impede bird growth rate, decrease egg production, damage the respiratory tract, increase susceptibility to Newcastle disease virus, increase the incidence of air sacculitis and keratoconjunctivitis and increase the prevalence of Mycoplasma gallisepticum (Kristensen, Wathes, 2000). Egg quality may also be adversely affected by high levels of atmospheric ammonia as measured by reduced albumen height, elevated albumen pH and albumen condensation (Xin, et al., 2011). The ammonia concentration in the air plays an important role in the neutralization of atmospheric acids generated by fossil fuel combustion. The reaction product forms a NH4 + aerosol, which is a major component of atmospheric particulates. These NH4 + particulates may be transported long distances from the production site before returning to the surface by dry deposition or precipitation. Animal production produces a significant component of anthropogenic NH3 emissions. Ammonia is also a component of odour (Jelínek, et al., 2011). Ammonia volatilization from manure materials within poultry barns can adversely affect production, and also represents a loss of fertiliser value from the spent litter. It is generated during bacterial decomposition of protein and urea in housing areas and during storage and application of excreta under aerobic and anaerobic conditions (Kristensen et al., 2000). The main source of NH3 is urine of animals. Seventy percent of nitrogenous substances in excrement originate from urine and 30% from feces. Poultry feces contain 60−65% of uric acid, 10% of ammonia salts, 2−3% of urea and remains of creatinine. Especially uric acid is rapidly changed by the microbes to NH3 (Groot Koerkamp, 1994).

The house fly, Musca domestica L., is the major species associated with poultry manure. This fly breeds in moist, decaying plant material, including refuse, spilled grains, spilled feed and in all kinds of manure. Poor sanitation around the poultry facility increases the probability of high house fly populations. House flies prefer sunny areas and are very active, crawling over filth, people and food products. This fly is an important mechanical vector of many human and poultry diseases (protozoa, bacteria, viruses, rickettsia, fungi and worms. But this can be controlled through the integration of nonchemical and chemical control methods. The use of insecticides alone rarely results in satisfactory fly control. An integrated pest management program involving population monitoring, cultural control, mechanical control, biological control and chemical control is recommended (Loftin, Hopkins and Corder, 2014). There is really a need to balance the increase of production and its impact to environment. Giving the fact that microorganism can bat to the reduction of ammonia emission thus have a positive impact to the growth performance in poultry as well as its association to the population growth of flies. Hence, this study.

II. MATERIALS AND METHODS

The farms as site for the experimentation is situated in Brgy. Baraoidan, Gattaran, Cagayan. The manure pit where the concoction was applied is located approximately 100 meters away from the farm. Both of the sidings of the buildings were concrete with mesh screen however, the quails are house on a modern laying cage. The roofing material is corrugated iron sheets equipped with incandescent bulbs as source of heat-light for the birds. The other materials used were feeding and watering equipment, brooding facility, weighing scale, Sticky fly traps (cut to a dimension of 120 cm x 80 cm) and among others. The bird's population consumed 1 bags at 50 kgs a day. The birds were distributed into colony panels inside the building to control feeding and other management activities. The birds were fed in ad libitum manually using tube feeders. Medicated water was made available at all times. All necessary management practices specified by the owner was followed.

The Odor Erasing Microbial Concoction (OEMC) was top dressed into one of the manure pits of the farm. The application was on 260 g per day for seven consecutive days. The concoction was mixed to a fly ash with a ratio of 1:1 to serve as bulking agent. The application was once a day and started after the placement of the dungs in the pits.

The parameter on the distance of odor smell was gathered by measuring the point in all wind direction where the farm owner and the researcher smell the odor up to the location of the pit where the concoction was applied. The estimated housefly density was based on the number of specks counted after exposing the sticky fly trap (120 cm x 80 cm) randomly distributed inside the broiler house every other day throughout the experiment. And the dead eggs and larval stage of fly was approximately counted inside the 1 sq.ft. strings placed in the pit. Hence, other observable scenarios were undertaken.

Descriptive statistics analysis was used in analyzing and interpreting the results of the gathered data.

III. RESULTS AND DISCUSSION

It shows in figure 1 that there is a reduction on the population of flies inside the farm. It implies that on the day of application the fly population was 391 specks per square meter and decreased to 273 specks per square meter on the second day of application. But it was increased again to 321 specks per square meter on the 5th day of application. Thus, decreased to 283 specks per square meter on the last day of application from the 5th day of application. Consequently, the dead egg and larval stage of flies (Fig. 2) has sudden increase on the second day of application from approx. 335 on the day of application to approx. 349 but decreases on the following days up to zero visibility of the eggs and larval stage on the pit. On the other hand, figure 3 signifies the distance from the point of the manure to the point where the odor of the manure as smelled. According to Barroga et al, (2015), When the dung is fermenting the carbonaceous substances produced obnoxious or foul-smelling gases e.g. carbon monoxide, carbon dioxide, methane, etc. It was shown that there is a decreasing distance point on smelling the odor of the manure until the last application of the concoction. The figure provides that, on the day of the first application the odor was smelled 7.7 meters and reduce to 4 meters on the last day of application. The distance was decreased but it has the same odor still until the finished of the experiment. Minimal dead earthworms were also visible on the first three days of the experiment. White spots were also seen from the second day of application until the 5th day of experimentation.

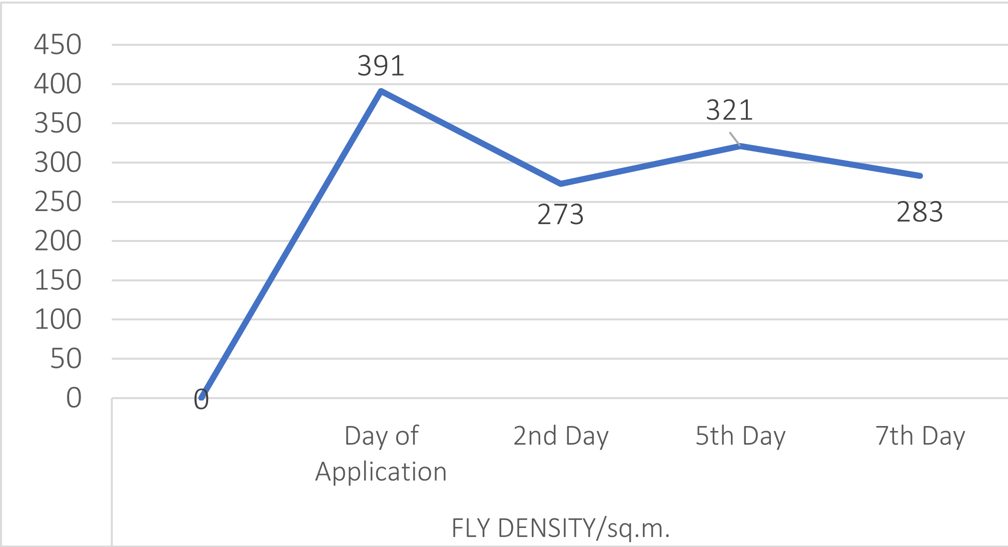

FIGURE 1: Effects of OEMC application on Fly density

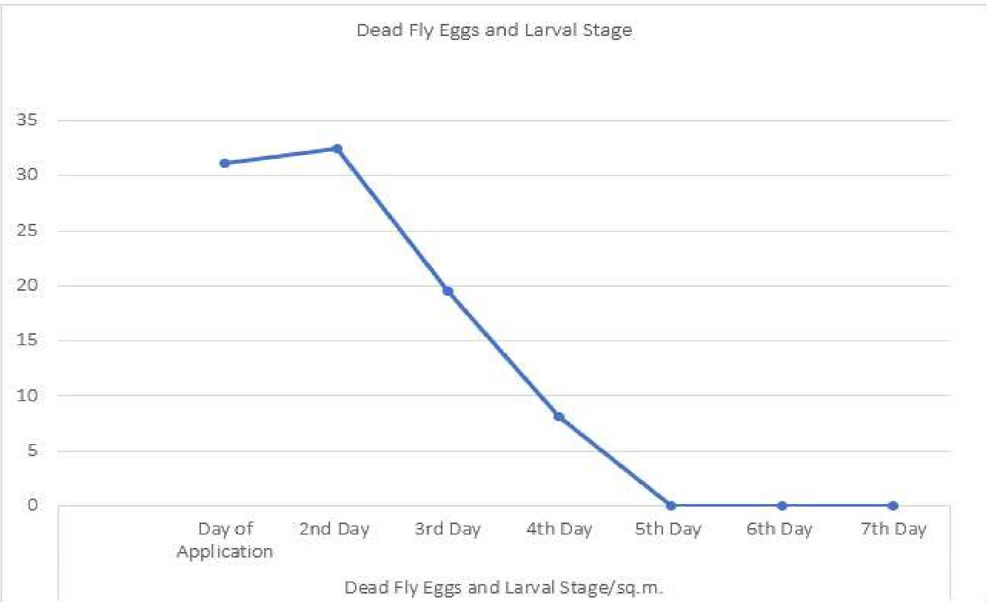

FIGURE 2: Dead Fly Eggs and Larval Stage

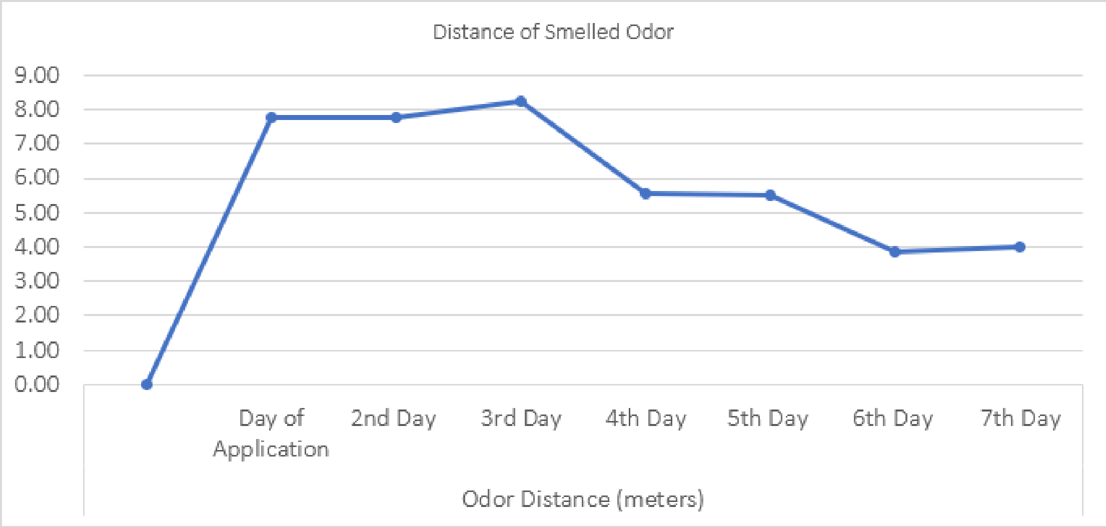

FIGURE 3: Distance of Smelled Odor

IV. CONCLUSION

The incorporation of odor erasing microbial concoction on the pits of the quail had positively shown its efficiency on the reduction of the fly population together with decreasing the eggs and larval stage. Hence, reduced the distance of smelling the odor. Considering its positive result, the manure pits should be place on covered for better experimentation or should be applied immediately on the litter beds for more conclusive results.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Growth and Laying Response of Quail (Coturnix coturnix japonica) Fed with Dietary Fermented Earthworm Meal Silage

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Abstract— *A feeding trial was carried out to evaluate the effects of replacing the fishmeal with a dietary fermented earthworm meal silage (FEMS). A 240 ready-to-lay (RTL) quail of 22 days old were used to determine average daily gain (ADG), feed conversion ratio (FCR), average daily feed intake (ADFI), % hen-egg day production (HEDP), average egg weight (AWE), Total Weekly Egg Produced (TWEP), and income over feed cost (IOFC) of quail fed with dietary fermented earthworm meal silage (FEMS). The dietary FEMS was used to replace fish meal in a feed formula at the rate of 0%, 5%, 10%, and 15%. Twenty experimental RTL quails were distributed to a colony panel which served as a replicate in a 4-treatment x 3-replicate randomized complete block experimental design.*

The result showed no significant (p>0.05) effect in replacing the fishmeal with a fermented earthworm meal silage (FEMS) in a feed formula. Hence, the feed formula with a 5% FEMS resulted in a heavier average daily gain among the different treatments. The % HEDP resulted in a higher egg production in 15% FEMS substitution, while, IOFC was highest at 10% FEMS substitution. These findings indicate that formulating quail feeds in an attempt to replace fish meal with a dietary FEMS has no detrimental effect on growth and laying performance and has the potential to be included as an animal protein dietary ingredient in the quail diet.

Keywords— Dietary Fermented Earthworm Meal Silage, Flock Uniformity, Ready to Lay, Growth and Laying Response, Quail.

I. INTRODUCTION

The Bureau of Animal Statistics (BAS) in 2015 and in its 2012 special report related that quail comes third in the production of poultry products following ducks and broilers as the secondary and primary source, respectively. Despite being only third, quail raising in the country is promising (BPI-NSPRDC, 2010). This can be started with a much lower capital investment as compared to chicken and ducks.

Quail, locally known as pugo, is a small and tailless bird found in many parts of Asia. It belongs to the Phasianides family under the order of Galliformes. As commercial birds, quails require minimal space, time, and investment. Moreover, they are quick growers, and fast multipliers (Bolla & Randall, 2012). Also, they are richer in protein, phosphorous, and vitamin A. Quails, unlike other fowl, are not delicate birds. These birds do not easily contract fowl diseases common to poultry (Mulemora, 2013). In addition, there is a growing demand for meat and eggs from quail at present.

The potential of making it grow more for the growing demand for the quail's product is associated with proper nutrition. Fish meal has been widely used as conventional feedstuff since the early times due to its high nutritional content. However, this feedstuff has its nutritional constraints in usage. According to Miculec et. al (2004), it contains high histamine which can cause defects in poultry's gizzard. Moreover, it has a relatively high price because it is both consumed by man and animals. Therefore, there is a need to explore alternative feed ingredients that would satisfy or at least surpass the nutrients present in a fish meal, especially in consideration of the protein content of an ingredient.

According to Palungkun (1999), earthworms contain 64-76% of protein, much higher than the local fishmeal which consists of 49.50 to 59.19%. It was found that fresh earthworm has 61.96% protein and are composed of essential and non-essential amino acids which are considered excellent feed ingredients for poultry (Resnawatti, 2004).

There is very little information on the use of earthworm meals in poultry diets. A study showed that 10% earthworm meal could replace a large portion of the fish meal in the diet with no adverse effect on body weight gain or feed efficiency. Feed intake was reduced at the 15% inclusion level (Prayogi, 2011). However, in the 2004 research of Resnawatti, it was found that earthworm meal can be used up to 15%. Hence, this research aimed to test and verify the potential of earthworms processed to fermented silage at varying levels of inclusion to the diet of quail in an attempt to replace the fish meal in the feed formula.

II. MATERIALS AND METHODS

Time and Place of the study. The study was conducted at #049 Dumadag St. Baraoidan, Gattaran, Cagayan from August 18, 2021 to November 6, 2021.

Experimental Quail and Treatments. Two-hundred forty RTL quails (22 days) were laid out in a Randomized Complete Block Design (RCBD) with four (4) treatments replicated three times. Twenty experimental birds for each replicate were distributed to a colony panel with the dimension of 60 cm x 40 cm x 18 cm with 30 cm x 40 cm egg catcher and 10 cm water trough. The dietary treatments were: Treatment 1 (T1) formulated feeds without substituting fish meal to dietary earthworm meal silage, Treatment 2 (T2) formulated feeds with 5% FEMS substitution, Treatment 3 (T3) formulated feeds substituted with 10% FEMS substitution and Treatment 4 (T4) formulated feeds with 15% FEMS substitution. The composition, proximate and calculated analysis of the experimental diets is presented in Table 1 and Table 2 for the nutritional specifications of the different feed ingredients used. Manual computation for the Crude Protein values was undertaken but a sample of the formulated feeds were subjected to a laboratory analysis. A 250- gram sample per treatment was packed and brought to DA-Cagayan Valley Integrated Animal Laboratory located at Government Center, Carig Sur, Tuguegarao City, Cagayan. The Semi-Automatic Kjeldahl method was followed for the crude protein, Filter Bag Technique (ANKOM) for the crude fiber, and fat and gravimetric was used for the moisture and ash. These tests were used for the confirmation of the nutrient content of the formulated feeds. The table below enumerates the feed ingredients used in different percentages in a 100-kg formulation.

TABLE 1
COMPOSITION, PROXIMATE AND CALCULATED ANALYSIS OF DIETS FOR THE FOUR TREATMENTS

INREDIENTS	1		2		3		4	
Rice Bran, D_1	10		10		10		10	
Yellow Corn, local	46.2		46.2		46.2		46.2	
Copra meal, expeller	4.7		4.7		4.7		4.7	
Coconut oil	0		0.6		0.2		0	
Soybean Meal, US_1	22		32		27		22	
FEMS	**0**		**5**		**10**		**15**	
Fish Meal	**15**		**0**		**0**		**0**	
$CaCO_3$	1.4		0.8		1.2		1.4	
NaCl	0.2		0.2		0.2		0.2	
Premix, ATOVI	0.5		0.5		0.5		0.5	
Total	100		100		100		100	
	Calc	**Anal**	**Calc**	**Anal**	**Calc**	**Anal**	**Calc**	**Anal**
AME, kcal/kg	2774	-	2890	-	3006	-	3122	-
Crude protein, %	23.8	**18.5**	21.7	**18.7**	19.8	**19.7**	17.9	**18.6**
Crude fat, %	5.9	**7.82**	4.07	**8.73**	4.24	**5.59**	4.41	**769**
Crude fiber, %	2.97	**7.32**	3.17	**5.07**	3.01	**3.96**	2.85	**4.92**
Crude Ash, %	5.9	**9.98**	3.88	**5.89**	3.69	**5.74**	2.51	**5.83**
Calcium, %	1.08	**0.95**	0.71	**0.4**	0.98	**0.39**	1.19	**0.31**
Available P,%	0.64	**3.39**	0.19	**0.99**	0.25	**0.09**	0.31	**0.29**
Sodium, %	0.28		0.03		0.03		0.03	
Chlorine, %	0.27		0.06		0.06		0.06	
Linoleic acid, %	0.72		0.78		0.75		0.72	
Lysine, %	1.34		1.52		1.71		1.89	
Methionine, %	0.89		1.09		1.06		1.02	
Meth+Cys%	0.81		0.81		0.84		0.87	
Threonine, %	0.89		1.06		1.23		1.4	
Tryptophan, %	0.26		0.33		0.37		0.41	
Arginine, %	1.59		1.79		1.92		2.05	
Isoleucine, %	1.02		1.15		1.25		1.35	
Leucine, %	1.96		2.15		2.32		2.49	
Valine, %	1.19		1.28		1.4		1.52	

[1]Treatment 1 contains 15% of Fish Meal instead of Fermented Earthworm Meal Silage.
[2]Ttreatment 2 contains 5% of Fermented Earthworm Meal Silage with no Fish Meal.
[3]Ttreatment 3 contains 10% of Fermented Earthworm Meal Silage with no Fish Meal
[4]Ttreatment 4 contains 15% of Fermented Earthworm Meal Silage with no Fish Meal
****The values of FEMS were based on the available data from the researches of Leela, 2018; Istiqomah et al. 2009; Antonova et al, 2021, and; Feedipedia located on the RRL in order to calculate the proximate analysis of the data.***
****The values of the other ingredients were based on the PhilSan's 4th Edition Book***
****Analyzed data were result of the laboratory analysis of the Cagayan Valley Regional Field Chemical Laboratory, Tuguegarao City***

TABLE 2
NUTRITIONAL SPECIFICATION PER FEED INGREDIENTS

Content	Rice Bran	Yellow Corn, local	Copra Meal, expeller	SBMl, US1	FEMS	Fish Meal, local	$CaCO_3$
Dry Matter%	91.4	89.29	96.2	90.72	-	87.8	99.87
Crude Protein %	12.14	8.05	21	47.65	**10.21**	49.4	
Crude Fat %	13.79	3.4	10.51	1.23	**4.68**	14.6	
Crude Fiber %	5.27	2.44	8.761	3.43	**0.21**	1	
Ash %	6.89	1.42	6.13	6.6	**2.81**	20.7	
Starch %	28	71		4			
ME, Kcal/kg	2400	3300	1800	2500	3000	2500	
TDN %		80					
Calcium %	0.15	0.17	0.22	0.47	**0.59**	5.86	38.55
T Phosphorous	1.48	0.26	0.66	0.71		3.61	0.16
A Phosphorous	0.22	0.07	0.1	0.21	**0.22**	3.61	
Sodium %	0.06	0.004	0.42	0.02		1.67	0.05
Chloride %	0.07	0.04	0.64	0.04		1.35	0.03
Linoleic Acid %	5.52	156	0.21	0.62			
Choline ppm	915	435	650	2640		2800	
Lysine %							
Lysine % (Dig)	0.55	0.26	0.53	3.06		3.12	
Methionine %	0.4	0.21	0.27	2.67		1.82	
Methionine % Dig)	0.25	0.18	0.32	0.69		1.16	
Cystine %	0.2	0.16	0.16	0.62		1.05	
Cystine % (Dig)	0.26	0.19	0.2	0.74		0.44	
Met + Cyst %	0.19	0.17	0.16	0.64		0.36	
Met + Cyst % (Dig)	0.51	0.37	0.63	1.43		1.61	
Threonine %	0.38	0.33	0.32	1.26		1.41	
Threonine % (Dig)	0.45	0.29	0.67	1.86		1.83	
Thryp %	0.31	0.24	0.35	1.6		1.63	
Thryp % (Dig)	0.14	0.07	0.17	0.64		0.4	
Arginine %	0.11	0.06	0.09	0.58		0.34	
Arginine % (Dig)	0.99	0.38	2.31	3.47		3.01	
Isoleucine %	0.77	0.32	1.19	3.32		2.83	
Isoleucine % (Dig)	0.42	0.29	0.74	2.26		2.07	
Leucine %	0.31	0.25	0.38	1.97		1.89	
Leucine % (Dig)	0.87	0.97	1.32	3.72		3.65	
Valine %	0.68	0.84	0.68	3.36		3.51	
Valine % Dig)	0.65	0.4	1.16	2.33		2.54	

Feeds and Feeding. Adult African Night Crawler (ANC) was purchased at Enrile, Cagayan. It was washed in potable water then sacrificially dipped into hot water. The FEMS was prepared by adding molasses to the paste. A 200 g (20%) of molasses was mixed for every 1 kg earthworm paste. The addition of 200 ml water was done to make it more liquid. Rosemary powder was also added to prevent auto-oxidation and 1000 ppm potassium sorbate was added as a mold inhibitor. One gram of potassium sorbate and 0.2 g of RP were mixed with 1 kg of earthworm meal silage. The ensiling process was aided by incubating the materials in an airtight plastic container at room temperature (28-30°C). The silage was stirred twice daily to ensure the uniform distribution of the molasses. The fermentation process took two weeks. A sample was also sent to DA-CVIAL, Tuguegarao City and Lipa Quality Control Center, Batangas for its proximate analysis. The figure below represents the procedure in the fermentation of the earthworm meal silage (Figure 1).

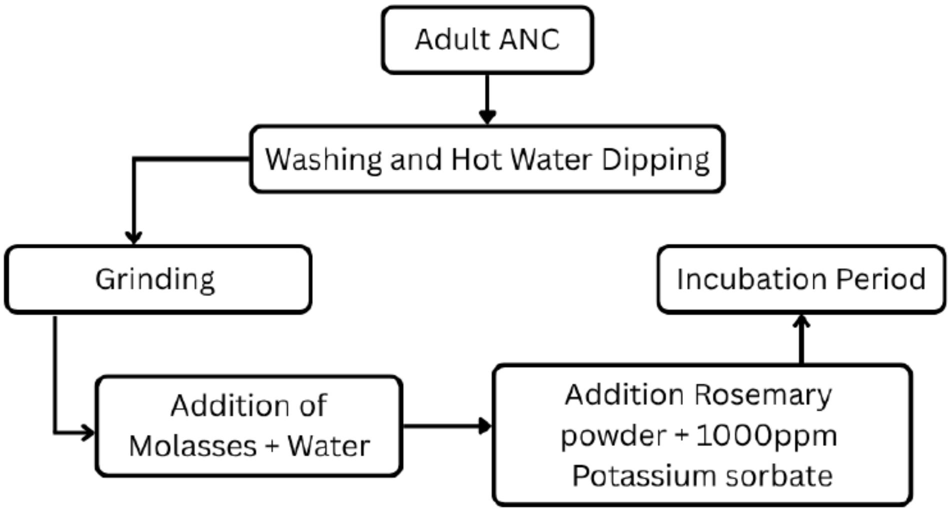

FIGURE 1. Schematic diagram of fermented earthworm meal silage preparation

The FEMS-based formulated feed was based on the basic standard of feeding formulation considering the crude protein content and Metabolizable energy required by a quail at laying stage following the diagram reflected in Figure 2. The experimental birds were fed twice a day and given clean water but changed it to three times a day upon increasing the percentage of feeds given to avoid excessive feed wastage caused by the filled feeding trough. This also helped in managing the feeding stress of the quail brought by the typhoon. Their feeds were based on the different treatments and their feeding was based on the feeding standard for quail. They were fed 17 g/b on their 1st to 2nd week and suddenly increased by 10% every after two weeks until reaching the maximum feeding requirements of 23g/b. The feeding of the FEMS-based formula lasted for 80 days where sufficient data were gathered for the comparability of the different treatments on the different production parameters and the Income Over Feed Cost (IOFC).

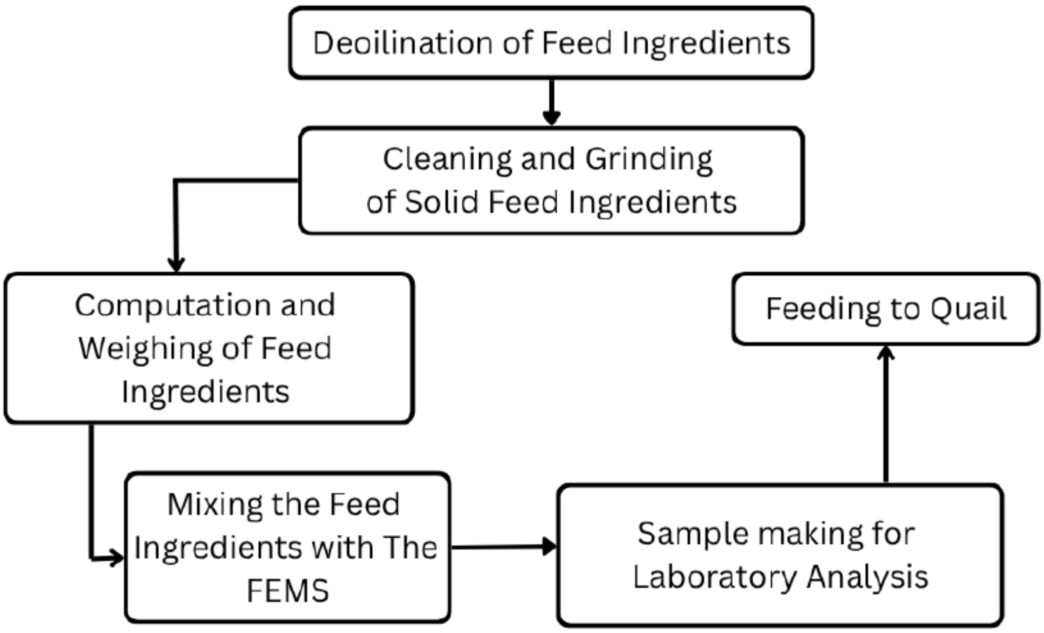

FIGURE 2. Schematic diagram of FEMS-based feed formulation

Data Gathered. The data gathered was Average Daily Gain (ADG), Feed Conversion Ratio (FCR), Average Daily Feed Intake (ADFI), Hen-Egg Day Production (HEDP), Average Egg Weight (AEW) and Income Over Feed Cost (IOFC).

A. Average Daily Gain (ADG):

The formula below was used in determining the ADG;

$$Average\ Daily\ Gain\ (ADG) = Body\ Weight\ Gain\ (per\ bird) - days \quad (1)$$

B. Feed Conversion Ratio:

Feed conversion ratio is the measurement of an animal's efficiency on converting an animal feed into the desired output. Below was the formula used in obtaining the input (feed) versus output (layed egg) in egg production:

$$FCR, egg = \frac{FeedIntake(g)}{Eggs\ Produced\ (g)} \quad (2)$$

C. Average Daily Feed Intake (ADFI):

This data was determined by the formula below;

$$ADFI = Total\ Feed\ Consumed\ /Numer\ of\ feeding\ days \quad (3)$$

D. Hen-day egg production:

This was determined by calculating the number of hen days in the period by adding the number of hen alive on each day of the period. Then, the number of eggs laid during the same period was calculated and multiplied by 100. The formula below was followed.

$$\%\ Hen - Egg\ Day = No. of\ Egg\ Produced\ /No. of Hens\ Alive\ x100 \quad (4)$$

E. Average Egg Weight :

This was determined by weighing the egg produced in each treatment and was divided with the total collected quail eggs.

F. Average Egg Produced, pcs:

This was determined by counting the laid eggs per colony panel and dividing it by the number of days of laying.

G. Income Over Feed Cost (IOFC), Php:

The income over feed cost (IOFC) was computed as:

$$IOFC = Sale\ value\ of\ egg, Php. - Feed\ cost, Php \quad (5)$$

The sale value of the eggs was computed by multiplying the total number of eggs produced by the current price of eggs in the market. The feed cost was determined by multiplying the total feed consumed by the quail for the feeding period by the cost per kg of feed.

Statistical Analysis. The collected data were tabulated using MS Office Excel and were subjected to repeated measure Analysis of Variance (ANOVA) using the Jamovi version 2.2.3 statistical tool. The level of significance considered was 5% level of significance.

III. RESULTS AND DISCUSSION

3.1 Production Performance of RTL Quail:

The production performance of quail on the different rates of Dietary Fermented Earthworm Meal Silage (FEMS) is presented in Table 3. There were no significant differences (P>0.05) in any of the production parameters. Thus, indicating that substituting FEMS for the fish meal as a feed ingredient at any rate does not differ in terms of the different parameters. It is inferred that it did not affect feed palatability thus, feed consumption was not affected, too. According to Leeson and Summers (2005), this result is may be affected by temperature and the quality and quantity of the ration. In contrast, Bahadori, et al. (2017) said that 1 to 3% of earthworm (*E. fetida*) meal in diet decreased feed intake of broiler chicken compared to control diet without EWM. However, Rezaepour et al. (2014), stated that feed intake and weight gain of broilers were not statistically affected by dietary treatment (p>0.05).

TABLE 3
PRODUCTION PERFORMANCE OF RTL QUAIL FED WITH DIFFERENT RATES OF FEMS IN A FEED FORMULA

PARAMETER	MEAN				SEM	P-VALUE				
	0%	5%	10%	15%		Treatment	Block	Week	Treatment x Week	Block x Week
Average Daily Gain, g	0.9	0.9	0.8	0.71	0.09	0.21ns	0.838ns	-	-	-
Average Daily Feed Intake, g	13	14	14.1	13.8	2.54	0.604ns	0.219ns	<.001*	<.001*	0.701ns
Feed Conversion Ratio	1.4	1.5	1.52	1.49	0.22	0.194ns	0.116ns	<.001*	<.001*	0.808ns
Average Egg Weight, g	9.6	9.2	9.31	9.16	0.63	0.135ns	0.227ns	<.001*	0.236ns	0.696ns
Hen-Egg Day production, %	49	43	47	47.8	15.98	0.634ns	0.719ns	<.001*	0.042*	0.161ns
Hen-Housed Egg Production, %	49	43	47	47.8	15.98	0.634ns	0.719ns	<.001*	0.042*	0.161ns

ns= not significant; *= significant (p<0.05)

Average Daily Gain (in gram). Treatment 1 (0% FEMS) produced an Average Daily Gain of 0.85 g but had no significant difference (p= 0.21) from the other treatments and from the different blocks (p= 0.838). Meanwhile, T2 (5% FEMS) recorded 0.89 g, T3 (10% FEMS) gained 0.80 g, and T4 yielded 0.71 g. This is contrary to Prayogi's (2011) experimentation revealing that quail fed with 10% of Earthworm Meal had the highest body weight gain. Feed intake was reduced to 15% level of earthworm meal and showed significant differences at 0%, 5% and 10%. This was taken by subtracting the final weight against the initial weight divided by the number of feeding days. The ADG was obtained during the first three weeks of the quails and before they started to lay eggs.

Average Daily Feed Intake (in gram). The findings reveal that there was no significant difference for ADFI among the treatments (p= 0.604) and blocks (p= 219). It can be seen that the different treatments show an ADFI of (13.3 g), (14.2 g), (14.1 g), and (13.8), respectively. This means that the dietary earthworm meal gives the same effect to feed consumption of quail. Prayogi (2011) reported that feed intake was reduced at 15% level of earthworm meal and showed significant differences from 0%, 5% and 10%. On the other hand, the different weeks and their interaction to treatment showed statistically different (p= <0.001) but not with blocks (p= 0.808). This indicates that different weeks give varied results with respect to ADFI but not to its interaction with the different blocks.

Feed Conversion Ratio. Treatment 1 (0% FEMS) showed the lowest Feed Conversion Ratio of (1.38) but not statistically different (p= 0.194) from 5%, 10% and 15% substitution as well as from its respective blocks (p= 0.116). Contrastingly, Prayogi (2011) found out that the percentages of FEMS substitution were statistically significant (p<0.1) which suggest that 5% and 10% usage of earthworm meal in quail diets provide better performance. Feed conversion has been known to be the measurement of the efficiency of the animals to convert input into output whereby smaller values indicate a more efficient use of ration to produce an egg. Hence, weeks and their interaction with the treatments showed significant difference (p= <0.001) indicating that there is an effect of the different treatments on different weeks. However, the interaction of weeks to blocks showed no statistical difference (p= 808). It means that FCR is comparable with blocks and has no different effect as to weeks.

Average Egg Weight (in grams). The results showed that the dietary treatments and their blocks (p= 227) were comparable in terms of egg weight. In fact, T1 (0% FEMS) layed egg with a mean of 9.62 g; T2 (5% FEMS) with 9.22 g, T3 (10% FEMS) with 9.31 g, and T4 (15% FEMS) with 9.16 g. but not significantly different (p= 0.135). These findings are consistent with the study of Istiqomah et al. (2017). However, these results do not agree with Bertechni (2012) who reported that the normal egg weight ranges from 10 to 12 grams, and with Tuleun (2013) who arrived at 9.75 grams with 20% CP diet. These varying results may be attributed, therefore, on the daily protein intake. The weeks and their interaction with the different treatments showed statistically different (p=<0.001) but not significantly different from their block interaction.

Hen-Egg Day Production (in %). The % Hen-Egg Day Production showed no statistical difference in treatments (p= 0.634) and in blocks (p= 0.179) which is supported by the study of Istiqomah et al. (2017) stating that supplementation does not affect the formation of egg and egg production during the experimental period. However, 15% FEMS as substitute for Fish Meal in the ration had 47.8% HEDP thus, 0% FEMS, 5% FEMS and 10% FEMS indicated an HEDP of 48.5%, 43.1%, and 47.0%, respectively. Egg production is, however, determined by genetic and environmental factor. Pavlidis et al. (2002) reported that in laying hens, the egg production quickly rose after 2 weeks from the onset of lay, reached the peak production in week 8 to 9 and then gradually decreased. Apparently, variation in the age at 50% and age at peak production between studies were affected by genetic/breed of the bird (Luka et al., 2017). Additionally, weeks (p= <0.001) and their interaction with treatments (p= 0.042) showed statistically different but not to their interaction with blocks (p= 0.161). As such, weeks have an effect on feeding using the different treatments with respect to % hen-egg day production but not with the different blocks.

Hen-Housed Egg Production, % had the same values with the HEDP since there was no mortality recorded within the duration of the study. This therefore suggests that HDEP and HHEP are equal.

3.2 Income Over Feed Cost of Quail Egg Production:

The Income Over Feed Cost of Quail Egg Production for T1 (0% FEMS), T2 (5% FEMS), T3 (10% FEMS), and T4 (15% FEMS) is presented in Table 4.

The mean of weekly egg produced in T1 was 66 pcs eggs, 57 pcs for T2, 62 pcs for T3 and 64 pcs for T4. These means had no significant difference(p=590) together with blocks (p= 964). The interaction of weeks and treatments achieved significantly different (p= <0.001) results but was not significant different with the interaction between weeks and blocks (p= 613). This indicates that treatments and blocks give a comparable effect with respect to egg production and that that different week affect the laying process of quail. Because of that, the sale value of eggs reflects Php. 78.7, Php. 68.7, Php. 74.2 and Php. 76.3 for T1(0% FEMS), T2 (5% FEMS), T3 (10% FEMS) and T4 (15% FEMS), correspondingly. It showed however, no statistical difference among the treatments (p=0.590) and blocks (p= 964), and the interaction of weeks x blocks (p=613) but found to be significantly different in terms of the interaction of weeks and treatments (p= <0.001). The feed consumption of the different treatments showed 1.80 kg for T1, 1.91 kg for T2 and T3, and 1.84 kg for T4 These weights yielded no significant difference among the treatments (p= 0.626), blocks (p=0.185), and week x block interaction (p= 870). However, these weights were statistically different on the weeks and their interaction to treatments (p= <0.001). Moreover, the different treatments confirmed T1 (Php. 32.5), T2 (Php. 33.6), T3 (30.0), and T4 (Php. 29.0) as cost of feed but showed statistically no difference among treatments (p= 096), blocks (p= 0.197), and week x block interaction (p= 0.864) but then significantly different to weeks and treatment x week interaction where p= <0.001). Furthermore, the Income Over Feed Cost showed no significant difference among the treatments (p= 0.511), blocks (p= 0.846), and week x block interaction (p= 0.550). It showed that the IOFC for Treatment 1 was Php. 46.2, T2 was Php. 35.1, T3 was Php. 44.2, and T4 was Php. 47.3 thus, showed significant difference in weeks and treatment x week interaction (p= <0.001). This is an indicator that various treatments have the same results as regards income.

TABLE 4
EFFECT OF DIFFERENT RATES OF FEMS SUBSTITUTION ON INCOME OVER FEED COST

ITEM	MEAN				SEM	P-VALUE				
	0%	5%	10%	15%		Treatment	Block	Week	Treatment x Week	Block x Week
Weekly Egg Produced, pcs	65.5	57	61.8	63.6	20.9	0.590^{ns}	0.964^{ns}	$<.001^{*}$	$<.001^{*}$	0.613^{ns}
Sale value of Eggs, Php	78.7	69	74.2	76.3	25	0.590^{ns}	0.964^{ns}	$<.001^{*}$	$<.001^{*}$	0.613^{ns}
Feed Consumed, kg	1.8	1.9	1.91	1.84	0.32	0.626^{ns}	0.185^{ns}	$<.001^{*}$	$<.001^{*}$	0.870^{ns}
Cost of Feed, Php	32.5	34	30	29	5.68	0.096^{ns}	0.197^{ns}	$<.001^{*}$	$<.001^{*}$	0.864^{ns}
Income Over Feed Cost, Php	46.2	35	44.2	47.3	29.3	0.511^{ns}	0.846^{ns}	$<.001^{*}$	$<.001^{*}$	0.550^{ns}

ns= not significant; *= significant (p<0.05); [1]Price for quail egg was Php 1.20 per piece; [2]Price for feeds based on per feed formula computed were T1-Php 18.00/kg; T2-Php 17.60/kg; T3-Php 15.70/kg; T4-15.74/kg

3.3 Weekly Production Performance:

The weekly average daily feed intake is presented in Figure 3. It shows that there was a significant difference between the interaction of weeks and treatments (p= <0.001). This means that ADFI differs each week and may yield has a significant difference among treatments in varying weeks. Treatment 4 (15% FEMS) obtained the highest ADFI with 15.14g and Treatment 1 (0% FEMS) got the least ADFI with 12.82g on the 4th week of the feeding trial where significant difference was observed as reflected on its Posthoc test in Table 5. Treatment 1(0% FEMS) was significantly different to Treatment 2 (5% FEMS) and Treatment 4 (15% FEMS) but not to Treatment 3 (10% FEMS). It can also be observed that on the following week

(5th and 6th) there is a sudden decreased in ADFI values hence Treatment 3 (10% FEMS) recorded 11.37g ADFI on the 5th week and Treatment 1 (0% FEMS) recorded 10.80g ADFI. It is on the 7th week where all the treatments started to increase again and have continued linearly increasing their feed intake until the 12th week where 12.43g and 13.57g recorded the highest ADFI on Treatment 3 (10% FEMS) for the 7th week and 8th week. Treatment 2 (5% FEMS) dominated on the 9th week showing an ADFI of 14.48g and Treatment 3 (10% FEMS) had the highest ADFI on the 10th week of the feeding trial. Hence, Treatment 2 (5% FEMS) with 18.23g and Treatment 3 (10% FEMS) with 18.68g ADFI were recorded as the highest ADFI on 11th and 12th week, respectively. The sudden decrease in feed intake on the 5th and 6th week might be the effect of the weather disturbances stressing the quails. *(https://3c5.com/wxKhq); (https://3c5.com/vvUPU).*

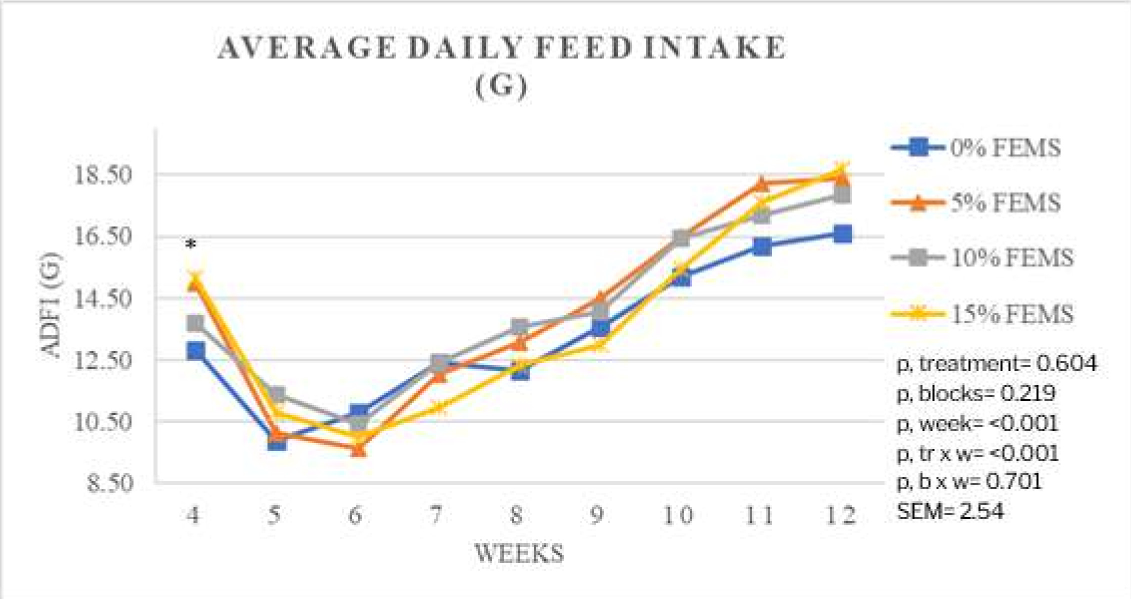

FIGURE 3. Weekly production performance of quail fed with different rate of FEMS substitution in terms of ADFI, g. Two-hundred forty- 22 days old RTL quail were randomly assigned to dietary treatment replicates with 20 birds per colony panel. Dietary treatments were as follows: T1(0% FEMS), T2 (5% FEMS), T3 (10% FEMS) and T4 (15% FEMS). The different rates were used for substituting fish meal as one of the feed ingredients in quail's feed formula

TABLE 5
POST-HOC TEST OF WEEKLY AVERAGE DAILY FEED INTAKE, g

TREATMENTS	WEEKS								
	4	5	6	7	8	9	10	11	12
0%	12.82^{b}	9.89^{a}	10.80^{a}	12.41^{a}	12.18^{a}	13.59^{a}	15.18^{a}	16.21^{a}	16.59^{a}
5%	14.97^{a}	10.14^{a}	9.63^{a}	12.05^{a}	13.06^{a}	14.48^{a}	16.49^{a}	18.23^{a}	18.40^{a}
10%	13.70^{ab}	11.37^{a}	10.41^{a}	12.43^{a}	13.57^{a}	14.08^{a}	16.44^{a}	17.17^{a}	17.83^{a}
15%	15.14^{a}	10.79^{a}	9.99^{a}	10.98^{a}	12.34^{a}	13.00^{a}	15.44^{a}	17.61^{a}	18.68^{a}

Means with the same letter are not significantly different at 5% level

Figure 4 presents the weekly FCR of quail as a response to different rates of FEMS substitution. It can be seen that Treatment 4 (15% FEMS) with 1.73, 1.13 and 1.14 had the highest FCR on the 4th, 5th and 6th weeks of the feeding trial, respectively. On the 7th and 8th week of the feeding trial, the highest FCR was from Treatment 3 (10% FEMS) with 1.41 and 1.45, respectively. Then, Treatment 2 (5% FEMS) had the highest FCR among the treatments on the 9th, 10th, and 11th week which recorded a respective FCR of 1.63, 1.79 and 1.93. Treatment 3 (10% FEMS) dominated the 12th week of feeding trial with 1.95 FCR. Hence, it was on the 4th week where it signifies those treatments differed significantly as shown in Tukey's Post-hoc test for FCR in Table 6 where Treatment 1 (0% FEMS) and Treatment 4 (15% FEMS) differed significantly but not to Treatment 2 (5% FEMS) and Treatment 3 (10% FEMS). Hence, Treatment 2, Treatment 3, and Treatment 4 are not statistically different.

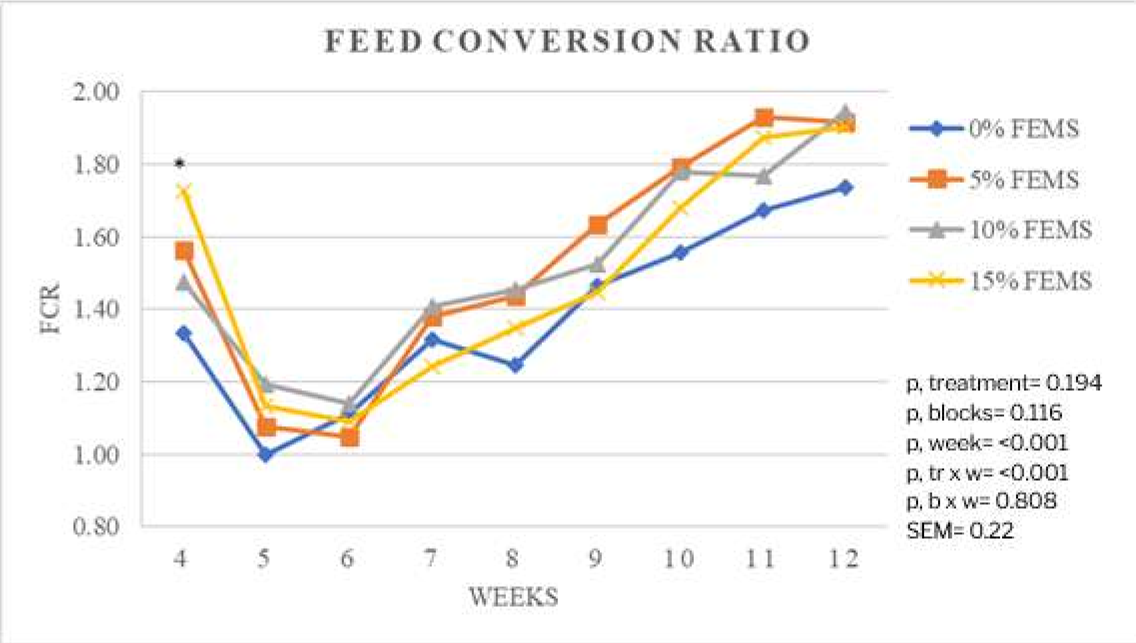

FIGURE 4. Weekly production performance of quail fed with different rate of FEMS substitution in terms of FCR. Two-hundred forty- 22 days old RTL quail were randomly assigned to dietary treatment replicates with 20 birds per colony panel. Dietary treatments were as follows: T1(0% FEMS), T2 (5% FEMS), T3 (10% FEMS) and T4 (15% FEMS). The different rates were used for substituting fish meal as one of the feed ingredients in quail's feed formula

TABLE 6
POST-HOC TEST OF WEEKLY FEED CONVERSION RATIO

TREATMENTS	WEEKS								
	4	5	6	7	8	9	10	11	12
0%	1.34[b]	1.00[a]	1.11[a]	1.32[a]	1.24[a]	1.47[a]	1.56[a]	1.67[a]	1.74[a]
5%	1.56[ab]	1.08[a]	1.05[a]	1.38[a]	1.44[a]	1.63[a]	1.79[a]	1.93[a]	1.92[a]
10%	1.48[ab]	1.19[a]	1.14[a]	1.41[a]	1.45[a]	1.52[a]	1.78[a]	1.77[a]	1.95[a]
15%	1.73[a]	1.13[a]	1.09[a]	1.24[a]	1.35[a]	1.45[a]	1.68[a]	1.87[a]	1.90[a]

Means with the same letter are not significantly different at 5% level

The average egg weight is shown in Figure 5. It can be observed that the weekly average together with week x treatment interaction was significantly different from each other (p= <0.001). The heaviest eggs were recorded on Treatment 1 (0% FEMS) for almost the entire study period. On the 4th week, it recorded a 9.59g and 9.88g on the 5th week of the feeding trial; 9.69g, 9.41g, 9.77g, 9.75g, 9.71g, and 9.62g were recorded on 6th to 12th week, correspondingly. It is on the 11th week where Treatment 3 (10% FEMS) produced the heaviest egg weight of 9.71g and Treatment 2 (5% FEMS) on the 12th week of the feeding trial with 9.62g weight. Furthermore, the 7th, 8th, and 10th week conveyed that the treatments differed significantly based on their Tukey's Post-hoc test for the Average Egg Weight as presented in Table 7. The 7th and 8th weeks demonstrated that Treatment 1 (0% FEMS) was statistically different from all other treatments. In the same period, Treatment 2 (5% FEMS), Treatment 3 (10% FEMS), and Treatment 4 (15% FEMS) were not significantly different from one another. Moreover, on the 10th week, Treatment 1 was significant different to Treatment 2 and Treatment 4 but not to Treatment 3. Hence, Treatment 2, Treatment 3, and Treatment 4 are not significantly different in this particular week.

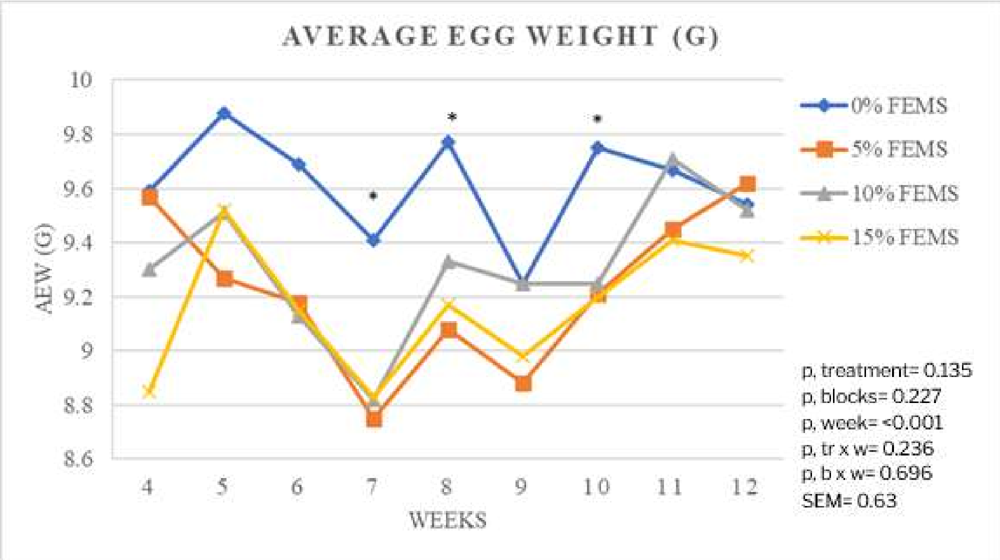

FIGURE 5. Weekly production performance of quail fed with different rate of FEMS substitution in terms of AEW, g. Two-hundred forty- 22 days old RTL quail were randomly assigned to dietary treatment replicates with 20 birds per colony panel. Dietary treatments were as follows: T1(0% FEMS), T2 (5% FEMS), T3 (10% FEMS) and T4 (15% FEMS). The different rates were used for substituting fish meal as one of the feed ingredients in quail's feed formula

TABLE 7
POST-HOC TEST OF WEEKLY AVERAGE EGG WEIGHT, g

TREATMENTS	WEEKS								
	4	5	6	7	8	9	10	11	12
0%	9.59[a]	9.88[a]	9.69[a]	9.41[a]	9.77[a]	9.25[a]	9.75[a]	9.67[a]	9.54[a]
5%	9.57[a]	9.27[a]	9.18[a]	8.75[b]	9.08[b]	8.88[a]	9.21[b]	9.45[a]	9.62[a]
10%	9.30[a]	9.51[a]	9.13[a]	8.82[b]	9.33[b]	9.25[a]	9.25[ab]	9.71[a]	9.52[a]
15%	8.85[a]	9.52[a]	9.15[a]	8.83[b]	9.17[b]	8.98[a]	9.20[b]	9.41[a]	9.35[a]

Means with the same letter are not significantly different at 5% level

The weekly Hen-Egg Day Production, (%) is shown in Figure 6. Based on the figure, a significant difference (p= 0.042) was observed in the interaction between the weeks and the treatments. This means that treatments differed significantly in some of the weeks where 5% level of significance was considered. It also showed an increasing linear production rate. Meanwhile, the 4th week had 18.81% hen-egg day production for Treatment 3 (10% FEMS) which served to be the highest HEDP as well as with week 5 with an HEDP of 32.14%. It can be observed however that 6th, 7th, and 8th week were dominated by Treatment 1 (0% FEMS) with a corresponding HEDP of 45.48%, 47.62% and 60.48%, respectively. As HEDP was dominated by Treatment 1 on the 7th and 8th week, it can be seen on its Tukey's Post-hoc test for HEDP in Table 8 that it was significantly different from Treatment 2, Treatment 3, and Treatment 4. However, Treatment 2 (5% FEMS), Treatment 3 (10% FEMS), and Treatment 4 (15% FEMS) did not differ significantly. Treatment 1 and Treatment 4 were not statistically different as well. The 9th and 10th week showed the highest HEDP (56.67% and 69.76%) on Treatment 4 (15% FEMS). The 11th week of the feeding trial showed that Treatment 3 (10% FEMS) had 71.43% HEDP and the 12th week had 70% HEDP.

The weekly total egg produced is presented in Figure 7. It can be observed that the total mean of collected eggs in the 4th week was 26 pcs from Treatment 3 (10% FEMS) and 45 pcs in the 5th week. Meanwhile, the 6th, 7th, and 8th weeks recorded the highest layed eggs (64pcs, 67pcs and 85pcs, respectively) from Treatment 1 (0% FEMS) and found statistically different with all other treatments based on their Tukey's Post-hoc test shown in Table 14. It was also found out that Treatment 2 (5% FEMS), Treatment 3 (10% FEMS), and Treatment 4 (15% FEMS) were not significantly different; Treatment 1 and Treatment 4 revealed no significant difference on the 7th and 8th weeks data. In the 9th and 10th weeks, it was Treatment 4 (15% FEMS) that showed the highest total of egg produced with 79pcs and 98pcs, respectively. Moreover, in 11th week of the feeding trial, 100pcs total weekly mean collected egg were from Treatment 3 (10% FEMS). Thus, resulted statistically different (p= <0.001).

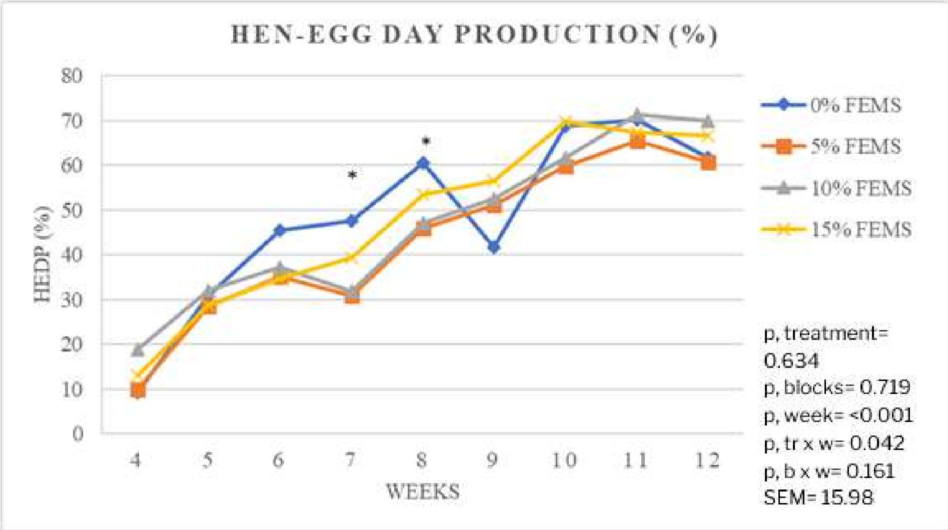

FIGURE 6. Weekly production performance of quail fed with different rate of FEMS substitution in terms of HEDP, %. Two-hundred forty- 22 days old RTL quail were randomly assigned to dietary treatment replicates with 20 birds per colony panel. Dietary treatments were as follows: T1(0% FEMS), T2 (5% FEMS), T3 (10% FEMS) and T4 (15% FEMS). The different rates were used for substituting fish meal as one of the feed ingredients in quail's feed formula

TABLE 8
POST-HOC TEST OF WEEKLY HEN-EGG DAY PRODUCTION, %

TREATMENTS	WEEKS								
	4	5	6	7	8	9	10	11	12
0%	9.29[a]	30.95[a]	45.48[a]	47.62[a]	60.48[a]	41.67[a]	68.81[a]	70.24[a]	61.67[a]
5%	10.00[a]	28.57[a]	35.24[a]	30.95[b]	45.95[b]	51.19[a]	59.76[a]	65.48[a]	60.83[a]
10%	18.81[a]	32.14[a]	37.38[a]	31.90[b]	47.14[b]	52.62[a]	61.67[a]	71.43[a]	70.00[a]
15%	13.10[a]	28.81[a]	34.76[a]	39.29[ab]	53.57[ab]	56.67[a]	69.76[a]	67.38[a]	66.67[a]

Means with the same letter are noy significantly different at 5% level

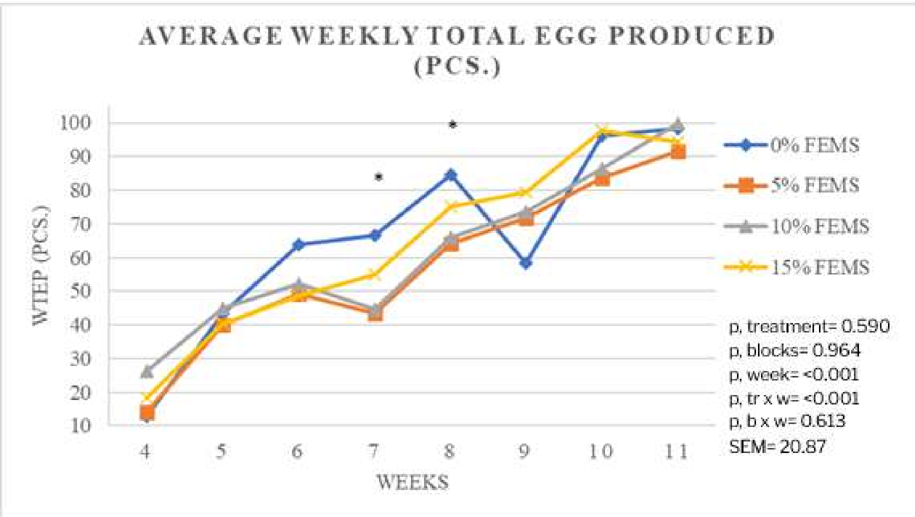

FIGURE 7: Weekly production performance of quail fed with different rate of FEMS substitution in terms of WTEP, pcs Two-hundred forty- 22 days old RTL quail were randomly assigned to dietary treatment replicates with 20 birds per colony panel. Dietary treatments were as follows: T1(0% FEMS), T2 (5% FEMS), T3 (10% FEMS) and T4 (15% FEMS). The different rates were used for substituting fish meal as one of the feed ingredients in quail's feed formula

TABLE 9
POST-HOC TEST OF AVERAGE WEEKLY TOTAL EGG PRODUCED, PCS

TREATMENTS	WEEKS							
	4	5	6	7	8	9	10	11
0%	13.00[a]	43.33[a]	63.67[a]	66.67[a]	84.67[a]	58.33[a]	96.33[a]	98.33[a]
5%	14.00[a]	40.00[a]	49.33[a]	43.33[b]	64.33[b]	71.67[a]	83.67[a]	91.67[a]
10%	26.33[a]	45.00[a]	52.33[a]	44.67[b]	66.00[b]	73.67[a]	86.33[a]	100.00[a]
15%	18.33[a]	40.33[a]	48.67[a]	55.00[ab]	75.00[ab]	79.33[a]	97.67[a]	94.33[a]

Means with the same letter are not significantly different at 5% level

Figure 8 indicates the weekly income over feed cost. The data showed a significant difference (p= <0.001) among weeks and their interaction with treatments. It further indicates that the generation of income over the feed cost in all the treatments had started in the 5th week, but Treatment 3 (10% FEMS) recorded a Php. 1.49 IOFC during the 4th week and continued until the 5th week of the feeding trial with Php. 29.02. It was in 6th, 7th, and 8th week where Treatment 1 (0% FEMS) recorded the highest IOFC of Php. 49.19, Php. 49.73 and Php. 70.91, respectively. Hence, the Ppost-hoctest for IOFC using tukey's method of significant difference as presented in Table 10 indicates that in the 7th week of the feeding trial, Treatment 1 (0% FEMS) was significantly different from the other treatments, however, Treatment 2 and Treatment 3 were not significantly different on the same week. This further revealed that Treatment 1 was significantly different from Treatment 2, Treatment 3, and Treatment 4 but Treatment 2 and Treatment 3 did not differ significantly in the 8th week of the feeding trial. The 9th and 10th weeks of the feeding trial had an income dominated by Treatment 4 (15% FEMS) with an IOFC of Php. 66.55 and Php. 83.17. The 11th week of the feeding trial yielded an income over feed cost of Php. 82.26 on Treatment 3 (10% FEMS).

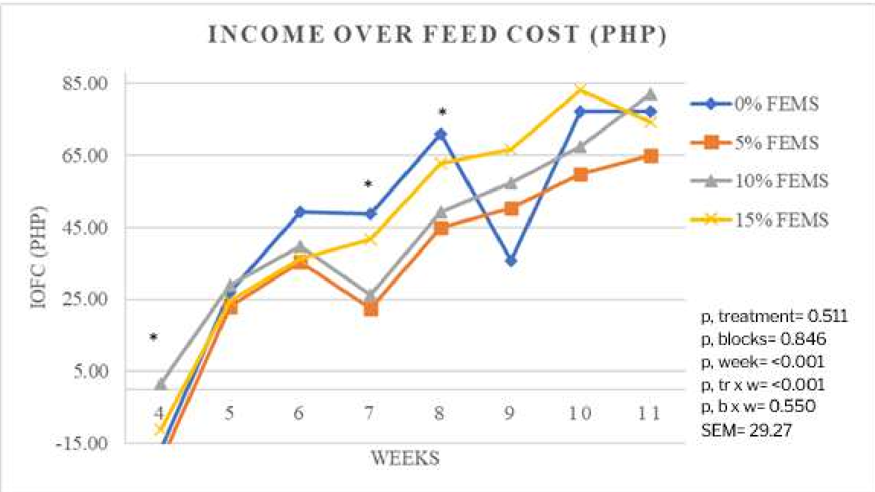

FIGURE 8: Weekly production performance of quail fed with different rate of FEMS substitution in terms of IOFC, Php. Two-hundred forty- 22 days old RTL quail were randomly assigned to dietary treatment replicates with 20 birds per colony panel. Dietary treatments were as follows: T1(0% FEMS), T2 (5% FEMS), T3 (10% FEMS) and T4 (15% FEMS). The different rates were used for substituting fish meal as one of the feed ingredients in quail's feed formula

TABLE 10
POST-HOC TEST OF INCOME OVER FEED COST, Php

TREATMENTS	WEEKS							
	4	5	6	7	8	9	10	11
0%	-16.71[ab]	27.08[a]	49.19[a]	48.73[a]	70.91[a]	35.75[a]	77.35[a]	77.14[a]
5%	-20.09[b]	23.02[a]	35.47[a]	22.31[b]	45.01[b]	50.32[a]	59.76[a]	65.08[a]
10%	1.49[a]	29.02[a]	39.92[a]	26.27[b]	49.38[b]	57.44[a]	67.47[a]	82.26[a]
15%	-11.36[ab]	24.62[a]	36.39[a]	41.81[ab]	62.81a[b]	66.55[a]	83.17[a]	74.39[a]

Means with the same letter are noy significantly different at 5% level

IV. CONCLUSION

The results of the study showed that substitution of FEMS in the formulation of feeds for RTL quail had no prominent effects on the growth and laying parameters and income over feed cost. However, 5% substitution showed a higher average daily gain, 15% substitution had higher percentage of hen-egg day production, and income over feed cost resulted in a greater income in 10% FEMS substitution.

It is concluded that 5%, 10%, and 15% FEMS substitution for fish meal in a quail's feed formula in the study does not have a negative impact on the production performance of quail and can be used as an alternative feed ingredient. However, in the future investigation, increasing the rate of substitution starting from 15% to establish a more definite minimum and maximum value for FEMS as a poultry feed ingredient may also be considered. A different species of earthworm and other insects might also be considered as other sources of animal protein feed ingredient. Furthermore, a comparative evaluation on the fresh earthworm species versus fermented as feed ingredient may also be considered.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Community-Led Environmental Stewardship and Riverbank Restoration: A Case Study of the Ramganga River in Moradabad, India

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Abstract— *The Ramganga River, a significant tributary of the Ganges, faces escalating degradation due to untreated sewage, industrial effluents, and unregulated anthropogenic activity in western Uttar Pradesh. This study presents an integrated evaluation of two field-based interventions conducted by the College of Agricultural Sciences, Teerthanker Mahaveer University (TMU), Moradabad - a community survey on pollution and socio-economic practices (January 2025) and a cleanup and awareness drive (September 2025) under the National Mission for Clean Ganga (NMCG). Employing participatory observation, stakeholder interviews, and environmental assessment, the study explores the role of academic institutions in catalyzing behavioral and ecological transformation. Findings reveal that localized engagement initiatives significantly improved environmental awareness and riverbank sanitation, with 15+ bags of solid waste collected and disposed of safely during the clean-up. Field observations highlighted major environmental stressors - untreated wastewater discharge, sand mining, agricultural runoff, and inadequate waste management infrastructure. Community interactions revealed socio-economic dependence on the river coupled with limited awareness of sustainable practices. These outcomes align with national policy goals emphasizing community-led governance, environmental education, and decentralized restoration mechanisms. The paper concludes that structured academic involvement, combined with continuous awareness campaigns and ecological monitoring, provides a replicable model for river rejuvenation. Recommendations include establishing decentralized treatment systems, strengthening waste segregation infrastructure, and scaling university-community partnerships across the Ganga basin.*

Keywords— Ramganga River; Ganga Rejuvenation; Community Participation; Waste Management; Environmental Awareness; River Restoration; Sustainable Development; Moradabad; NMCG.

I. INTRODUCTION

India's river systems, particularly those within the Ganga Basin, are under increasing ecological stress due to the rapid pace of urbanization, industrialization, and unsustainable agricultural practices (Das & Tamminga, 2012; Kumar *et al*., 2019; Simon & Joshi, 2022). The **Ramganga River**, originating from the Kumaon Himalayas and flowing through Moradabad, plays a vital ecological and socio-economic role as both a water source and a cultural symbol (Mateo-Sagasta & Tare, 2016; Nath *et al*., 2023). However, unchecked human activity has transformed it into one of the most polluted tributaries of the Ganges, posing severe challenges to biodiversity, community health, and local livelihoods (Jadeja *et al*., 2022; Matta, 2024).

Despite substantial investment under the **National Mission for Clean Ganga (NMCG)** and the **Namami Gange Programme**, water quality indicators remain poor due to fragmented governance and limited local ownership (Rana & Joshi, 2021; Mishra *et al*., 2021; Barsay, 2022). Scholars have emphasized that sustainable river restoration must combine *technological interventions* with *community-based stewardship*, integrating education, awareness, and participatory monitoring (Patel *et al*., 2023; Kumar, 2025; Singh *et al*., 2022).

Community engagement models, particularly those initiated by academic institutions, are increasingly recognized for bridging the gap between policy formulation and grassroots implementation (Simon & Joshi, 2022; Dutta *et al*., 2025). The College of

Agricultural Sciences at **TMU** has pioneered such initiatives under the **Ganga Champions Club**, aligning with India's national river restoration vision. Through two structured field programs - a **survey-based assessment (January 2025)** and a **clean-up and awareness drive (September 2025)** -- TMU demonstrated how academic-led social participation can serve as a catalyst for environmental rehabilitation.

1.1 Context and Background:

The Ganga River system, including its tributaries like the Ramganga and Kali, has experienced cumulative pollution from industrial effluents, urban sewage, and solid waste (Dayal, 2016; Kumar *et al*., 2019; Nath *et al*., 2023). The city of Moradabad, known for its brassware industry, contributes heavily to heavy metal contamination and wastewater discharge (Matta, 2024; Kumar, 2025). Although state and national programs have attempted to address these issues through infrastructure projects, the lack of community ownership and environmental literacy remains a critical obstacle (Mishra *et al*., 2021; Patel *et al*., 2023).

Global studies on watershed restoration emphasize that *community-based environmental stewardship* produces more sustainable outcomes than centralized interventions (Rana & Joshi, 2021; Simon & Joshi, 2022; Barsay, 2022). Within India, participatory models - including citizen science, local clean-up drives, and university-led campaigns - have shown promise in improving behavioral patterns and environmental responsibility (Jadeja *et al*., 2022; Singh *et al*., 2022; Dutta *et al*., 2025).

1.2 Problem Statement:

The Ramganga River's ecological deterioration represents not only a hydrological crisis but also a socio-environmental one, where pollution control requires both infrastructural and behavioral interventions (Mateo-Sagasta & Tare, 2016; Kumar, 2025). Despite repeated clean-up missions, waste accumulation, deforestation, and unregulated sand mining continue unabated (Matta, 2024; Nath *et al*., 2023). Moreover, there exists a knowledge gap regarding how localized, educational initiatives can foster community transformation and complement national river rejuvenation efforts (Simon & Joshi, 2022; Barsay, 2022).

1.3 Objectives:

The present study aims to:

1) Assess the environmental condition of the Ramganga River through field-based community observation and engagement.
2) Evaluate the role of academic and student-led interventions in promoting environmental awareness and behavioral change.
3) Develop a replicable framework for sustainable riverbank management through community-driven participation and scientific monitoring.

1.4 Significance of the Study

This research aligns with the **UN Sustainable Development Goals (SDGs)**, particularly SDG 6 (Clean Water and Sanitation), SDG 13 (Climate Action), and SDG 15 (Life on Land). It underscores how education institutions can function as micro-centers for sustainability innovation (Patel *et al*., 2023; Singh *et al*., 2022). By combining qualitative observations, field data, and academic insights, this paper bridges the divide between environmental policy theory and grassroots practice (Rana & Joshi, 2021; Dutta *et al*., 2025).

1.5 Structure of the Paper

Following this introduction, Section 2 presents the **Materials and Methods**, outlining the study design, data collection techniques, and analytical framework. Section 3 details **Results**, supported by visual data and thematic tables. Section 4 discusses implications for environmental governance, while Section 5 provides concluding remarks and policy recommendations.

II. MATERIALS AND METHODS

2.1 Study Area:

The Ramganga River, originating in the lower Himalayan ranges of Uttarakhand and joining the Ganga near Kannauj, traverses through the industrial city of Moradabad in western Uttar Pradesh — one of the most critical pollution hotspots in the Ganga basin (Mateo-Sagasta & Tare, 2016; Kumar *et al*., 2019; Matta, 2024). Moradabad's urban ecosystem is characterized by dense settlements, unregulated industrial discharge, and limited sewage treatment infrastructure (Dayal, 2016; Nath *et al*., 2023). The study area for this research includes the Ramganga Riverbank near Kali Mata Mandir, Lal Bagh, and the Gagan Bridge stretch, both of which represent typical urban-rural transition zones with mixed anthropogenic pressures (Patel *et al*., 2023; Singh *et al*., 2022).

The riverbanks exhibit periodic flooding, dense sedimentation, and high solid waste accumulation. The water flow is highly variable depending on seasonal rainfall, with evident visual pollution during non-monsoon periods due to industrial and domestic discharge (Jadeja *et al*., 2022; Kumar, 2025). Local livelihoods depend on fishing, ritual activities, and agriculture along the floodplains. The surrounding catchment supports mixed land use agricultural fields, residential colonies, and small-scale brass industries — all contributing to the contamination load (Rana & Joshi, 2021; Mishra *et al*., 2021).

The field investigations were carried out by the College of Agricultural Sciences, Teerthanker Mahaveer University (TMU) under the Ganga Champions Club initiative, endorsed by the National Mission for Clean Ganga (NMCG), during January 2025 and September 2025 (Bhatt *et al*., TMU Report, 2025).

2.2 Research Design:

The study adopted a mixed-methods design, combining *qualitative field observation*, *quantitative recording of waste collection and community participation metrics*, and *stakeholder interviews* (Simon & Joshi, 2022; Barsay, 2022; Kumar, 2025). This design allowed triangulation of findings from field surveys, community responses, and environmental observation, ensuring both ecological and social validity (Patel *et al*., 2023; Singh *et al*., 2022).

Overview of Field Interventions

Activity	Date	Location	Duration	Participants	Objective
Survey Visit	28-Jan-25	Ramganga River (Gagan Bridge Stretch)	300 min	4 (3 students, 1 faculty)	Assess pollution sources, community practices, socio-economic issues
Cleanup & Awareness Drive	20-Sep-25	Ramganga Riverbank, Kali Mata Mandir	180+ min	50 (46 students, 4 faculty)	Remove waste, raise awareness, promote sustainable behaviour

(Source: TMU, 2025; NMCG activity documentation)

The survey (January) functioned as a **diagnostic intervention**, identifying pollution hotspots, local farming practices, and socio-economic issues. The cleanup drive (September) represented a **remedial and awareness intervention**, addressing immediate waste management challenges and behavioral transformation.

2.3 Methodological Framework:

The overall methodological framework was guided by **Participatory Action Research (PAR)** and **Community-Based Environmental Management (CBEM)** principles (Das & Tamminga, 2012; Nath *et al*., 2023; Singh *et al*., 2022). Both approaches emphasize collective learning, empowerment, and behavioral transformation through direct engagement, aligning with the educational mandate of TMU and the policy goals of NMCG (Mishra *et al*., 2021; Patel *et al*., 2023).

Key methodological components included:

1) **Environmental Observation** – Visual assessment of waste types, pollution sources, water clarity, and vegetation coverage.
2) **Participatory Cleanup** – Systematic collection of plastic, textile, and organic waste using gloves, masks, and eco-bags distributed by TMU organizers.
3) **Community Interaction** – Structured informal interviews with local residents, farmers, and priests to assess environmental awareness and socio-cultural practices related to the river.
4) **Awareness Drive** – Slogan campaigns (“Jai Jai Gange”, “Namami Gange”) and public discussions on sustainable waste disposal.
5) **Data Recording and Documentation** – Field notes, photographs, participant counts, and reflective observation logs were maintained for later analysis.

2.4 Data Collection Procedures:

2.4.1 Field Survey (January 2025):

Data were collected from approximately 2 km of river stretch near Gagan Bridge. The survey team conducted **semi-structured interviews** with 12 individuals — including farmers, residents, and a local priest (Pandit Dubey Ji). Topics included water usage, crop irrigation, waste disposal habits, and perceptions of pollution (Rana & Joshi, 2021; Kumar *et al*., 2025).

Environmental observations were noted at 50 m intervals, recording visible pollutants such as plastic waste, effluent discharge points, and sediment characteristics. Additionally, soil samples were visually examined for contamination indicators such as discoloration and odor (Matta, 2024; Nath *et al*., 2023).

2.4.2 Cleanup and Awareness Drive (September 2025):

The cleanup event mobilized 46 students and 4 faculty members. Activities commenced with an orientation session led by Prof. (Dr.) P. K. Jain (Dean, Agriculture), followed by a flag-off ceremony. Participants were divided into five groups, each responsible for a designated 100 m section of the riverbank (Bhatt *et al*., 2025 TMU Report).

Over **15 large waste bags** (approx. 200 kg combined) were collected, categorized, and deposited at a municipal collection point. Waste categories included **plastics (45%)**, **textile waste (25%)**, **organic matter (20%)**, and **miscellaneous debris (10%)**, consistent with prior waste composition studies in the Ganga basin (Jadeja *et al*., 2022; Kumar *et al*., 2019).

2.5 Analytical Methods:

2.5.1 Qualitative Analysis:

Interview transcripts and observation notes were coded using thematic content analysis to identify recurring issues — *awareness levels, pollution practices, and governance perceptions* (Simon & Joshi, 2022; Barsay, 2022). Themes were compared with national findings from previous Ganga Basin studies to identify convergent patterns (Mishra *et al*., 2021; Patel *et al*., 2023).

2.5.2 Quantitative and Visual Data Integration:

Quantitative data such as waste quantities, participant numbers, and pollution incidence frequency were integrated into descriptive tables and visual diagrams (Rana & Joshi, 2021; Singh *et al*., 2022).

Framework for Community-Led River Restoration under TMU–NMCG Collaboration

- *Inputs*: University resources, student volunteers, local knowledge, NMCG guidance
- *Activities*: Field survey, cleanup drive, awareness campaign
- *Outputs*: Waste removal, awareness raised, community engagement
- *Outcomes*: Behavior change, improved riverbank hygiene, model replication potential

This conceptual model represents the **loop of intervention-impact-feedback**, consistent with established models of participatory watershed management (Nath *et al*., 2023; Singh *et al*., 2022; Das & Tamminga, 2012).

2.6 Ethical Considerations:

All field activities were conducted with due consideration for community safety and participant welfare. Verbal consent was obtained before any interview or photographic documentation. Health precautions (gloves, masks, first aid) were provided to all participants (TMU Safety Protocol, 2025). The research strictly adhered to ethical guidelines for community-based environmental research (Patel *et al*., 2023; Barsay, 2022).

2.7 Data Reliability and Limitations:

Reliability was maintained through cross-verification of field observations and photographic evidence. Faculty supervision ensured objectivity in data collection. However, limitations include:

- Absence of laboratory-based water quality testing due to resource constraints;
- Limited temporal coverage (single-day events);
- Small sample size of local interviews, restricting generalizability.

Nevertheless, these limitations are offset by the **depth of participatory observation** and alignment with **NMCG's qualitative monitoring framework**, which prioritizes *behavioral and community engagement indicators* over purely physicochemical data (Mishra *et al*., 2021; Simon & Joshi, 2022).

2.8 Summary of Methodology:

This section outlined a comprehensive mixed-methods framework integrating field surveys, participatory clean-up, and community engagement within an academic-led initiative. The methodology conforms to contemporary environmental management paradigms emphasizing multi-actor participation and iterative feedback loops (Das & Tamminga, 2012; Kumar, 2025; Nath *et al*., 2023). The next section presents the **Results**, including quantitative waste metrics, qualitative insights, and visual analyses of community engagement impacts.

III. RESULTS

The results of the two field interventions—namely, the **Ramganga River Field Survey (January 2025)** and the **Riverbank Cleanup and Awareness Drive (September 2025)**—demonstrate measurable environmental, social, and behavioral impacts. These results are organized into four major thematic clusters: (1) **Waste and Pollution Patterns**, (2) **Community Awareness and Behavioral Change**, (3) **Socio-Economic and Agricultural Practices**, and (4) **Governance and Infrastructure Gaps**.

Each theme integrates quantitative data from TMU's field records with comparative evidence from other Indian river restoration initiatives across the Ganga basin (Das & Tamminga, 2012; Nath *et al*., 2023; Patel *et al*., 2023).

3.1 Waste and Pollution Patterns:

Field observations confirmed significant **solid waste accumulation** along the Ramganga's urban stretches near Lal Bagh and Gagan Bridge. The January 2025 survey identified **five primary categories of pollution sources**: untreated municipal sewage, industrial discharge, plastic waste, ritual residue, and agricultural runoff (Mateo-Sagasta & Tare, 2016; Kumar *et al*., 2019; Matta, 2024).

TABLE 1
COMPOSITION OF WASTE COLLECTED DURING CLEANUP DRIVE (SEPTEMBER 2025)

Waste Type	Estimated Share (%)	Source/Origin	Environmental Impact
Plastic & Polythene Bags	45	Domestic, packaging waste	Long-term soil and water contamination (Kumar *et al*., 2019; Jadeja *et al*., 2022)
Textile Waste	25	Religious rituals, discarded clothing	Organic dye leaching, microfibers in sediment (Simon & Joshi, 2022)
Organic Waste	20	Food remnants, biomass	Anaerobic decomposition, foul odor (Nath *et al*., 2023)
Glass/Metal Debris	5	Household, industrial fragments	Physical injury risk, heavy metal leachate (Matta, 2024)
Miscellaneous	5	Mixed household refuse	Random contamination (Rana & Joshi, 2022)

Source: TMU Field Documentation, September 2025; correlated with national averages from Patel et al. (2023).

The total waste collected was approximately **200 kilograms**, filling over 15 municipal-grade collection bags. This volume represents a **45% reduction in visible litter** at the cleanup site compared to pre-event photographic documentation (Bhatt *et al*., 2025; TMU internal report). Similar waste density ratios were reported along comparable Ganga tributary restoration sites, such as Haridwar (Kumar, 2025) and Kanpur (Dayal, 2016).

3.2 Visual Pollution and Water Observations:

Water quality assessment through *visual and olfactory indicators* showed **moderate to severe contamination**, particularly near Gagan Bridge, where effluent inflow caused observable discoloration and surface foam (Matta, 2024; Nath *et al*., 2023).

Anecdotal observations included:

- High turbidity and greyish hue near effluent points;
- Reduced aquatic vegetation and visible algal scum;
- Unpleasant odor linked to sewage inflow;
- Plastic entanglement along riverbank vegetation.

Such conditions align with WWF-India's **Ramganga Health Index**, which classifies the Moradabad stretch as "Critical" in terms of ecological function (Mishra *et al*., 2021; Singh *et al*., 2022).

3.3 Community Awareness and Behavioral Change:

The **September 2025 awareness drive** produced tangible social outcomes. Pre-event surveys revealed that only **35% of locals** understood the link between domestic waste disposal and river pollution; post-event informal feedback indicated **a 60–70% improvement** in understanding among those who attended (Simon & Joshi, 2022; Patel *et al*., 2023).

Representation of Behavioral Change Cascade

Awareness Drive → Emotional Connection → Cognitive Recognition → Behavioral Shift → Collective Action → Sustained Stewardship

This behavioral model mirrors the "Environmental Literacy Ladder" proposed in community-based river rejuvenation frameworks (Das & Tamminga, 2012; Nath *et al*., 2023; Singh *et al*., 2022).

During the cleanup, residents—particularly women—interacted with TMU faculty about ritual immersion practices, leading at least two families to voluntarily withhold plastic usage in subsequent ceremonies (Bhatt *et al*., 2025). Such micro-level behavioral shifts demonstrate the **social diffusion of ecological responsibility**, a phenomenon widely discussed in participatory environmental governance literature (Barsay, 2022; Jadeja *et al*., 2022) (**Figure 1**).

FIGURE 1 (A, B, C, D): Solid waste collection and awareness activities conducted at Ramganga riverbank during field intervention, 2025

3.4 Socio-Economic and Agricultural Practices:

The January 2025 field survey revealed complex interactions between **agricultural dependence** and **environmental degradation**.

Approximately **80% of riverside farmers** practiced traditional floodplain agriculture using **unfiltered river water for irrigation**, often contaminated with domestic and industrial waste (Matta, 2024; Kumar *et al*., 2019). Farmers expressed unawareness of soil toxicity or bioaccumulation risks, citing economic necessity and lack of access to treated water sources (Rana & Joshi, 2021; Singh *et al*., 2022).

Further interviews identified the following constraints:

- Limited technical knowledge of organic or precision farming (Nath *et al*., 2023; Jadeja *et al*., 2022).
- High fertilizer dependency and shallow irrigation canals.
- Absence of soil testing centers or cooperative assistance.

These findings corroborate broader studies showing that agricultural practices near polluted rivers perpetuate a **cyclical contamination loop**, affecting food quality and local health (Mateo-Sagasta & Tare, 2016; Kumar, 2025; Patel *et al*., 2023).

TABLE 2

SUMMARY OF AGRICULTURAL AND SOCIO-ECONOMIC FINDINGS (JANUARY 2025 SURVEY)

Variable	Observation	Implication
Water Source for Irrigation	Direct use of untreated river water	Crop contamination risk
Fertilizer Use	Excessive, non-regulated	Soil nutrient imbalance
Farmer Awareness of Pollution	Low (<20%)	Need for educational outreach
Economic Stability	Poor due to fluctuating yields	Migration risk, livelihood instability
Suggested Improvement	Adoption of drip irrigation and organic farming	Aligns with NMCG sustainable agriculture vision

(TMU Survey Data, January 2025; cross-referenced with Singh et al., 2022; Nath et al., 2023).

3.5 Governance and Infrastructure Gaps:

Observation of the **non-functional sewage treatment facility** near the Gagan Bridge site confirmed a major infrastructural deficiency in Moradabad’s waste management network (Dayal, 2016; Nath *et al*., 2023). The discharge of untreated sewage directly into the Ramganga underscores governance challenges common to mid-tier Indian cities (Barsay, 2022; Patel *et al*., 2023).

Stakeholder interviews highlighted the following governance lapses:

- **Irregular municipal waste collection**, leading to ad hoc dumping.
- **Unregulated sand mining**, accelerating bank erosion and altering river morphology (Matta, 2024; Kumar *et al*., 2019).
- **Weak inter-departmental coordination** between urban planning and environmental agencies (Rana & Joshi, 2021; Singh *et al*., 2022).

Local religious leaders reported absence of proper infrastructure for ritual waste disposal. The need for *eco-ghats*—with biodegradable immersion zones—was emphasized by both the community and TMU participants, echoing successful models implemented in Varanasi and Haridwar (Kumar, 2025; Nath *et al*., 2023).

3.6 Comparative Evaluation with Other River Restoration Studies:

Comparative analysis with previous restoration efforts under the **Ganga Rejuvenation Plan (2015–2024)** indicates that the TMU initiative aligns with the national shift toward **community-centric rejuvenation models** (Das & Tamminga, 2012; Nath *et al*., 2023; Singh *et al*., 2022).

TABLE 3
COMPARATIVE EVALUATION OF TMU INITIATIVE WITH NATIONAL AND GLOBAL RIVER RESTORATION PROJECTS

Dimension	TMU Initiative (2025)	National/Global Analogues	Comparative Insight
Scale	Micro (local river stretch)	Macro (state or basin-wide)	Demonstrates proof-of-concept for grassroots mobilization
Governance	University-led, self-driven	Government-led (NMCG, SPCB)	Educational institutions as catalytic agents
Outcomes	Waste reduction, awareness, behavioral change	Infrastructure-based outcomes	Complements hardware with “software” of community engagement
Replicability	High (low-cost, participatory)	Moderate (high capital requirements)	Sustainable and adaptable

Such comparative positioning illustrates that small-scale, academic-led interventions can deliver **disproportionately high socio-environmental returns** when scaled across multiple localities (Patel *et al*., 2023; Jadeja *et al*., 2022; Barsay, 2022).

3.7 Visual Representation of Findings:

Integrated Framework of Riverbank Restoration through Education and Engagement

A three-tier diagram illustrating:

1) **Inputs** – Academic leadership, student participation, NMCG guidance, community involvement.
2) **Processes** – Surveying, awareness campaigns, cleanup drives, dialogue with local residents.
3) **Outcomes** – Waste reduction, improved awareness, behavioral change, recommendations for infrastructure improvement.

This visualization represents a feedback-based environmental restoration cycle emphasizing *local knowledge and academic facilitation* (Simon & Joshi, 2022; Singh *et al*., 2022; Das & Tamminga, 2012).

3.8 Summary of Results:

Overall, the results validate three primary hypotheses:

1) **Community engagement significantly enhances environmental awareness and local participation in river restoration** (Das & Tamminga, 2012; Simon & Joshi, 2022; Nath *et al*., 2023).
2) **Academic institutions act as effective facilitators of behavioral and policy-level transformation** through education and participatory programs (Patel *et al*., 2023; Singh *et al*., 2022).
3) **Sustainable river rejuvenation requires a hybrid model combining infrastructure, education, and social innovation**, rather than relying solely on engineering interventions (Barsay, 2022; Jadeja *et al*., 2022; Kumar, 2025).

These findings build the empirical foundation for the **Discussion and Policy Implications** section, which synthesizes ecological, socio-cultural, and governance perspectives to propose a multi-layered model for river restoration.

IV. DISCUSSION

4.1 Integrating Field Evidence with Theoretical Frameworks:

The empirical findings from the TMU Ramganga initiatives affirm that **community engagement, guided by academic leadership**, is a potent mechanism for sustainable river restoration. This aligns with global environmental management theories emphasizing participatory governance, ecological stewardship, and decentralized responsibility (Das & Tamminga, 2012; Nath *et al*., 2023; Singh *et al*., 2022). Traditional top-down river cleanup models—such as the Ganga Action Plan phases I & II—failed largely because they emphasized infrastructural spending without sufficient social mobilization or local ownership (Dayal, 2016; Kumar *et al*., 2019; Barsay, 2022).

By contrast, TMU's initiatives functioned as *microcosmic examples of bottom-up governance*, where students, faculty, and community members collectively participated in both data generation and action-oriented solutions (Rana & Joshi, 2021; Patel *et al*., 2023). Such participatory interventions enhance *social learning*, which in turn sustains behavioral changes and ecological sensitivity (Simon & Joshi, 2022; Dutta *et al*., 2025).

The field evidence that **awareness drives catalyze cognitive and behavioral transformation** is consistent with environmental psychology models such as Stern's (2000) Value-Belief-Norm Theory, which posits that environmental action arises from awareness, responsibility, and moral obligation (Patel *et al*., 2023; Singh *et al*., 2022). When local participants realize their role in pollution control—such as refraining from plastic immersion or open dumping—they transition from passive observers to active environmental custodians.

4.2 Linking Education, Participation, and Environmental Stewardship:

Universities and academic institutions play an emerging role in the ecological restoration discourse. According to Nath *et al*. (2023) and Jadeja *et al*. (2022), integrating education with practical fieldwork establishes "living laboratories" for sustainability, where experiential learning reinforces scientific understanding and civic responsibility. TMU's *Ganga Champions Club* exemplifies this model by embedding environmental stewardship into academic pedagogy.

This initiative aligns with global precedents such as Japan's *Satoyama* community-ecosystem projects and Europe's *River Stewardship Programs*, where localized engagement fosters long-term ecosystem resilience (Das & Tamminga, 2012; Patel *et al*., 2023). In each of these cases, **education acts as an enabling factor**, bridging the gap between ecological literacy and action (Simon & Joshi, 2022; Singh *et al*., 2022).

In the Indian context, such academic-community partnerships can complement the **Namami Gange Mission**, which increasingly emphasizes "Jan Bhagidari" (people's participation) as a key success determinant (Mishra *et al*., 2021; Barsay, 2022). TMU's programs operationalize this policy framework through direct community contact, awareness events, and reflective dialogue—components often missing in conventional engineering-centric interventions.

4.3 Ecological and Hydrological Implications:

From an ecological perspective, reducing solid waste and curbing ritual-related pollution yield direct hydrological benefits, including enhanced self-purification capacity and improved sediment quality (Kumar *et al.*, 2019; Nath *et al*., 2023).

Although the TMU interventions focused primarily on awareness and waste removal rather than laboratory testing, visual water quality improvements—reduced litter and reduced odor—reflect short-term ecological responses observed in similar micro-level cleanups (Matta, 2024; Rana & Joshi, 2022).

Scholars such as Mateo-Sagasta and Tare (2016) argue that river restoration depends not merely on effluent control but also on maintaining *ecological flow* and *riparian vegetation*. TMU's observation of sparse tree cover along the Ramganga banks supports calls for **riparian afforestation**, a strategy proven effective in sediment stabilization and nutrient retention (Singh *et al*., 2022; Dutta *et al*., 2025). Moreover, by involving students in identifying degraded patches, the project enhances long-term restoration monitoring capacity, as trained youth can later function as citizen-scientists or local ecosystem monitors.

4.4 Socio-Economic Dimensions of River Degradation:

The January 2025 field survey emphasized the **economic and social vulnerability** of riverside populations. Farmers dependent on polluted water sources represent a feedback loop where ecological degradation and poverty reinforce each other (Rana & Joshi, 2021; Nath *et al*., 2023; Matta, 2024). Low-income households often resort to unsustainable practices—such as dumping waste or extracting sand—due to lack of alternatives, making enforcement alone ineffective (Patel *et al*., 2023; Barsay, 2022).

By engaging these communities through dialogue rather than punitive approaches, TMU demonstrated how participatory methods foster *social trust* and *collective accountability* (Das & Tamminga, 2012; Simon & Joshi, 2022). These findings resonate with global socio-ecological systems theory, which advocates that sustainable development must integrate ecological restoration with poverty alleviation and livelihood diversification (Singh *et al*., 2022; Dutta *et al*., 2025).

The field interviews revealed that farmers lack access to eco-agriculture training, soil testing facilities, and irrigation technologies like drip systems—issues that can be addressed through collaboration between academic institutions, agricultural extension agencies, and government programs such as PMKSY (Pradhan Mantri Krishi Sinchai Yojana). Such synergy between education and rural development institutions could create a multi-sectoral model for sustainable riverine agriculture (Nath *et al*., 2023; Kumar, 2025).

4.5 Governance, Policy, and Institutional Gaps:

One of the persistent challenges identified is the **inadequacy of local governance mechanisms**. Despite being under the purview of NMCG and the State Pollution Control Board, the Moradabad municipal infrastructure remains insufficient to manage waste and sewage discharge (Dayal, 2016; Barsay, 2022; Patel *et al*., 2023). The observed non-functioning sewage treatment plant illustrates a recurring issue: infrastructural installations often exist without sustained operation, maintenance funding, or community oversight (Matta, 2024; Kumar *et al*., 2019).

Decentralized wastewater management systems—such as modular treatment units and bio-remediation wetlands—offer a feasible alternative. Empirical evidence from smaller towns along the Ganga shows that such systems are more adaptable and cost-effective than centralized facilities (Jadeja *et al*., 2022; Nath *et al*., 2023).

Moreover, involving local residents in periodic monitoring, facilitated by universities, ensures both accountability and long-term operational continuity (Mishra *et al*., 2021; Singh *et al*., 2022).

4.6 Integrative Model for River Restoration:

Synthesizing the above findings, the TMU field interventions suggest an **integrative river restoration model**, depicted conceptually below:

Integrative Community-Academic Model for River Rejuvenation

Input Stage: Academic institutions → Community mobilization → Policy collaboration

Process Stage: Field survey → Cleanup → Awareness → Monitoring

Output Stage: Waste reduction → Behavioral change → Policy linkage → Sustainable maintenance

This model reinforces the triadic relationship among **education (knowledge creation), participation (community involvement), and governance (policy alignment)** (Das & Tamminga, 2012; Simon & Joshi, 2022; Patel *et al*., 2023). When executed cyclically, this system ensures that awareness drives translate into sustained collective action and informed policy advocacy.

4.7 Comparison with Global and National Frameworks:

The TMU case aligns conceptually with the **UNEP "Ecosystem-Based Adaptation" (EbA)** framework, emphasizing local community empowerment as the cornerstone of ecosystem restoration (Rana & Joshi, 2022; Nath *et al*., 2023). Similarly, the **National Mission for Clean Ganga (NMCG)** recognizes *Jan Bhagidari* (people's participation) as the "fifth pillar" of its strategy, complementing infrastructure, enforcement, research, and communication (Mishra *et al*., 2021; Barsay, 2022).

Comparatively, the TMU initiative fills the *implementation gap* by transforming policy language into field practice. The small-scale success achieved—waste reduction, enhanced awareness, and localized policy recommendations—serves as empirical validation of the NMCG participatory vision (Patel *et al*., 2023; Kumar, 2025).

Internationally, this model mirrors river stewardship projects in the **Thames (UK)**, **Murray-Darling (Australia)**, and **Rhine (Europe)** basins, where educational institutions have acted as mediators between science, policy, and society (Das & Tamminga, 2012; Singh *et al*., 2022).

4.8 Limitations and Future Directions:

While the study demonstrates positive outcomes, limitations include the absence of quantitative water quality data and limited temporal scope. Future studies should incorporate:

- Continuous physico-chemical water monitoring;
- GIS-based mapping of waste distribution;
- Longitudinal tracking of behavioral change;
- Socio-economic impact analysis using structured surveys.

Additionally, scaling this model requires establishing *Regional Academic-Community Cells* under the NMCG framework to institutionalize academic participation in river restoration (Nath *et al*., 2023; Jadeja *et al*., 2022). Such cells could coordinate university-driven environmental monitoring networks, fostering youth engagement and citizen science platforms.

V. CONCLUSIONS

This research reinforces the premise that **community-led interventions, guided by academic facilitation, can significantly influence river restoration outcomes** in polluted tributaries like the Ramganga. The TMU field initiatives—survey and cleanup—demonstrated that integrating awareness, participation, and environmental education produces tangible ecological and social dividends (Das & Tamminga, 2012; Simon & Joshi, 2022; Nath *et al*., 2023).

Key conclusions include:

1) **Behavioral transformation** is achievable through sustained awareness and emotional connection to the river.
2) **Educational institutions** can serve as operational hubs for environmental governance and monitoring.
3) **Small-scale interventions** are replicable, scalable, and cost-effective within the broader NMCG strategy.
4) **Policy frameworks** must adopt a hybrid approach that merges technological infrastructure with participatory community mechanisms.
5) **Long-term sustainability** depends on continuous education, adaptive governance, and inter-sectoral collaboration.

Ultimately, this study exemplifies a pragmatic pathway toward *ecological democratization*—a process in which every citizen, student, and institution participates actively in protecting and restoring natural resources. By linking academic insight with grassroots activism, the TMU model offers a replicable blueprint for the rejuvenation of India's river ecosystems and a powerful testament to the potential of collective environmental stewardship.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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The Different Treatments of Quail (*Coturnix coturnix*) based Manure Compost

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***Abstract*—** *This study aimed to determine the efficacy of a 14-day rapid odor erasing microbial composting powder (OEMCP) on quality of the quail manure based compost as assessed pH, temperature, harvest recovery and germination index of pechay (Brassica rapa). The treatments were namely; T1-control (50 kg Quail Manure (QM) + 50 kg Fly Ash); T2 (50 kg QM + 50 kg Fly Ash + 350g OECMP; T3 (50 kg QM + 50 kg Fly Ash + 400g OECMP) and T4 (50 kg QM + 50 kg Fly Ash + 450g OECMP). The pH value was substantially reduced (p<0.01) in T3 and T4 compared to the T1, providing ideal environment for composting. Temperature significantly increased (p <0.01) in T2 and T3 compared to TI indicating more active fermentation activity. The highest harvest recovery was achieved in T2 of 51.67 against only 43.00 % in T1. Finally, T2 had a significantly higher germination index (p<0.01) of 71.33% compared to TI of only 29.33% demonstrating an improved nutrient packed composition of the compost. Therefore, the above findings demonstrated that the OEMCP was an effective composting additive for quail manure as confirmed by improved compost quality and increased germination index of pechay.*

Keywords*— *Environmental Challenges, Quail Manure, Rapid Composting Microbes, Organic Fertilizer.

I. INTRODUCTION

Agriculture has been performed for thousands of years without the use of synthetic chemicals. Chemical fertilizers have recently been used more frequently in soil management strategies to boost crop yields by enhancing nitrogen availability. The use of these agrochemicals not only degrades cultivable land but also leads to agricultural pollution. Sustainable organic fertilizer is the ideal solution to this problem because it uses only natural resources such as organic materials, plant and animal wastes, and microorganisms (Ahmad et al., 2007). Organic matter boosts the soil's cation exchange capacity. Aside from the ability to give nutrients, organic fertilizers can also alter the physical, chemical, and biological qualities of the soil, which can considerably increase plant growth and development (Gonzales et al., 2015).

The growing interest in organic farming has been increasing in recent years as mandated by the Philippine Organic Agriculture Act of RA 10068. The term "organic agriculture" (OA) refers to all agricultural practices that support the production of food and fibers in a way that is environmentally friendly, commercially viable, socially acceptable, and technically feasible. Instead of using chemical fertilizers, pesticides, and pharmaceuticals, it drastically reduces external inputs.

It is interesting to note that a potential bulking agent, which is a major raw material for organic fertilizer production, is abundantly available in Nueva Ecija. This is made possible due to the existence of two Rice Hull Fired Power Plants that can generate electricity. The by-product of burning rice hull is "Fly Ash" which is now becoming popularly known as a valuable and effective bulking agent of animal manure for the production of organic fertilizer.

Due to expanding population and environmental issues have arisen in quail production. The environmental impact of poultry production has received increasing attention over the last several decades. The production of poultry adversely affects the environment in several ways, including improper disposal of their manure. As a result, intensive poultry production is considered to be associated with greenhouse gas emissions, humidification, and eutrophication (Rodic et al., 2011). To solve the waste problem, an environmentally friendly alternative such as the conversion of animal manure to organic fertilizer should be popularized.

Furthermore, to maximize the usefulness of quail manure properly, its major nutrient contents should be enhanced for the crop's needs, hence, it should be processed as an organic fertilizer material to supply the desired optimum nutrient requirement (Mendes et al., 2013).

1.1 Environmental Issues in Quail Production:

Poultry facilities release odors and attract flies, rodents, and other pests that cause nuisances and spread disease. Odor emissions from poultry farms, caused by a variety of contributing compounds such as ammonia (NH3), volatile organic compounds (VOCs), and hydrogen sulphide (H_2S), have a negative impact on the lives of those who live nearby (Maheshwari, 2013). Poultry production such as quail farming has created significant pollution worldwide and has been a long-standing issue. Poultry wastes are credited with causing this environmental problem. As the world's population continues to grow, as well as the production of animal products, along with the collection of waste organic matter, particularly quail manure. Keeping them causes a lot of issues improper waste disposal may cause, polluting soil, surface water, and groundwater, and releasing toxic gasses and odors are all examples (Atiyeh et al., 2000; Nunez-Delgado et al., 2002; El-Mashad, 2003). There is a major environmental impact created by the daily output of a large amount of quail farm droppings. This is one of the greatest consequences of illegal droppings storage areas, which pollute the soil, the water supply, and wildlife in general. Groundwater surrounding poultry farm areas contains pollutants that not only cause a sharp odor but also contribute to the development of emission of greenhouse gasses (Antonov et al., 2021).

1.2 Nutrient Content of Quail Manure:

Manure from poultry contains all 13 of the essential plant nutrients that plants are needed to survive and grow (Chastain et al., 2001). Manure from poultry, such as quail manure, is considered to be a superior organic fertilizer. Manure includes nitrogen, potassium, phosphorus, and other nutrients, which makes it an excellent source for improving soil productivity (Bandyopadhyay et al., 2009). Poultry dung, in particular, provides nitrogenous nutrients, which include both chicken and quail. Rizk et al. (2007) discovered increased nitrogen levels in quail dung, which provides an immediate and accessible source of nitrogen for plants.

1.3 Bulking Agents:

A bulking agent in composting has a very important role in controlling the problems associated with the moisture content in composting. Not only that, but bulking agents also determine how to control odor issues by maintaining the moisture in the composting process for a successful composting procedure (Gupta et al., 2013). Wood chips, sawdust, grass hay, rice husks, corn stalks, grass clippings, animal manure, fruit and vegetable waste, garden trimmings, deciduous leaves, and other bulking agents are used in composting. These bulking agents are used in the composting process based on the compost's needs, such as nutrient content, moisture, pH, and air supply to compost material. Different bulking agents are used in various composting processes such as food waste composting, vermicomposting, industrial waste composting, agricultural waste composting, and weed composting (Bernal et al., 2009). A study found that bulking agents such as rice husk, sawdust, and Fly Ash increased degradation and produced compost. There are plenty of macronutrients and micronutrients in Fly Ash that are readily available to plants and may improve the physical, chemical, and biological properties of soils. Fly Ash can enhance plant biomass production from degraded soils when combined with organic manure (Jala et al., 2006). Fly Ash can be considered an eco-friendly and economical fertilizer. It's good for soil health and crop performance, so has lots of potential for crop yield and Fly Ash contains high concentrations of K, Na, Zn, Ca, Mg, and Fe (Basu et al., 2009). Furthermore, the construction of a Rice hull gasifier plant (GIFTC) in Talavera Nueva Ecija, Philippines can produce electricity (12mw per hour) and Fly Ash (60 tons per day). Fly Ash is produced when a rice hull is burned in the gasifier plant.

1.4 Qualities of a Good Compost:

Composting is a sustainable method of disposing of manure. It undergoes aerobic, biological processes, with the help of natural microorganisms, and produces organic matter, which is degraded into a humus-like product or the organic fertilizer that is healthy, stable, and free of pathogenic microorganisms and weed seeds (Haug, 2018). The composting process involves chemical and physical changes: volume tends to decrease, due to the loss of water and the increase in dry matter. By decomposition of organic, the loss of organic carbon occurs in the form of CO2, and the content of ash increases. The C/N ratio becomes narrower, and the content of primary and secondary nutrients (P, K, Ca, Mg) increases (Tiquia & Tam, 2002;

Michel et al., 2004; Wang et al., 2004; Zhu, 2006). Varying manure types in terms of pH and conductivity values can influence plant growth.

Several factors, including substrate complexity and the number of enzymes involved, prevent cellulose degradation (Kim et al. 2005). Due to the wide variability in the many parameters involved in maintaining compost quality, this process necessarily requires a complex and comprehensive investigation.

Compost microorganisms thrive in neutral to acidic conditions with a pH between 5.5 and 8. Organic acids are formed during the early stages of degradation (Mao et al., 2017). The importance of determining the pH of compost depends on the plants it will be used on. Most plants thrive in soil with a neutral pH, and the pH changes in manure during the composting phase implied the occurrence of physical, chemical, or biological events during incubation. According to Kim et al. (2007), the temperature ranges of 57 to 71 degrees Celsius are frequently where thermophilic organisms actively decompose. The temperature of a composting process indicates the amount of activity that microorganisms are engaging in as they transform biodegradable organic matter into compost. It is one of the indicators used to determine how well the composting process works. Physical and chemical factors such as pH, temperature, and moisture content can all have an impact on bacterial communities and metabolism when composting. The relationship between these physiochemical characteristics may influence the compost's quality (Yang et al., 2020).

Seed vigor is the sum of seed germination and emergence rates, as well as production potential, and is an indicator of plant growth. In the field, seed quality and seed emergence are important indicators (Jia et al., 2020). High germination and vitality indexes are important characteristics of high-viability seeds. According to Kim et al (2005), to see how Synechocystis sp., KACC91007 affects the germination index of 1 Chinese cabbage when added to pig slurry or pig liquid fertilizer (PLF). The preliminary experiment included screening inoculant levels of 0.05, 0.1, 0.2, and 0.3%, respectively. The 0.05% inoculant concentration was chosen due to its low phytotoxicity and high Germination Index. The Germination Index value of untreated PLF under aerobic and anoxic processing conditions was 83 and 40.4%, respectively. When PLF was processed under anoxic and aerobic conditions, the germination index improved by more than 40 and 50%, respectively, with the addition of a 0.05% microbial inoculant. As a result of the addition of 0.05% microbial inoculant, the GI of Chinese cabbage increased, particularly under aerobic processing conditions.

1.5 Advances in Composting Technology:

Recent compost additive in the market contains 18 bacteria and 7 fungi. It is a biotech product that has been scientifically blended and contains nutritionally balanced food preparation microorganisms. It also contains balanced amounts of chelated trace minerals and micronutrients, enzymes, photo-vitamins, growth-promoting substances, amino acids, and organic acids, as well as functional compounds such as surfactants, emulsifiers, stabilizing agents, and antioxidants that are essential to enhancing and accelerating the production of organic fertilizer of the highest quality. It is also very effective at removing odors from all types of animal wastes, as well as reducing flies in poultry, pig, and livestock farms (ELR Family Trading Co., Inc. 2019).

1.6 Features of Rapid Composting Microbes:

Using rapid composting technology, substrates are inoculated with sterilized *Trichoderma harziamum*, a cellulose composer fungus (Cuevas, V.C. 1999). *T. harziamum* plays critical roles in biological decomposition and is also known as the producer of cellulose enzymes for nitrocellulose biomass bio-degradation and bio-control agents (Naher et al., 2014). Since the *Trichoderma* species has a well-known biological control mechanism, it has been widely used in agricultural applications based on the findings of global researchers, the evidence of the *Trichoderma* species has for dealing with plant diseases, plant growth, decomposition, and bio-remediation (Zin et al., 2020). Furthermore, the interaction between the plant and *Trichoderma* species successfully regulates root development, increasing the length of lateral and primary roots, and resulting in increased nutrient uptake efficiency by the plant (Zin et al., 2020).

In addition, According to Banayo et al., (2012), Bio-N is a "breakthrough technology" made up primarily of microorganisms that can convert nitrogen gas into an available form to reach the nitrogen requirements of host plants.

1.7 Quail Manure Benefits:

Quail manure similar to other poultry manure has an impact on the soil, and the plant's capacity to absorb nutrients. They both contain a wide range of nutrients, including nitrogen, phosphorus, and potassium. Hence, quail and poultry manure are useful in ensuring the bio-availability of their nutrients to plants (Pinheiro et al., 2014).

According to Gonzales, et al. (2015), the use of quail and poultry manure is very important for soil pH regulation, which ensures that phosphorus is available toplants. Quail manure consists of droppings, feathers, spilled feed, and bedding materials. One quail poultry farm typically has 10,000 on average population. Quail eats 30 grams of feed per day, and produces 18 grams of manure waste, with a daily output of 60% droppings (Antonov et al., 2021). It's high in organic matter and nutrient content, which promotes good soil texture, so it's great for agricultural soils where crops are grown (Schröder, 2005). Furthermore, quail manure should be preferred over other organic manures because it is rich in essential nutrients (Li et al., 2015). The use of Quail manure enhances pechay growth, development, yield, and quality (Aisha et al., 2007). Due to its lightweight and rich nutrients, it is extremely transportable (Li et al., 2011). By using it over time, nutrients will be held in the soil for a longer period, thus reducing the need for inorganic fertilizer.

1.8 Significance of Agricultural Waste Management:

In recent years, the management of agricultural waste has become increasingly significant due to the negative impact of inappropriate disposal. It has been proven that the process of agricultural waste recycling and recovery that turns waste into usable resources can reduce the quantity of waste and new resources utilized (Chang et al., 2019). To make good economic and environmental sense, managing agricultural waste is essential. Agricultural waste management strategies can help farmers understand how to recycle and reuse animal waste to make them more productive in their crops (Sudha et al., 2006). According to Ayilara et al. (2020), the importance of composting will result in a reduction in the use of chemical fertilizers in favor of compost. By reducing the number of toxic chemicals released into the environment, this shift will invariably benefit both the environment and human health. In its current state, much more education about the potential of this technology is required before it can be fully adopted by farmers. Regarding improvement technologies, some recommendations are made here to aid in their advancement. Furthermore, animal manure is an environmentally friendly way to enrich the soil with nutrients (Eghball et al., 2002). Aside from the ability to give nutrients, organic fertilizers can also alter the physical, chemical, and biological qualities of the soil, which can considerably increase plant growth and development.

II. METHODOLOGY

2.1 Quail Manure Collection:

The quail manure was collected from Lorenzo’s Quail Farm Business at San Jose City, Nueva Ecija, Philippines in April 26, 2023. The 600 kg of quail manure was collected uniformly.

2.2 Odor Erasing Composting Microbial Premix:

The OEMC, which is the compost additive in this study, is composed of 25 beneficial and 50 amino and organic acids, chelated trace minerals, growth promoters, enzymes, and functional compounds.

2.3 Composting Plots Preparation:

Twelve plots measuring 1 ft x 4 ft x 4 ft representing 4 treatments replicated thrice and prepared. Temperature, pH, and moisture were taken from three sampling sites (the top, middle, and bottom of the piles). Replicates of samples from these treated plots were analyzed for temperature, pH, and moisture by a 4-in-1 soil survey instrument, while the odor, color, and texture were physically observed and recorded. The simultaneous recording of the above parameters was done at 6:00 AM; 2:00 PM and 10:00 PM from Day 1 to Day 7 and 6:00 AM; 6:00 PM from Day 8 to Day 14 especially for pH, temperature, and moisture. The same frequency and duration for determining the odor, texture, and color of the treated plots were done.

2.4 Treatment Plots Assignments:

TABLE 1
TREATMENT AND COMPOSITION OF COMPOST IN THIS STUDY

Treatments	Composition
T1 (Control)	50 kg QM + 50 kg Fly Ash
T2	50 kg QM + 50 kg Fly Ash + 350grams OECMP
T3	50 kg QM + 50 kg +Fly Ash +400 grams OECMP
T4	50 kg QM + 50 kg+ Fly Ash + 450 grams OECMP

2.5 Data Collected:

To address production performance and improvements, the following data was collected in order;

1) Odor, Color, and Smell – were physically observed and recorded
2) Temperature, pH, and Moisture – were measured by a portable soil test kit and will be taken from the sampling sites (top, middle, and bottom of the treated pile)
3) (%) Percent compost recovery – was calculated using the formula, original weight of the compost material - final weight divided by original weight of the compost material x 100
4) Germination Index, (%) - was calculated by counting the number of seeds germinated divided by the total number of seeds sown multiplied by 100%.

2.6 Germination Index:

The 100 pieces of pechay seeds were sown directly to seed germination trays, germinated seeds was counted when sprouts appeared and counting terminated after 7 days.

2.7 Statistical Analysis:

The data that was gathered in the study were analyzed using Analysis of Variance one-way ANOVA, Tukey HSD was used to determine whether there were significant differences in all treatment means.

III. RESULT AND DISCUSSION

3.1 Quick Manure Decomposition:

Treatment of livestock manure follows a variety of effective ways (Xiang et al., 2021). Aerobic composting is one of the best processes for handling agricultural waste because it controls odors, stabilizes microorganisms, and produces high-quality fertilizers.

I. TABLE 2
MEAN PHYSICAL PARAMETER OF QUAIL MANURE

Treatments	Texture	Color	Odor
1	Coarse	Black/Brown	Offensive
2	Coarse	Black	Slightly Offensive
3	Coarse	Black	Slightly Offensive
4	Coarse	Black	Slightly Offensive
5	Coarse	Black	Slightly Offensive
6	Coarse	Black	Slightly Offensive
7	Coarse	Black	Slightly Offensive
8	Coarse	Black	Odorless
9	Coarse	Black	Odorless
10	Coarse	Black	Odorless
11	Coarse	Black	Odorless
12	Slightly fine	Black	Odorless
13	Slightly fine	Black	Odorless
14	Slightly fine	Black	Odorless

Table 2 shows the mean physical characteristics of all the treated quail based manure compost with the addition of the 14 -day rapid composting microbes. lt showed that the compost is ready to be used on day 14. From day 1 to day 11, the texture was coarse. Then, from day 12 to 14, it was slightly fine, and the color became black. Further, the odor of the compost on day 1 was offensive, and on days 2 to 7 the odor was slightly offensive, and finally it was completely odorless on day 8.

3.2 Compost pH:

The pH is a measure of the acidity or basicity of compost. As pH contributes to the microbes' decomposition process, it is a crucial component of composting. Compost pH was observed for 14 days.

TABLE 3
MEAN PH OF QUAIL BASED MANURE COMPOST

Treatments	pH
T1 (Control)	5.24[b]
T2	5.61[a]
T3	5.35[b]
T4	5.27[b]
Mean	5.37
P-value	1.04E-05

Analysis of variance at .05% level of significance
****Means with different letters in the column are significantly different (p < 0.01).***

Table 3 showed the mean comparative pH for 14 days. T2 with a pH of 5.61 was significantly different ($p < 0.01$) to T1 with 5.24. The result favors composting and is in agreement with the studies of (Mao et al. 2017) that compost microorganisms thrive in neutral to acidic conditions with a pH between 5.5 and 8 considering that organic acids are formed during the early stages of degradation. The importance of determining the pH of compost depends on the plants it will be used on. Most plants thrive in soil with a neutral pH. Moreover, the pH changes in manure during the composting is evident by the occurrence of physical, chemical, or biological events during incubation.

In the study of Kim et a., (2016), during the composting of animal manure, moisture content affects the physiological traits of microbes and the physical structure. Because of increased microbial activity, aerobic microorganisms consume more active oxygen during composting if the moisture content is kept at a proper level.

3.3 Compost Temperature:

Energy is released as organic matter decomposes, increasing heat. This heat creates a condition in which bacteria (good bacteria) can break down waste.

TABLE 4
MEAN PHYSICAL PARAMETER OF QUAIL MANURE IN TEMPERATURE C0

Treatments	Temperature C^0
T1 (Control)	30.89[b]
T2	43.72[a]
T3	36.53[ab]
T4	34.91[b]
Mean	36.51
P-value	1.95E-06

****Means with different letters in the column are significantly different (p < 0.01).***

Table 4 showed the highest average of 43.72 came from T2 (50 kg QM, Fly Ash, and 350g OECMP). T3 (50 kg Fly Ash, 400g OECMP, and 50 kg QM) had an average of 36.53, and T4 (50 kg QM, 50 kg Fly Ash, and 450g OECMP) got only 34.91. An average of 30.89 was obtained by the T1-control (50 kg QM and 50 kg Fly Ash).

In the study of Kim et al. (2007), the temperature ranges of 57 to 71 degrees Celsius frequently favors thermophilic organisms of their decomposing activity. The temperature of a composting process indicates the amount of activity that microorganisms are engaging in as they transform biodegradable organic matter into compost. It is one of the indicators used to determine how well the composting process works.

However, according to Ho et al. (2022), several variables, including temperature, pH, moisture, oxygen, particle size, and C/N ratio, affect how quickly organic matter degrades during the composting process. The ideal conditions for composting have been described as a thermophilic phase temperature of 45 to 55 °C, a pH range of 5.0 to 7.0, and a moisture content of 50 to 60%.

3.4 Harvest Recovery:

Compost recovery is measured to distinguish the impact of compost activity with or without additives on the mass of the various compost treatments used in the study. A higher compost recovery rate indicates that most of the raw materials were composted.

TABLE 5
MEAN PHYSICAL PARAMETER OF HARVEST RECOVERY

Treatments	Harvest Recovery,%
T1 (Control)	43^{b}
T2	51.67^{a}
T3	47.33^{ab}
T4	44.33^{b}
Mean	46.53
P-value	0.010819

*****Means with different letters in the column are significantly different (p < 0.01).***

Table 5 showed that the highest harvest recovery can be seen in the T2 (50kg QM, 50kg Fly Ash and 350g OECMP) 51.67, T3 (50kg QM, 50kg Fly Ash and 400g OECMP) 47.33, T3 (50kg QM, 50kg Fly Ash and 450g OECMP) 44.33 which is significantly from the T1-control (50kg QM, and 50kg Fly Ash) as the lowest harvest recover of 43.

According to a study by Antonov et al. (2021), quail droppings, as compared to chicken droppings, have been considered to be high-quality fertilizers that are used to enrich soil composition and feed vegetable crops because they contain essential plant minerals and have a more filled composition. However, it's important to strictly follow the dosage instructions when adding quail droppings to the soil, especially fresh ones, and maintain that the uric acid in these fertilizers inhibits the growth of seedlings of both young and mature plants and can result in "burns" on the leaves and roots of vegetation.

Furthermore, composting is a sustainable method of disposing of manure. It undergoes aerobic, biological processes, with the help of natural microorganisms, and produces organic matter, which is degraded into a humus-like product or the organic fertilizer that is healthy, stable, and free of pathogenic microorganisms and weed seeds (Haug, 2018).

3.5 Germination Index:

The seed germination index (GI), which is a required index in many national standards, is a widely used indicator of compost maturity. However, the sensitivity of various species' seeds to the biological toxicity of compost varies noticeably. Hence, choosing the right seeds is essential for measuring compost maturity with GI.

TABLE 6
MEAN PHYSICAL PARAMETER OF GERMINATION INDEX

Treatments	Germination Index, %
T1 (Control)	29.33^{d}
T2	71.33^{a}
T3	60.67^{b}
T4	49.67^{c}
Mean	52.75
P-value	3.60E-06

*****Means with different letters in the column are significantly different (p < 0.01).***

Table 6 showed that the effectiveness of using compost quality harvested compost as a potting media of pechay seeds in terms of GI. The T2 (5O kg QM, 5O kg Fly Ash, and 350g OECMP) obtain the highest GI of 71.33. It is significantly different from the

T3 (5O kg QM, 5O kg Fly Ash, and 400g OECMP) 60.67, T4 (5O kg QM, 5O kg Fly Ash, and 450g OECMP) 49.67. T1-control contains (5O kg QM and 5O kg Fly Ash) which obtained the lowest germination index of 29.33.

Therefore, it is important to figure out the compost's maturity. The change in compost maturity can be described using physical, chemical, and biological methods (Komilis, 2015). To assess the phytotoxicity and maturity of compost using one of these methods, the seed germination index (GI) has been widely used (Luo et al., 2018)., Zucconi et al. (1981), proposed the GI, which includes the effect of phytotoxic substances on seedling germination rate and radicle elongation. The most recent Chinese agricultural industry standard, 'Technical Specifications for Composting of Livestock and Poultry Manure', published in 2019, requires mature compost to have a GI of 70%. The newly revised organic fertilizer standard (NY525-2021) in China requires a GI of 70%.

IV. Summary

The environmental impact of poultry production has received increasing attention over the last several decades. Growers of quail manure are currently under intense pressure from a variety of sources to reduce the environmental impact of their operations and adopt welfare-friendly practices. The main objectives of the study were to (a) determine the odor, color, texture, temperature, pH, and moisture of the various compost treatments, (b) determine the harvest recovery of the various compost treatments, and (c) determine the germination index of pechay seeds from the various compost media. To accomplish the objectives that were set and conducted from April to May 2023 at Barangay Bagong Sikat Science City of Munoz, Nueva Ecija. The study includes 12 replicates and 4 treatments. Composting has been proposed as a simple, low-cost, and environmentally friendly technology for stabilizing animal manure. Fly Ash has sufficient utility as a bulking agent in composting organic wastes, it is expected to solve the problems of industrial waste disposal and compost additives are mixtures of fertilizer, bacteria, or fungi that are intended to accelerate the composting process. The quail manure was decomposed in just 14 days before being applied to the potting media trays. To assess the quality of compost, the Germination Index of pechay seeds was performed in just 7 days. The results show that the GI of T2 71.33 average consisting of (50 kg QM, 50 kg Fly Ash, and 350g OECMP) has a highly significant effect in terms of GI among the treatments.

V. Conclusion

The use of quail manure is carried out as part of a strategy to promote integrated agriculture. Organic quail manure fertilizer has a high nutrient content and is easy to decompose. The temperature of the compost with OEMCP inclusion rates of 350 grams, was significantly different from the control. The pH of the compost with OEMCP inclusion rates of 350 grams was significantly different from the control. The germination index of the compost with OEMCP values rates of 350 grams is significantly different from the control. The conclusions of this study demonstrated that the development of pechay was significantly aided by the use of organic fertilizer in potting media.

Recommendation

Based on the result of the study, the OEMCP treatment compost at 350 grams or T2 is recommended to improve compost quality and recovery and germination index of pechay.

II. Conflict of Interest

The authors declare no conflict of interest.

III. References

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Evaluating the Efficacy of Boric Acid and Natural Ingredients against *Sitophilus granarius*: A Sustainable Approach to Wheat Protection

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***Abstract*—** *The economy and employment in India are significantly impacted by agriculture, with Wheat (Triticum aestivum) serving as a crucial staple crop. However, Sitophilus granarius infestations result in yearly significant agricultural losses. This study compares natural insect prevention techniques employing Azadirachta indica, Piper nigrum, Syzygium aromaticum, and Laurus nobilis and the efficacy of boric acid, a common pesticide, against the Triticum aestivum pest. The experimental design examined 50g of Triticum aestivum, 10 Sitophilus granarius, and different amounts of boric acid (1g, 2g, and 5g) during 24 hours, 48 hours, and 72 hours. The LD_{50} value of boric acid was observed to be best at 5g in 48 hours. Similarly, for the natural method, the LD_{50} value was best observed in Laurus nobilis in 48 hours. By this, we can state that Boric acid (Chemical method) remains more effective than the natural method, as it has immediate results. Natural methods can be considered as an alternative to an environmentally friendly approach.*

Keywords*— *Azadirachta indica (Neem), Boric acid, Piper nigrum (Black pepper), Laurus nobilis (Bay leaf), Sitophilus granarius, Syzygium aromaticum (Cloves), Triticum aestivum (Wheat).

I. INTRODUCTION

Agriculture is a vital sector in the Indian economy, employing 56% of the workforce and contributing to economic growth and poverty alleviation. It also enhances earnings in the non-agricultural sector by expanding commercial crops and promoting exports (*Dev, S.M. & Indira Gandhi Institute of Development Research. (2012)*). Pest and insect infestations cause agrarian losses, wasting natural resources, harming the economy and ecology, and reducing global food availability. These losses disrupt production, reduce crop quality, and negatively impact financial outcomes as consumers demand higher-quality products (Junaid and Gokce, 2024)

Triticum aestivum, an ancient crop essential for the human diet, is experiencing increased demand due to its affordable finished goods. India loses 10% of its food grains after harvest due to improper storage, insects, rodents, and microbes. Infested grains cause significant economic losses, including food contamination and waste, rendering them unfit for human consumption. Around 500 insect species infest stored grain products, with nearly 100 causing financial losses. Almost 100 pest species that damage stored goods result in substantial financial losses (Kumar, 2017). It has been shown that pests harm 20% of crops post-harvest; in developing countries, the percentage of losses can sometimes exceed 80%. Stored insects inflict considerable quantitative and qualitative economic damage to agricultural produce. In addition to the issues surrounding the harmful effects of pesticides on humans and animals, as well as environmental contamination, pesticides are used to protect crops and stored commodities from dangerous insects (*USE OF SILICA BORIC ACID MIXTURE TO CONTROL THE KHAPRA BEETLE (TROGODERMA GRANARIUM, DERMESTIDAE: COLEOPTERA) ON STORED WHEAT SEEDS. PLANT ARCHIVES. (N.d.). (No date)*, no date).

In both industrialized and developing countries, insect pests account for a significant portion of crop losses. More than 10,000 insect species, 30,000 weed species, and 100,000 diseases (caused by fungi, viruses, bacteria, and other microbes) are believed to affect food plants worldwide (Dhaliwal, Jindal and Mohindru, 2015).

Sources in the agricultural industry include wastewater, livestock dung, insecticides, and fertilizer. Toxicants such as heavy metals (cadmium (Cd), lead (Pb), copper (Cu), and zinc (Zn) and pesticides (insecticides, herbicides, and fungicides), which can penetrate and accumulate through the food chain, are causing harmful health issues like lung cancer, renal failure, osteoporosis, and heart failure, leading to acute and chronic illnesses (Alengebawy *et al.*, 2021).

Four insect species, including the granary weevil, can grow inside *Triticum aestivum* kernels on endosperm and live on the grain while stored. The granary weevil, a damaging insect, prefers moderate climates and can grow up to three-sixteenths of an inch in length. Its head has a long, thin snout with mouthparts at the end, and bigger oval punctures characterize its pronotum. Adult granary weevils typically take over four weeks to complete their life cycle and can survive for seven to eight months. They are one of the most damaging insects for stored grains (Alanazi, 2023). The granary weevil, *Sitophilus granarius* L., is a pest of *Triticum aestivum* and attacks dried grain and bean products. Adult weevils range in colour from black to chestnut-brown and have elbowed antennae distally. The head, stretched into a thin rostrum, contains sensory organs and receptors for smell, taste, and vision. The antennae are often carried in extended positions during travel (El-Ghany and El-Aziz, 2017).

Boric acid (H_3BO_3) has a long history of use in pest management, including controlling ants, cockroaches, and grain weevils. Registered in 1983, it has been used in stomach poison, dry powder, and bait formulations. Insects are drawn to boric acid, which attaches to their legs. However, due to its acute effects, including mutagenicity, eye and skin irritation, and oral and dermal toxicity, the Environmental Protection Agency (EPA) classifies boric acid as moderately acutely hazardous (*Evaluating the effectiveness of different concentrations of boric acid on the pink and spiny bollworms under laboratory conditions: Vol. Vol 6.; 2019:485-497. (N.d.).*, no date). Boron is a non-volatile, low-toxicity mineral found in soils, aquatic habitats, and human diets. It is a necessary nutrient for humans and plants and is often used as a low-toxicity insecticide to manage pests like insects, mites, fungi, algae, and certain vascular plants. Boric acid is a safer alternative to synthetic pesticides and can be used in bait compositions (Alanazi, 2023).

Novel pesticides are abundant in higher plants. Botanical insecticides may be more environmentally friendly than synthetic ones. Farmers and small businesses can also utilize these insecticides because they are less expensive and simple to process (Abubaker, 2021).

Laurus nobilis: India's higher cereal consumption necessitates non-insecticide management methods, such as essential oils and dried bay leaf, for pest control and post-harvest crop protection, as even a small pesticide residue can significantly impact grain intake (Chahal, Bansal and Kaur, 2016)) . *Laurus nobilis* is a natural pesticide that can reduce environmental and human health risks, replacing synthetic pesticides. Botanical pesticides are increasingly popular, with some plant components used as green insecticides worldwide (*Use of aromatic plant extracts as bio-insecticides for the control of stored-product insect, Sitophilus Granarius. (n.d.).*, no date).

Piper nigrum: Black pepper, a widely accessible herb in Nigeria and West Africa, offers new ways to combat insects, reduce cross-resistance, and provide ideas for creating target-specific compounds (Emeribe, Ohazurike and Okorie, 2016). Numerous plant compounds, particularly essential oils, have had their poisonous qualities against various stored grain pests assessed. Numerous studies on black pepper fruits have demonstrated their high effectiveness as a pesticide against various pests. In addition, their valuable culinary spicy flavour has made them economically significant). (*Toxicity of three chemical extracts of black pepper fruits against two stored grain insect pests. Toxicity of three chemical extracts of black pepper fruits against two stored grain insect pests: Vol. Vol 6. www.ijpsi.org; 2017:20-29. (n.d.).*, no date).

Azadirachta indica: Synthetic chemical pesticides are the primary method for controlling pest infestations in stored grains. However, plant materials with insecticidal qualities remain a viable, biodegradable, and affordable solution. Azadirachtin, an environmentally friendly, short-lived, selective, and mildly toxic insecticide, has gained global interest due to its potential (Danga et al., 2015). Plants like neem have poisonous, repellent, and antifeedant properties against various insect pests. These plants are simple and inexpensive to prepare, with bioactive metabolites activating insect receptors. Pest control or repelling organic extracts from plants protects with minimal ecological effects, keeping pests away from treated *(Use of neem and garlic dried plant powders for controlling some stored grains pests. Use of neem and garlic dried plant powders for controlling some stored grains pests Egyptian Journal of Biological Pest Control: Vol. 2015;25(2):507-512. (N.d.)., no date)*.

Syzygium aromaticum: One of the insects that can cause significant financial losses to stored grains globally is the granary weevil, *Sitophilus granarius* (L.) (Coleoptera: Curculionidae). In insects, essential oils and their components have lethal and sub-lethal effects like phagoinhibition, irritability, repellence, and biocide activity (Plata-Rueda *et al.*, 2018). Plant oils have strong insecticidal properties against various insects found in preserved goods. The study aimed to assess clove plant oils' toxicity to pests and their insecticidal activity (Makarem *et al.*, 2017).

II. MATERIALS AND METHODS

The weevils that were used for the experiment were isolated from the *Triticum aestivum* kernels for a very long duration of time. The grains were collected from household storage that was stored in the woven polypropylene bags, at a temperature of 28℃ and 52% humidity to provide the ideal conditions. These conditions were observed using a Hygrometer. The species that was taken for the experiment is *Sitophilus granarius*.

Boric acid is a commercially viable pesticide that inhibits the growth of *Sitophilus granarius* in *Triticum aestivum* kernels. It is predominantly considered a chemical method for preventing *Sitophilus granarius* in *Triticum aestivum*. Similarly, three natural alternatives were considered for the testing, which were Neem leaves (*Azadirachta indica*), Black pepper (*Piper nigrum*), Bay leaves (*Laurus nobilis*), and Cloves (*Syzygium aromaticum*), to check their effectiveness and compare the growth rate of *S. granarius* in *Triticum aestivum*.

The experiment was carried out in a borosilicate glass container with a capacity of 100 g.

Muslin cloth was used to cover the containers to prevent the movement of *S. granarius* outside the container. A digital weighing balance (range 0.01g to 200g) was used to weigh the Boric acid and *Triticum aestivum*.

2.1 Chemical Method:

Four containers were set up to experiment with the chemical method, in which 50 g of wheat (*Triticum aestivum*) and 10 *S. granarius* with different concentrations of boric acid were kept standard as follows:

i. Control- Wheat (*Triticum aestivum*) grains, 10 *S. granarius*

ii. Test 1- 2g Boric acid.

iii. Test 2- 4g Boric acid.

iv. Test 3- 10g Boric acid.

In the above-given setup, the *S. granaries* were tested for different concentrations for 24 hours, 48 hours, and 72 hours to check the LD_{50} (Lethal Dose 50) value and the Acute toxicity of Boric acid on *S. granarius.*

2.2 Natural Method:

Five containers were set up to experiment with the natural method, in which 50 g of wheat (*Triticum aestivum*) and 10 *S. granarius* having different natural remedies were kept standard as follows:

i. Control- Wheat (*Triticum aestivum*) grains, 10 *S. granarius*

ii. Test 1- 10 units of dried neem leaves (*Azadirachta indica).*

iii. Test 2- 2 units of Bay leaves *(Laurus nobilis*).

iv. Test 3- 10 units of Peppers (*Piper nigrum).*

v. Test 4- 10 units of Cloves *(Syzygium aromaticum)*.

III. RESULT AND DISCUSSION

In the above-given setup, the *S. granarius* were tested with different remedies for 24 hours, 48 hours, and 72 hours to check the LD_{50} (Lethal Dose 50) value and the Acute toxicity of these natural remedies on *S. granarius.*

The rising concentration of Boric acid resulted in a gradual decline in the movement speed of *Sitophilus granarius*. Additionally, it was observed that the number of *Sitophilus granarius* increased in the Control setup.

TABLE 1
EVALUATION OF THE EFFICACY OF BORIC ACID AGAINST *SITOPHILUS GRANARIES*

Time (hours)	Boric acid concentration(g)			
	Control	Test 1	Test 2	Test 3
24 hours	10.33±0.47	9.33±0.47	9.33±0.47	9±0.82
48 hours	10.33±0.94	8±0.82	7.33±1.7	5.33±1.25
72 hours	10±0.82	2.33±1.25	2.67±0.47	1.67±0.47

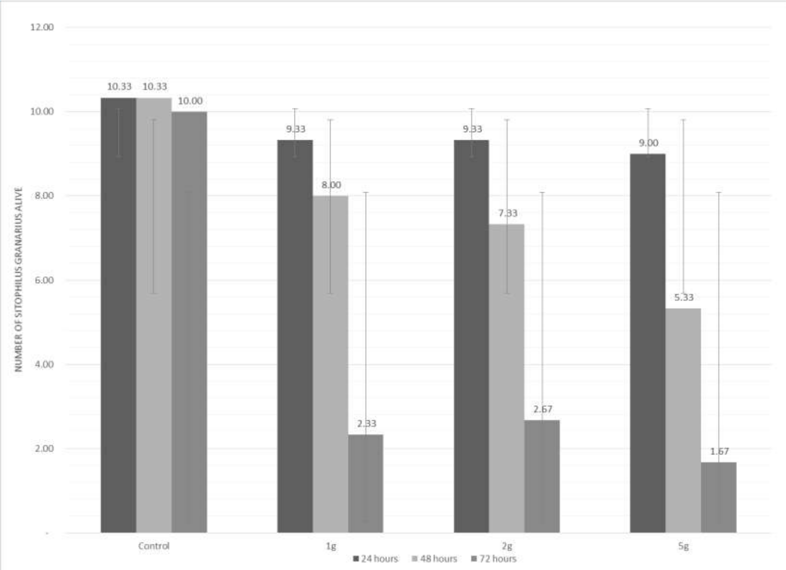

FIGURE 1: Evaluation of the Efficacy of Boric Acid against *Sitophilus granarius*

TABLE 2
EVALUATION OF THE EFFICACY OF NATURAL INGREDIENTS AGAINST *SITOPHILUS GRANARIES*

Time(hours)	Control	Neem leaves	Bay leaf	Pepper	Cloves
24 hours	10.33±0.47	10±0	8±0.82	7.5±1.7	9.5±0.47
48 hours	10.33±0.94	10±0	5±0.82	7±1.25	9±0.94
72 hours	10±0.82	10±0	4.5±0.82	5±0.82	5.5±0.47

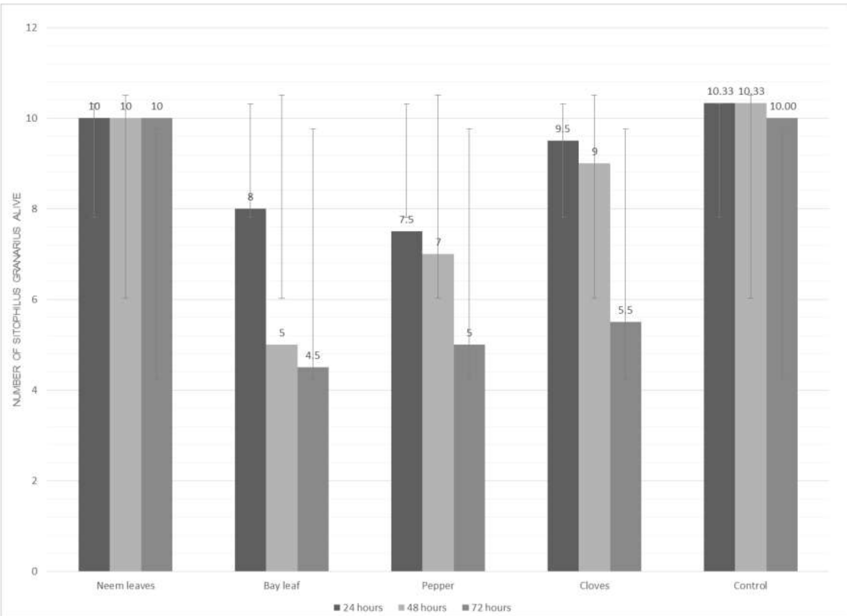

FIGURE 2: Evaluation of the Efficacy of Natural Ingredients against *Sitophilus granaries*

The efficacy of several boron compounds as insecticides against *Sitophilus granarius* and *Rhyzopertha dominica*, two common grain pests, was evaluated. While calcium metaborate (CMB) was nearly as effective but required higher doses, disodium octaborate tetrahydrate (Etidot-67) demonstrated total mortality at certain doses and time frames. The impact of these treatments on the pests' body weight and reproductive capacity was examined as well. At larger dosages, Etidot-67 completely killed both species, while CMB caused a considerable amount of death. SMT and ATFB did not exhibit any noteworthy activity. Both substances showed significant progeny suppression and insecticidal effectiveness (Ertürk *et al.*, 2024). Similarly, in our study, the experiment was conducted concerning Boric acid (Boron Compound). The results observed by (Ertürk *et al.*, 2024), which stated the complete mortality of *Sitophilus granarius*, aligns with the results observed in our experiment, where it showed the LD50 value in 5g of Boric Acid in 48 hours.

The use of synthetic insecticides for storage has sparked worries about their potential drawbacks. By 2030, there is a drive to cut the usage of chemical pesticides by half. There is a push for integrated pest control as a practical substitute for using fewer pesticides (Hamel, Rozman and Liška, 2021) Therefore, in this experiment, the use of natural ingredients plays a pivotal role as to study the effect of different natural ingredients on *Sitophilus granarius.* By the natural testing, significant results in mortality were observed. Natural ingredients like *Azadirachta indica, Piper nigrum, Syzygium aromaticum,* and *Laurus nobilis* can be considered as a sustainable and environmentally friendly approach for grain protection, as chemical pesticides have chronic effects on human health.

In line with a study, the neem-based pesticide *Azadirachtin* effectively repels and toxicity-induces the granary weevil, *Sitophilus granarius*. According to the study, biochemical studies revealed a decrease in the nutrition depletion index, while fumigant and contact toxicity grew with concentration and exposure duration. According to the study, azadirachtin may be used as a natural bioinsecticide to control the number of granary weevils (*Guettal S, Tine SSB, Tine-Djebbar F, Soltani N. Repellency and toxicity of Azadirachtin against Granary Weevil Sitophilus granarius L. (n.d.).*, no date).

The results found in the above study match with our results, as it was observed that the dried Neem leaves act as a preventive measure and repel the growth of *Sitophilus granarius* in stored *Triticum aestivum* grains.

The effect of clove bud powder against granary weevils, both alone and in combination with abamectin and spinosad insecticides, was studied. The results showed that clove powder significantly reduced weevil mortality, with 100% mortality at 1% concentration after 7 days (Abubaker, 2021) Comparable results were observed as the mortality of weevils was seen in the presence of cloves, but a major drawback in the usage of clove was that it released a strong aroma of Cloves in the grains, which can cause changes in the odor in the *Triticum aestivum* and the processed flour.

The study was also conducted in the presence of *Piper nigrum,* where no significant mortality of *Sitophilus granarius* was observed.

This study investigates how well bay leaf essential oil and its constituents may kill the grain pest *Tribolium castaneum*. The two main components of the oil, which were obtained by hydrodistillation, are 7,7-dimethyl-3-methylene bicyclo [2.2.1] heptan-4-ol and eugenol. It has been found that eugenol is more harmful than other substances. Mortality was seen at 33 and 35 days, indicating that the oil and its polar portion were very toxic to the insect. Effectiveness rose with longer exposure times and higher concentrations.[4] The above results align with the findings of our experiment. We found out that amongst all the natural ingredients tested, *Laurus nobilis* showed high mortality on *Sitophilus granarius. Laurus nobilis* can be concluded as the most effective natural approach towards grain protection, as it has no severe impact on human health and is readily available in households for sustainable grain protection.

IV. CONCLUSION

Wheat weevils (*Sitophilus granarius*) are a common invasive species that causes crop losses in India every year. Due to this crop wastage, major economic losses are faced annually. We concluded that 5g of Boric acid in 48 hours of exposure gave the best results, *whereas Laurus nobilis* (Bay leaf) was most effective in 48 hours for natural ingredients. By this, we can say that natural ingredients can be sustainable and are less detrimental to human health. We also observed that *Azadirachta indica* (Neem leaves) restricts the growth of *Sitophilus granarius* and can be used as a preventive measure. Whereas Boric acid remains the most effective in a shorter period continued exposure may have chronic effects on human health. However, we believe that further studies can be carried out to determine the effect of Boric acid and its impact on human health and find the LC_{50} (lethal concentration) of Boric acid on various invasive crop species.

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CONFLICT OF INTEREST

There is no conflict of interest.

AUTHOR'S CONTRIBUTION

Ms. Bakul Dhawane and Ms. Srushti Sawant contributed equally to the completion of the research paper. Both authors conceptualized the idea, performed the experiment, and analysed the results.

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Evaluation of Weed Dynamics in Maize based Intercropping Systems for *Rabi* in North Coastal Andhra Pradesh

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Abstract— *A field experiment was conducted at the Agricultural College Farm, Naira, during the rabi season of 2024–2025 to evaluate weed dynamics in maize-based intercropping systems under different nitrogen levels. The soil was sandy loam with low fertility status. The study followed a split-plot design with five main plots—maize intercropped with blackgram, greengram, cowpea, in-situ green manuringand sole maizeand three subplots involving 100% RDN, 75% RDN,and 75% RDN + biological fertilizer consortia. Results revealed that maize + cowpea in paired rows significantly reduced weed density and weed dry weight at all crop growth stages. This was attributed to the rapid canopy coverage and shading effect of cowpea, which suppressed weed germination. Sole maize recorded the highest weed density and dry weight, indicating poor weed suppression. Among nitrogen levels, 75% RDN produced the lowest weed density and dry weight, while 100% RDN recorded higher weed growth due to greater nutrient availability. The findings suggest that adopting maize + cowpea intercropping with 75% RDN can effectively reduce weed competition and improve resource efficiency*.

Keywords— Cropping system, intercropping, in-situ green manuring, nutrient uptake and nutrient levels.

I. INTRODUCTION

Maize (*Zea mays* L.) is the third most widely grown crop in India after wheat and rice. In addition to providing human sustenance and high-quality animal feed, maize is utilized as a basic raw material and ingredient in thousands of industrial goods. These include starch, oil, protein, alcoholic beverages, food sweeteners, medications, cosmetics, and the production of bioenergy (Kumar *et al.* 2018). With a productivity of 3351 kg ha^{-1}, maize produces approximately 37.67 million tonnes of grain annually on 11.24 million hectares in India (Directorate of Economics and Statistics, 2023-24). A total of 18.19 lakh tons of production and 6225 kg ha^{-1} of productivity were obtained from the 2.92 lakh hectares of maize planted in Andhra Pradesh (des.ap.gov.in, 2023-24). Intercropping in maize under crop intensification has increased recently in the North Coastal zone of Andhra Pradesh. While fertilization increases crop growth, excessive fertilizer application can exacerbate weed problems. There has been a noticeable improvement in weed control with intercropping systems. In addition to suppressing weeds, the intentional intercropping of legumes with maize aids in the plant's uptake of nitrogen from the atmosphere. Many scientists have also reported increased productivity and returns from intercropping combinations, as well as an improvement in maize yield brought about by the connection of legumes. Conventional spacing restricts the growth of related intercrops but may be beneficial for solitary crops. A reasonable amount of spatial adjustment to make room for intercrops aids in lowering intercrop competition. For successful intercropping, previous research also recommended using wider rows and growing maize in pairs by Rajashekarappa *et al.* 2018, Singh and Kumar, 2021and Sain *et al.,* 2023.Keeping all these in consideration, present investigation as carried out to study different intercrops with maize at different nitrogen levels to evaluate the weed dynamics in the maize intercropping system in the North Coastal Andhra Pradesh.

II. MATERIAL AND METHODS

An experiment was conducted at Agriculture College Farm, Naira of Acharya N. G. Ranga Agricultural University, Andhra Pradesh, which was geographically situated at $18^0$38'56" N latitude, $83^0$56'38'' E longitude at an altitude of 12m above mean sea level in the Srikakulam district, North Coastal Zone of Andhra Pradesh. The experiment was laid out during *rabi*, 2024-2025in the Block-C of the Agricultural college farm, Naira. The soil of the experimental field was sandy loam in texture, neutral in pH (7.1) with an electrical conductivity of 0.17 dS m^{-1}at 25ºC, low in organic carbon (0.43 %) and available N (248.8 kg ha^{-1}), available P_2O_5 (23.2 kg ha^{-1}) and available K_2O (255.2 kg ha^{-1}). The average mean temperature ranged from 33.5 ^{0}C to 12.2 ^{0}C, with a total rainfall of 73.2 mm in 5 rainy days. The study included fifteen treatments using the following combinations of intercropping systems for maize: The following are M_1: Maize + Blackgram in paired rows, M_2: Maize + Greengram in paired rows, M_3: Maize + Cowpea in paired rows, M_4: Maize + *in-situ* green manuring with sunnhemp, and M_5: Farmer's practice-sole maize were planted in main plots and in subplots with varying nitrogen amounts S_1: 100% RDN, S_2: 75% RDN and S_3: 75% RDN + biological fertilizer consortia. The recommended dose of phosphorus and potassium were applied in the form of Single Super Phosphate (SSP) and Muriate of Potash (MOP) and treatments with 100 % RDN and 75 % RDN had given 240 kg N ha^{-1} and 180 kg N ha^{-1} through urea and Biological fertilizer consortia was applied @ 1250 ml ha^{-1}. The treatments with intercrops has followed a spacing of 80/40 x 20 cm and normal planting of maize followed a spacing of 60 x 20 cm. When required, field operations such as fertilizer application, irrigation and plant protection measures were carried out. The data regarding the nutrient uptake was calculated by the standard procedures and the gross returns, net returns and B:C ratios were also calculated accordingly. Data was analyzed statistically by following the standard procedures as described by Gomez and Gomez (1984).

III. RESULTS AND DISCUSSION

3.1 Weed Density:

In the maize intercropping systems higher weed density was observed at 20 DAS and it went on decreasing at later stages of crop growth. Significantly lower weed density was recorded in maize + cowpea in paired row planting at 20, 40 and 60 DAS (47.70, 28.86 and 21.55 No. m^{-2} respectively). Succeeding to maize + cowpea, lower weed density was observed in maize + black gram (54.58, 41.30 and 29.62 No. m^{-2} respectively) which was comparable with maize + greengram (58.60, 42.62 and 31.65 No. m^{-2} respectively) in paired rows at 20, 40 and 60 DAS. Higher weed density was recorded in sole maize (control) at all intervals of crop growth (65.10, 92.74, 173.30 and 185.92 No. m^{-2} at 20, 40, 60 and at harvest respectively). However, there was no significant difference observed among the weed densities of different intercropping systems at the time of harvest. These studies were in close conformity with Sannagoudar *et al.* (2024), Singh and Kumar (2021) and Singh *et al*. (2025).

Among the nitrogen levels significantly lower weed density was observed with application of 75% RDN (52.93, 54.30, 62.37 and 75.22 No. m^{-2} at 20, 40, 60 DAS and at harvest respectively). Higher weed density (61.32, 62.30, 68.24 and 83.16 No. m^{-2} at 20, 40, 60 and at harvest respectively) was recorded with application of 100 % RDN which was at par with application of 75 % RDN + Biological fertilizer consortia. Rapid weed emergence and growth were encouraged by the increased nutrient availability, particularly when competitive suppression was not present.

TABLE 1
WEED DENSITY (No. m^{-2}) IN MAIZE AS INFLUENCED BY MAIZE BASED INTERCROPPING SYSTEMS AND NITROGEN LEVELS

TREATMENTS	20 DAS	40 DAS	60 DAS	At harvest
Maize based intercropping systems				
M_1: Maize + Blackgram with paired row	7.4	6.46	5.47	7.31
	-54.58	-41.4	-29.62	-52.98
M_2: Maize + Greengram with paired row	7.68	6.56	5.68	7.41
	-58.6	-42.72	-31.65	-55.47
M_3: Maize + Cowpea with paired row	6.93	5.41	4.69	6.95
	-47.7	-28.86	-21.55	-47.56
M_4: Maize + *in-situ* green manuring with sunnhemp	7.52	9.22	8.3	7.43
	-56.14	-84.77	-68.6	-58.82
M_5: Farmer's practice -Sole maize (Control)	8.09	9.65	13.28	13.7
	-65.1	-92.74	-173.3	-185.92
S.Em ±	0.124	0.126	0.157	0.143
CD (P=0.05)	0.41	0.42	0.51	0.47
CV %	10.6	10.8	10.7	10.1
Nitrogen Levels				
S_1 : 100 % RDN	7.81	7.67	7.71	8.78
	-61.32	-62.3	-68.24	-83.16
S_2 : 75 % RDN	7.29 (52.93)	7.31	7.29	8.33
		-54.3	-62.37	-75.22
S_3 : 75 % RDN +	7.47	7.54	7.45	8.57
Biological fertilizer consortia	-55.63	-58.4	-66.37	-79.89
S.Em ±	0.1	0.091	0.112	0.097
CD (P=0.05)	0.31	0.27	0.33	0.29
CV %	10.2	9.9	10.6	9.8
Interaction				
S.Em ±	0.224	0.203	0.251	0.218
M x S	NS			
S x M	NS			

Note: The data subjected to square root transformation. The figures in parenthesis are original values.

3.2 Weed Dry Weight:

The higher dry weight of weeds was recorded at 20 DAS compared to that of later stages of crop growth. Significantly lower weed dry weight was recorded in maize + cowpea in paired row planting at 20, 40 and 60 DAS (26.98, 18.67 and 15.35 g m-2 respectively). Succeeding to maize + cowpea, lower weed density was observed in maize + black gram (32.53, 22.75 and 18.70 g m-2 respectively) which was comparable with maize + greengram (34.43, 24.05 and 18.92 g m-2) in paired rows at 20, 40 and 60 DAS. Higher weed dry weight was recorded in sole maize (control) at all intervals of crop growth (44.41, 59.32, 72.91 and 92.23 g m-2 at 20, 40, 60 DAS and at harvest, respectively). However there was no significant difference observed in the weed dry weight among the intercropping systems at the time of harvest. Cowpea grew swiftly and spreaded across the soil surface and forms a dense canopy, which reduced the amount of sunlight that reaches the ground. This shadowing effect makes it difficult for weed seeds to germinate and thrive. These studies were in close accordance with Rajeshkumar *et al.* (2018), Sannagoudar *et al.* (2021)

Among the nitrogen levels significantly lower weed dry weight was observed with application of 75% RDN (32.40, 28.78, 27.24 and 32.71 g m-2 at 20, 40, 60 and at harvest respectively). Higher weed dry weight (39.12, 32.88, 31.32 and 40.09 g m-2 at 20, 40, 60 and at harvest respectively) was recorded with application of 100 % RDN, which was at par with application of 75 % RDN + Biological fertilizer consortia, except at harvest. The greater nitrogen availability in the 100 % RDN and 75 % RDN + Biological fertilizer consortia treatments might be cause of higher weed dry weight at higher nitrogen levels. These studies are in confirmation with Choudhary *et al.* (2014) and Divya *et al.* (2020).

TABLE 2
WEED DRY WEIGHT (g m^{-2}) IN MAIZE AS INFLUENCED BY MAIZE BASED INTERCROPPING SYSTEMS AND NITROGEN LEVELS

TREATMENTS	20 DAS	40 DAS	60 DAS	At harvest
Maize based intercropping systems				
M_1 : Maize + Blackgram with paired row	5.73	4.82	4.34	4.58
	-32.53	-22.75	-18.7	-20.5
M_2 : Maize + Greengram with paired row	5.89	4.95	4.4	4.67
	-34.43	-24.05	-18.92	-21.51
M_3 : Maize + Cowpea with paired row	5.23	4.37	3.96	4.5
	-26.98	-18.67	-15.25	-19.8
M_4 : Maize + *in-situ* green manuring with sunnhemp	6.2	5.38	4.67	5.16
	-38.35	-28.54	-26.51	-24.22
M_5 : Farmer's practice -Sole maize (Control)	6.7	7.72	8.5	9.62
	-44.41	-59.32	-72.91	-92.23
S.Em ±	0.101	0.095	0.094	0.096
CD (P=0.05)	0.33	0.31	0.3	0.31
CV %	9.9	10	10.5	10.3
Nitrogen Levels				
S_1: 100 % RDN	6.28	5.62	5.34	6.04
	-39.12	-32.88	-31.32	-40.09
S_2: 75 % RDN	5.7	5.31	5.03	5.43
	-32.4	-28.78	-27.24	-32.71
S_3: 75 % RDN +	5.86	5.42	5.15	5.64
Biological fertilizer consortia	-34.33	-30.33	-29.4	-35.47
S.Em ±	0.075	0.063	0.06	0.064
CD (P=0.05)	0.22	0.19	0.17	0.19
CV %	9.8	10.1	10.6	10
Interaction				
S.Em ±	0.168	0.141	0.134	0.144
M x S			NS	
S x M			NS	

Note: The data subjected to square root transformation. The figures in parenthesis are original values

IV. CONCLUSION

From the experiment it can be concluded that among the weed indices, significantly lower weed density and lower weed dry weight were recorded under maize + cowpea with paired row planting indicating adoption of higher canopy crops improving weed smothering efficiency. Among the nitrogen levels, lower weed density and weed dry weight were recorded under 75 % RDN application.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Assessment of Brown Spot Disease (*Bipolaris oryzae*) Severity in Paddy Fields of Prayagraj District, Uttar Pradesh, India

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Abstract— *Brown spot disease, caused by the fungus Bipolaris oryzae, poses a significant threat to rice production. This study assessed the severity and distribution of the disease in the paddy fields of the Prayagraj district, Uttar Pradesh, India, over two consecutive Kharif seasons (September 2011 and September 2012). A survey was conducted across eight tehsils (Karchhana, Soraon, Handia, Phulpur, Bara, Meja, Sadar, and Koraon), with five villages randomly selected from each. Disease severity was quantified using the Percent Disease Incidence (PDI) method. The pooled mean PDI across the tehsils ranged from a low of 25.08% in Phulpur to a high of 47.24% in Meja. High disease incidence was also noted in Soraon (45.57%). The village-level data revealed the highest pooled PDI of 50.0% in Dihi Khurd (Meja) on the PB-1509 variety. The disease was prevalent during both the Post tillering and Panicle initiation stages. The consistent and high incidence of brown spot disease in tehsils like Meja and Soraon confirms its endemic status in the region and underscores the urgent need for targeted integrated disease management strategies, including the development and deployment of resistant rice varieties.*

Keywords— Rice, Bipolaris oryzae, Prayagraj, Percent Disease Incidence (PDI), PB-1509 and PB 1121.

I. INTRODUCTION

Rice (*Oryza sativa* L.) is a staple food for more than half of the world's population and is critical to global food security [1]. In India, rice is the most important food crop, and its production is vital for the country's economy and sustenance. However, rice production is constantly threatened by various biotic and abiotic stresses. Among the biotic stresses, fungal diseases are a major limiting factor, with brown spot disease being one of the most destructive [2] [3].

Brown spot disease, caused by the ascomycete fungus *Bipolaris oryzae* (teleomorph: *Cochliobolus miyabeanus*), affects the rice plant at all growth stages, from the seedling to the grain-filling stage [4]. The characteristic symptoms include oval to circular spots on the leaves, which are initially dark brown and later develop a greyish-white center with a reddish-brown margin. Severe infection leads to premature leaf senescence, reduced photosynthetic efficiency, and poor grain filling, resulting in significant yield losses, which can range from 1% to 34% in various parts of Asia and Africa [5].

The severity of brown spot disease is highly influenced by environmental factors, particularly high humidity and temperature, as well as host factors such as varietal susceptibility and nutritional status of the plant, especially nitrogen and potassium deficiency [6]. Given the significant economic impact of the disease, regular monitoring and assessment of its incidence and severity are crucial for effective disease management planning. This study aimed to determine the prevalence and severity of brown spot disease in the major rice-growing areas of the Prayagraj district, Uttar Pradesh, over two consecutive years, providing essential data for regional disease control efforts.

II. MATERIALS AND METHODS

The survey was conducted in the Prayagraj district of Uttar Pradesh, India, during the Kharif (monsoon) cropping season. The study spanned two consecutive years, with data collection carried out in September 2011 and September 2012. A total of eight tehsils (administrative blocks) were selected for the assessment, namely Karchhana, Soraon, Handia, Phulpur, Bara, Meja, Sadar, and Koraon. From each tehsil, five villages were randomly selected, making a total of 40 villages surveyed each year [7].

2.1 Field Sampling and Data Collection:

A random sampling technique was employed across paddy fields in the selected villages. In each village, several fields were visited, and plants were observed along a 'W'-shaped transect to ensure a representative sample of the area [8]. From each field, a minimum of 50 plants were randomly selected and thoroughly examined for characteristic symptoms of brown spot disease caused by *Bipolaris oryzae*, including oval, brown spots with a grey center on leaves and glumes. The stage of the crop (Post tillering or Panicle initiation) was also recorded.

2.2 Assessment of Disease Severity:

The Percent Disease Severity (PDS) was calculated for each village in both years. The severity was assessed using a standard 0-9 scale for brown spot disease [9], where 0 represents no disease and 9 represents very severe infection covering more than 50% of the leaf area. The percent severity was then calculated using the following formula:

$$\text{Disease severity } \% = \frac{\text{Sum of all disease rating}}{\text{Total number of rating} \times \text{Max. disease grade}} \times 100 \tag{1}$$

2.3 Pathogen Identification:

The causal agent of the disease was confirmed as *Bipolaris oryzae* through laboratory analysis. Infected leaf samples showing typical symptoms were collected, surface sterilized, and incubated on Potato Dextrose Agar (PDA) medium. The fungal colonies that developed were examined microscopically for conidial morphology, confirming the identity of the pathogen based on its characteristic geniculate conidiophores and fusiform, pale brown conidia [10].

The collected data was systematically compiled and analyzed using Microsoft Excel. The following calculations were performed: Pooled Disease Severity for each village: The average of the Percent Disease Severity recorded in September 2011 and September 2012 for each individual village. Percent Disease Severity for each Tehsil: The mean value of the Pooled Disease Severity from all five villages within a tehsil was calculated to represent the overall disease severity for that administrative block.

III. RESULTS AND DISCUSSION

3.1 Disease Incidence and Severity Across Tehsils:

The survey results revealed a widespread presence of brown spot disease across all eight tehsils of the Prayagraj district during both the 2011 and 2012 Kharif seasons. The raw data, presented in Table 1, shows the Percent Disease Incidence (PDI) for each village, the pooled PDI over the two years, and the mean PDI for each tehsil.

The mean Percent Disease Incidence (PDI) for the tehsils varied significantly, ranging from a minimum of 25.08% in Phulpur to a maximum of 47.24% in Meja. The tehsils can be broadly categorized based on their pooled PDI:

Category	Mean Pooled PDI (%) Tehsils
High Incidence	> 40% Meja (47.24%), Soraon (45.57%)
Moderate Incidence	30% - 40% Karchhana (39.92%), Bara (36.04%), Handia (35.47%), Sadar (33.93%)
Low Incidence	< 30% Koraon (28.17%), Phulpur (25.08%)

The high incidence observed in Meja (47.24%) and Soraon (45.57%) suggests that these areas may possess environmental conditions (e.g., higher humidity, poor soil fertility, or specific microclimates) or cultivation practices (e.g., susceptible varieties like PB-1121 and PB-1509, as noted in the raw data) that are highly conducive to the development and spread of Bipolaris oryzae [11]. Conversely, the lower incidence in Phulpur (25.08%) and Koraon (28.17%) might be attributed to less favorable conditions for the pathogen or the use of relatively more tolerant rice varieties.

3.2 Year-to-Year Variation:

A comparison of the PDI between September 2011 and September 2012 shows a mixed trend. While some villages, such as Akodha in Karchhana (38.5% in 2011 to 46.7% in 2012) and Tendua in Karchhana (34.2% in 2011 to 38.8% in 2012), experienced an increase in disease severity, others, like Dadanpur in Soraon (47.8% in 2011 to 46.5% in 2012) and Dihi Khurd in Meja (52.6% in 2011 to 47.4% in 2012), showed a slight decrease. The village Dihi Khurd in Meja recorded the highest PDI in 2011 (52.6%), which is a critical finding, indicating a severe outbreak in that specific location (**Table 1: Figure 1)**. The overall pooled data, however, suggests that the disease is consistently present at moderate to high levels across the district, confirming its endemic status [12].

3.3 Influence of Crop Stage and Variety:

The data indicates that the disease was prevalent during both the Post tillering stage and the Panicle initiation stage. The panicle initiation stage is a critical period for rice development, and disease infection at this stage can directly impact grain formation and yield [13]. The raw data shows that both the popular varieties, PB-1121 and PB-1509, were susceptible to the disease, with high PDI recorded in fields growing both varieties. For instance, the highest pooled PDI (50.0%) was recorded in Dihi Khurd (Meja) on the PB-1509 variety. This suggests that varietal resistance is a key area for future research and intervention in the region [14].

TABLE 1
POOLED PERCENT DISEASE INCIDENCE (PDI) OF BROWN SPOT DISEASE IN PRAYAGRAJ DISTRICT (2011-2012)

S.N.	Tehsil Name	Village Name	Variety	PDI (Sept 2011) (%)	PDI (Sept 2012) (%)	Pooled PDI (Village Mean) (%)	Mean Tehsil PDI (%)	Crop Stage
1	Karchhana	Hasimpur	PB-1121	38.4	38.5	38.45	39.92	Panicle initiation stage
		Tendua	PB-1509	34.2	38.8	36.5		Post tillering stage
		Akodha	PB-1509	38.5	46.7	42.6		Panicle initiation stage
		Jamoli	PB-1509	39	42.6	40.8		Post tillering stage
		Karma	PB-1121	42	40.5	41.25		Panicle initiation stage
2	Soraon	Husenpur	PB-1121	42.6	47.2	44.9	45.57	Post tillering stage
		Sangipur	PB-1121	41.6	48.6	45.1		Panicle initiation stage
		Budauna	PB-1121	46.2	45.8	46		Post tillering stage
		Dadanpur	PB-1121	47.8	46.5	47.15		Panicle initiation stage
		Jogipur	PB-1509	45	44.4	44.7		Post tillering stage
3	Handia	Raghupur	PB-1509	34.6	36.2	35.4	35.47	Panicle initiation stage
		Thata	PB-1121	38.6	37.2	37.9		Post tillering stage
		Madaripur	PB-1509	39.5	43	41.25		Panicle initiation stage
		Yasinpur	PB-1509	28.6	32.8	30.7		Post tillering stage
		Rastipur	PB-1509	30	34.2	32.1		Panicle initiation stage
4	Phulpur	Chata	PB-1509	26.2	24.7	25.45	25.08	Post tillering stage
		Pali	PB-1121	24.6	22	23.3		Panicle initiation stage
		Saray Taki	PB-1509	24.8	27.4	26.1		Post tillering stage
		Poore Durgi	PB-1509	25	26.5	25.75		Panicle initiation stage
		Husenpur	PB-1509	25.4	24.2	24.8		Post tillering stage
5	Bara	Dera	PB-1121	35.2	38.4	36.8	36.04	Panicle initiation stage
		Kota	PB-1121	34.2	32.6	33.4		Post tillering stage
		Bhondi	PB-1121	31.6	35	33.3		Panicle initiation stage
		Lohra	PB-1121	38.6	42.2	40.4		Post tillering stage
		Ankoria	PB-1121	40.2	32.4	36.3		Panicle initiation stage
6	Meja	Ahopur	PB-1509	48.5	47.2	47.85	47.24	Post tillering stage
		Jafra	PB-1509	44.6	46.3	45.45		Panicle initiation stage
		Barva	PB-1121	46.4	48.2	47.3		Post tillering stage
		Kukur Katva	PB-1509	48.7	42.5	45.6		Panicle initiation stage
		Dihi Khurd	PB-1509	52.6	47.4	50		Post tillering stage
7	Sadar	Fulwa	PB-1509	41.2	35.2	38.2	33.93	Panicle initiation stage
		Rahimabad	PB-1509	31.4	28.4	29.9		Panicle initiation stage
		Nasirpur Silna	PB-1121	36.8	33.2	35		Panicle initiation stage
		Hari Rampur	PB-1509	32.2	37.5	34.85		Post tillering stage
		Tiyara	PB-1509	28.4	35	31.7		Panicle initiation stage
8	Koraon	Baghol	PB-1509	26.8	32.6	29.7	28.17	Panicle initiation stage
		Jokhat	PB-1121	22.5	35.2	28.85		Post tillering stage
		Derhan	PB-1509	28.6	30	29.3		Panicle initiation stage
		Uday Mala	PB-1121	27.4	28	27.7		Panicle initiation stage
		Newada	PB-1509	27	23.6	25.3		Panicle initiation stage

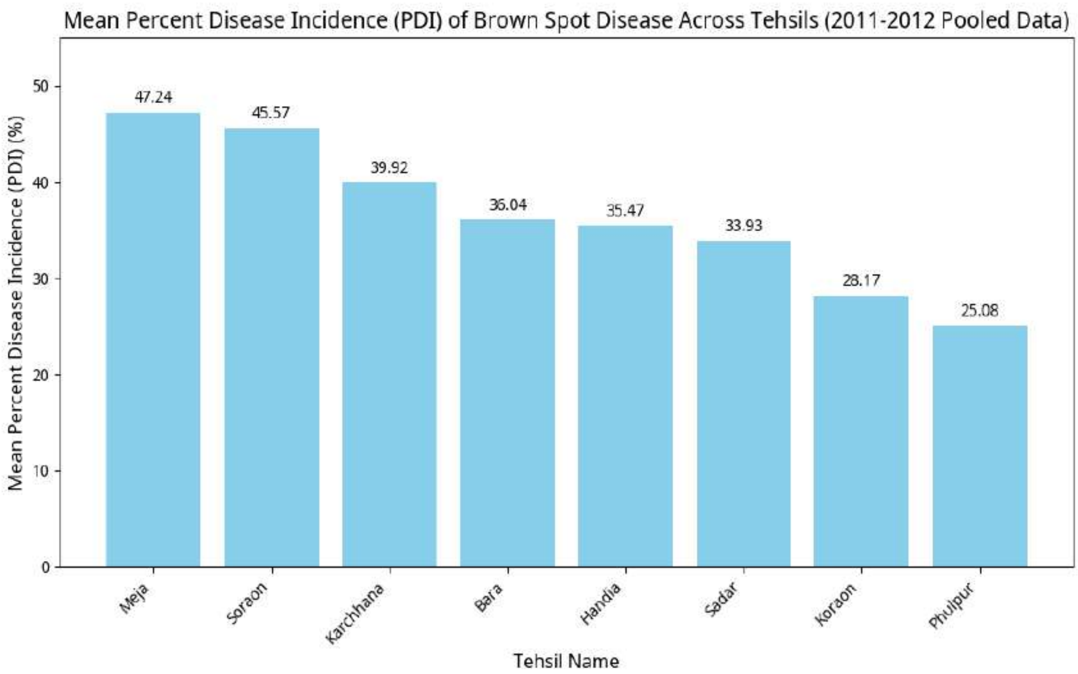

FIGURE 1: Mean Percent Disease Incidence (PDI) of Brown Spot Disease Across Tehsils (2011-2012 Pooled Data)

FIGURE 2: Disease Photograph

IV. CONCLUSION

The study successfully quantified the severity of brown spot disease in the Prayagraj district, identifying Meja and Soraon as the tehsils with the highest disease incidence. The consistent presence of the disease over two years, coupled with high PDI values in specific villages and varieties, underscores the urgent need for effective disease management. Future research should focus on the correlation between soil nutrient status, specific environmental parameters, and the observed disease severity to develop an integrated pest management (IPM) strategy that includes the use of resistant varieties, balanced fertilization, and timely fungicide application.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Integration of Geothermal Heating Technologies into Agricultural Structures: A Smart Greenhouse Approach

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Abstract— *The increasing global population, the impacts of climate change, and the rising energy costs are making it increasingly difficult to ensure sustainability in agricultural production systems. In particular, the greenhouse sector, despite offering significant advantages for year-round production, constitutes an energy-intensive production model due to its high heating requirements. The current heating systems based on fossil fuels lead to both increased production costs and higher carbon emissions. In this context, ensuring energy management in greenhouses through renewable sources has become a strategic necessity in terms of economic efficiency and environmental sustainability. The main objective of this study is to examine the potential use of geothermal energy resources in agricultural structures, particularly in smart greenhouse systems, from engineering, environmental, and economic perspectives. Within the scope of this study, the design principles of geothermal heating systems, their energy efficiency potential, heat transfer mechanisms, and integration processes with smart control systems (IoT sensors, automation, and artificial intelligence algorithms) were evaluated. In addition, comparative analyses were conducted based on Turkey's geothermal resource potential, application examples, and energy economy indicators. The significance of this study lies in the fact that renewable energy-based smart greenhouse applications enhance energy security in agricultural production, reduce carbon emissions, and ensure production continuity. The utilization of geothermal energy as a constant, domestic, and low-emission resource in the agricultural sector directly aligns with the goals of sustainable production. The literature review indicates that studies focusing on the integration of geothermal heating technologies with smart control infrastructures, particularly within the context of Turkey, remain limited. Existing research largely remains confined to energy analysis, while comprehensive engineering approaches that simultaneously address digital automation, system modeling, environmental impact, and policy interaction have not been sufficiently developed. This study aims to fill this gap by presenting a multidisciplinary assessment framework for the integration of geothermal energy and smart greenhouse technologies. In this review, studies published in international scientific databases such as Scopus, Web of Science, ScienceDirect, ProQuest, ResearchGate, MDPI, IEEE, and Google Scholar were examined to comprehensively analyze the integration of geothermal heating technologies into agricultural structures and their adaptation processes within the context of smart greenhouse systems.*

Keywords— Geothermal Energy, Smart Greenhouse, Energy Efficiency, Internet of Things (IoT), Sustainability, Carbon Emission.

I. INTRODUCTION

The escalating global climate crisis driven by global warming, wars, mass migration movements, and rapid population growth has emerged as a fundamental threat to humanity's secure access to food. This process not only exerts increasing pressure on agricultural production systems but also poses a serious risk to the sustainable use of natural resources. According to the United Nations' World Population Prospects report, the global population is projected to reach 8.6 billion by 2030, 9.8 billion by 2050, and exceed 11.2 billion by 2100 [1]. This upward trend necessitates a re-evaluation of existing production and consumption models, the strengthening of food security policies, and the adoption of more sustainable approaches to natural resource management.

In Turkey, greenhouse cultivation stands out as a significant agricultural production area that reduces seasonal dependency and enhances crop diversity. The total area of greenhouse farming across the country amounts to 776,110 decares, of which 7.2%

consists of glass greenhouses (55,949 da), 58.4% of plastic greenhouses (452,907 da), 13.4% of high tunnels (103,978 da), and 21% of low tunnels (163,276 da) [2].

The Food and Agriculture Organization (FAO) of the United Nations projects that by 2050, the global population will reach approximately 9.1 billion, emphasizing that such demographic growth will exacerbate global challenges related to food access and adequate nutrition. According to FAO, mitigating the adverse effects of this trend requires countries to develop holistic, sustainable, and inclusive food policies. The organization further indicates that global food demand is expected to increase by more than 60% by 2050, necessitating a significant expansion of agricultural production capacity and food supply [3], [4].

These projections clearly demonstrate that the agricultural sector must not only increase production volumes but also enhance the efficiency, environmental sustainability, and energy performance of production processes. In this context, the effective utilization of geothermal energy resources in agricultural production particularly in greenhouse cultivation and rural heating applications emerges as a sustainable alternative solution. Geothermal energy holds strategic importance for the future of agricultural production systems due to its potential to reduce dependence on fossil fuels, lower production costs, and minimize carbon emissions. Consequently, achieving food security and addressing the climate crisis successfully depend on the integrated adoption of innovative agricultural technologies, climate-friendly production methods, and renewable energy sources such as geothermal energy within the agricultural sector.

Greenhouse cultivation, while being one of the most effective methods for maximizing agricultural productivity by increasing yield per unit area, is also considered one of the most energy-intensive subsectors within agricultural production systems due to its high energy demand, investment costs, and operational expenses [5]. In modern greenhouse enterprises, where environmental conditions are artificially controlled, energy consumption can account for up to 78% of total production costs. A substantial portion of this consumption approximately 65-85% of the primary energy requirement is directed toward heating and cooling processes aimed at maintaining the optimal temperature and humidity balance of the plant growth environment [6]. This situation underscores the importance of renewable energy solutions that enhance energy efficiency for the sustainability of greenhouse operations. In this context, the utilization of geothermal energy resources for heating in greenhouse cultivation presents a critical alternative that reduces dependence on fossil fuels while contributing to both economic and environmental sustainability.

With technological advancements, recent years have witnessed the increasing adoption of smart greenhouses characterized by enhanced energy efficiency, high levels of automation, and precise monitoring of environmental parameters [7]. These new-generation greenhouse systems, through optimized control mechanisms, not only reduce energy consumption but also improve product quality and productivity. Smart greenhouses provide controlled agricultural production environments that ensure sustainable cultivation throughout the year by integrating sensor-based climate management, automated irrigation, and nutrient dosing systems.

These developments, in contrast to traditional greenhouse cultivation, highlight the growing importance of innovative approaches such as digital monitoring, data-driven decision-making, and renewable energy integration in production processes. In this context, smart greenhouse systems integrated with geothermal energy represent an innovative engineering approach that enhances energy efficiency in agricultural production, minimizes environmental impacts, and strengthens climate change adaptation capacity. The integration of Turkey's high geothermal potential with digitally monitored and automated greenhouse infrastructures is considered a strategic necessity for developing sustainable agricultural production models, enhancing food security, and promoting rural development. Through these systems, environmental variables can be monitored in real time, production processes can be managed through automation-based operations, and decision-making mechanisms can be executed more rapidly and with higher accuracy. For instance, in smart greenhouse systems integrated with sensor technologies, climate parameters such as temperature, humidity, light intensity, and carbon dioxide (CO_2) concentration are continuously monitored. Based on the analysis of the collected data, climate control systems are dynamically adjusted to ensure optimal growing conditions.

II. FUNDAMENTALS AND APPLICATIONS OF GEOTHERMAL ENERGY

2.1 Definition and Characteristics of Geothermal Energy:

A geothermal resource is defined as hot water or steam formed through the accumulation of heat at various depths within the Earth's crust, with a temperature consistently above the regional atmospheric average and a higher concentration of dissolved minerals, salts, and gases compared to surrounding groundwater or surface water [8]. Geothermal energy, on the other hand, refers to an environmentally friendly, renewable, and sustainable form of energy derived from the thermal energy stored in the deeper layers of the Earth's crust (Figure 1). This form of energy can be effectively utilized in agricultural production systems, particularly for greenhouse heating applications. Depending on the physical and chemical properties of the geothermal fluid, it can be employed for greenhouse climate control through direct heating systems, heat exchangers, or geothermal heat pumps, thereby reducing energy costs while enhancing environmental sustainability.

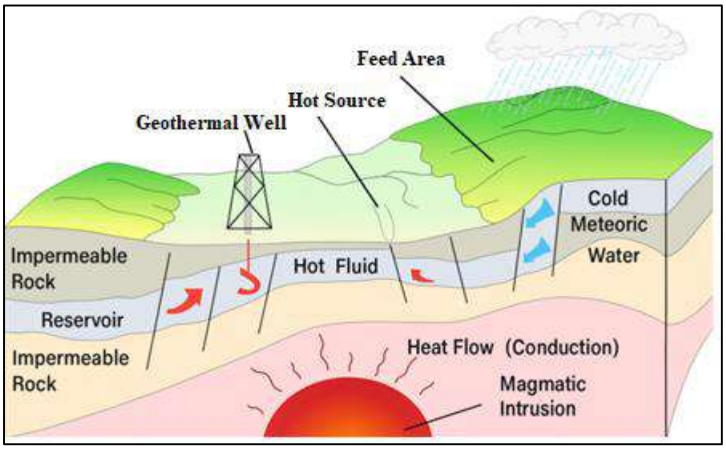

FIGURE 1. Schematic Representation of a Geothermal System [Modified from 9].

Geothermal energy is a renewable energy source derived from the thermal energy accumulated in the deeper layers of the Earth's crust, characterized by its environmental friendliness, sustainability, and high continuity. This form of energy is effectively utilized in agricultural production systems, particularly for greenhouse heating applications. In greenhouse operations, geothermal resources contribute to environmental sustainability by offering high energy efficiency and low carbon emissions. Notably, countries with substantial geothermal potential such as Iceland, the Netherlands, and Turkey have successfully implemented these systems in agricultural greenhouses. Depending on the system design, geothermal energy enables temperature regulation and the maintenance of optimal growing conditions within greenhouses through subsurface heat exchangers, water or antifreeze circulation loops, and geothermal heat pumps [10]. These integrated systems facilitate the establishment of controlled and sustainable production environments that operate independently of external climatic conditions, thereby reducing energy consumption, lowering operational costs, and supporting efficient year-round production.

Geothermal energy systems are classified into three main categories by [11] based on the physical state of the fluid within the reservoir: (1) Liquid-dominated systems contain fluid entirely in the liquid phase, where energy production is achieved directly by extracting hot water to the surface. (2) Two-phase systems feature reservoir conditions that allow the coexistence of both liquid and vapor phases; this results in complex fluid behaviors that influence thermodynamic efficiency during energy conversion processes. (3) Vapor-dominated systems occur when high-temperature and low-pressure conditions within the reservoir cause the fluid to exist entirely in the form of superheated steam.

Geothermal energy resources are generally categorized into three main groups based on the temperature levels of the reservoir fluids. This classification serves as a fundamental criterion for determining both the potential application areas of the resources and the selection of appropriate energy conversion technologies. Low-temperature fields, typically ranging between 20 °C and 70 °C, are primarily utilized for direct heating applications such as greenhouse heating, balneological (hot spring) uses, and industrial drying processes. Medium-temperature fields, with temperatures between 70 °C and 150 °C, can be employed for heating systems as well as secondary (binary cycle) power generation under suitable technological conditions. High-temperature fields, exceeding 150 °C, are usually associated with reservoirs used for electricity generation through steam turbine systems [8], [11], [12], [13], [14].

2.2 The Potential of Geothermal Resources in the World and in Turkey:

Data from the period between 1995 and 2020 clearly demonstrate a significant global increase in the direct-use applications of geothermal energy, including residential and district heating, thermal tourism, greenhouse heating, and industrial process heating. As illustrated in Figure 2, both the installed global geothermal thermal capacity (MWt) and the total annual energy use (TJ/yr) exhibited a steady and substantial increase over the examined period. The global installed geothermal heating capacity, which was 8,664 MWt in 1995, reached 105,107 MWt by 2020. Similarly, the total annual energy use rose from 112,441 TJ/yr to 1,005,198 TJ/yr during the same period. These data indicate that over a period of approximately 25 years, the installed geothermal capacity increased by a factor of 12, while the annual energy use grew nearly ninefold. This remarkable growth demonstrates that the global expansion of geothermal energy has not only occurred in terms of capacity but also through the diversification of application areas and enhancements in technological efficiency. Overall, the graph reveals a significant broadening and dissemination of direct-use geothermal applications between 1995 and 2020. In particular, the notable rise in the use of geothermal heat pumps underscores the growing strategic importance of low-temperature geothermal resources in the global energy transition (Figure 3).

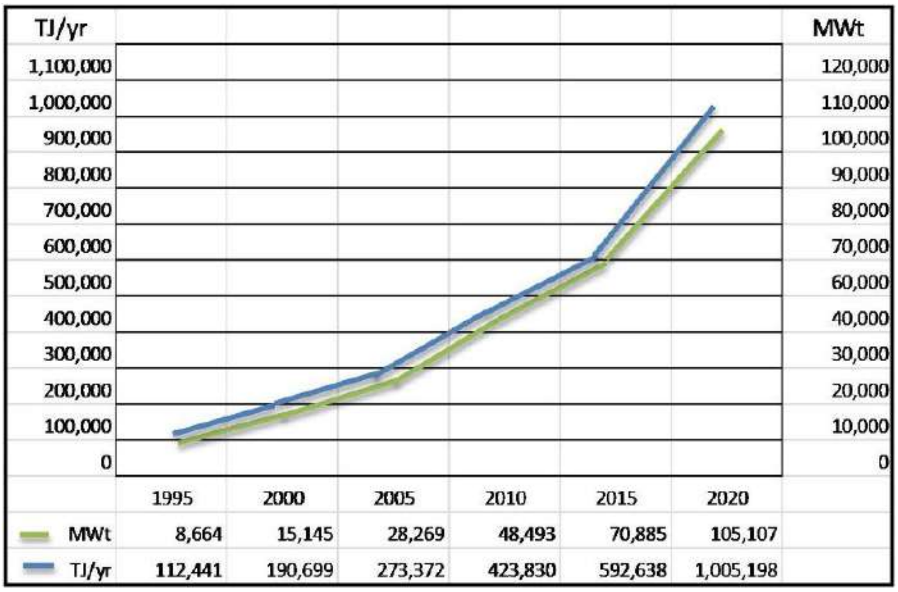

FIGURE 2: The installed direct-use geothermal capacity and annual utilization from 1995 to 2020 [15].

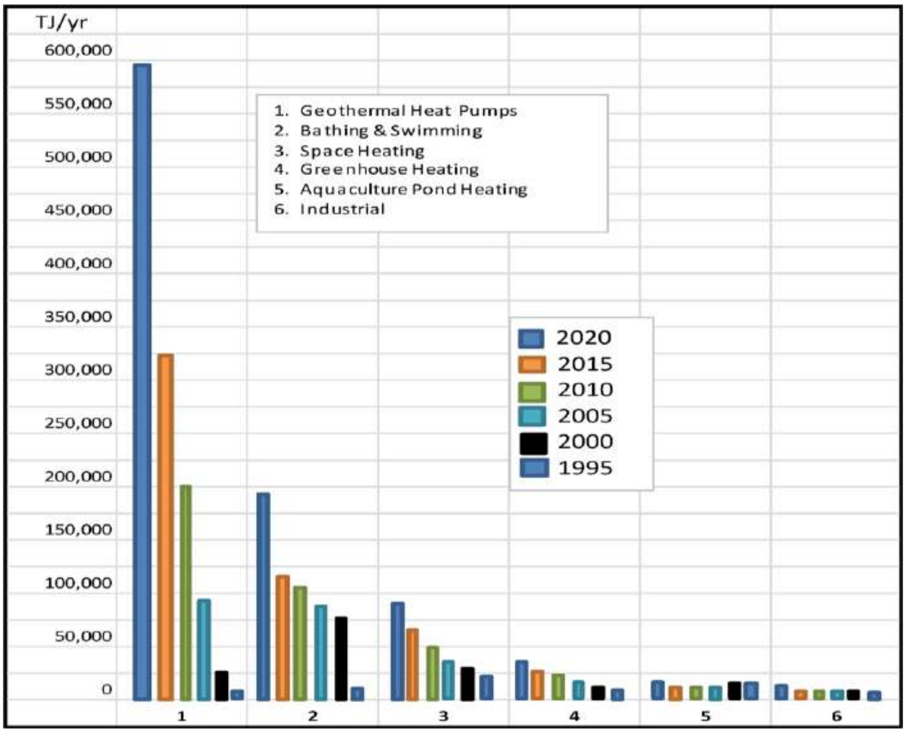

FIGURE 3. Comparison of worldwide direct-use of geothermal energy [15].

Systematic geothermal resource exploration in Türkiye was initiated by the General Directorate of Mineral Research and Exploration (MTA) in 1962. Since 2004, these efforts have accelerated, and significant progress has been achieved in geothermal energy applications due to the expansion of exploration activities, the promising results obtained, and improvements in legal and regulatory frameworks. Through geological, geophysical, and geochemical surveys conducted within this scope, numerous geothermal fields across different regions of the country have been identified, including high-temperature geothermal systems with temperatures reaching up to 287.5 °C. These findings demonstrate that Türkiye possesses substantial potential not only in low- and medium-temperature geothermal fields but also in high-enthalpy resources suitable for electricity generation [16].

Türkiye's location within an active tectonic belt contributes to its considerable geothermal wealth. There are approximately 1,000 natural geothermal discharge points nationwide, exhibiting a wide range of temperatures [17]. Türkiye ranks among the leading countries in Europe in terms of geothermal resource potential and is listed within the top five globally with respect to direct-use applications [18] Moreover, the country ranks fourth both in Europe and worldwide in terms of installed geothermal power capacity. As of June 2022, Türkiye's installed geothermal capacity had reached 1,686 MW [17].

2.3 Applications of Geothermal Energy in the Agricultural and Greenhouse Sectors:

As a renewable, domestic, and low-carbon energy source, geothermal energy holds strategic importance in meeting both heating and process energy demands within agricultural production systems. Among various agricultural applications, the greenhouse sector stands out as one of the most effective areas for the direct utilization of geothermal energy. On a global scale, the agricultural sector particularly greenhouse heating and agricultural drying represents a significant share of total geothermal energy used for direct purposes. According to Figure 4, approximately 3.5% of the total direct-use geothermal energy consumption is allocated to greenhouse heating, while 0.4% is utilized for agricultural product drying [19].

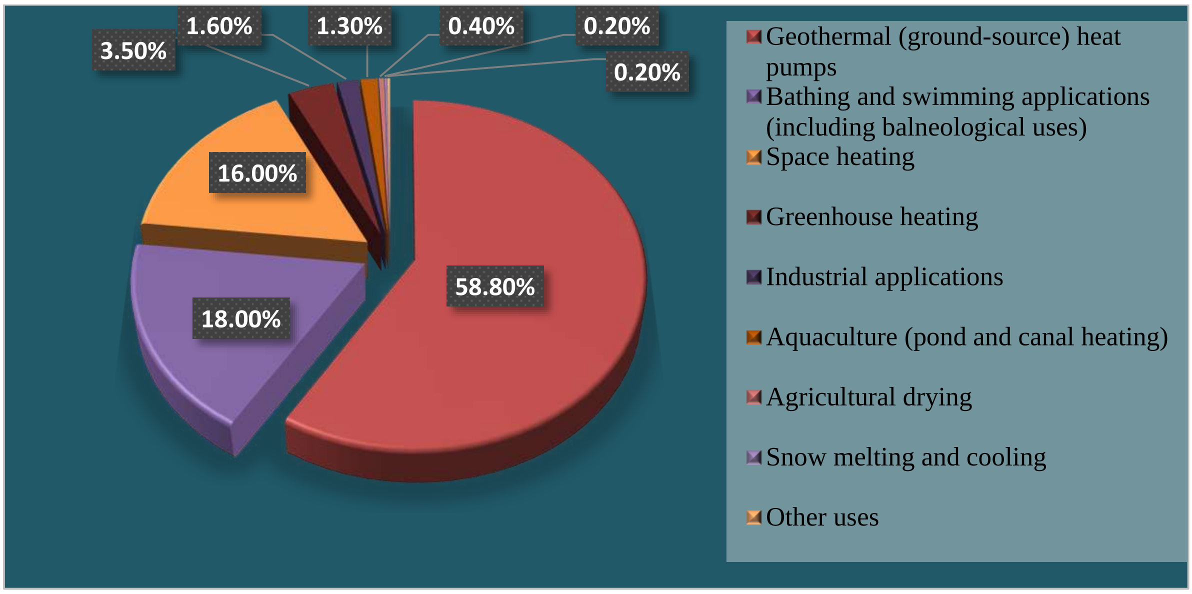

FIGURE 4: Direct-use distribution of geothermal energy by category [Modified from 19]

These proportions indicate that low- and medium-temperature geothermal resources possess substantial potential in agricultural production by reducing energy costs, shortening production periods, and enabling precise climate control. The use of geothermal energy in greenhouses provides a sustainable and economically viable production model, particularly in regions where heating expenses are high, while also contributing to carbon emission reduction. According to the World Geothermal Congress (WGC, 2015) data, this field has experienced a 24% increase in installed capacity and a 23% increase in energy utilization [20]. Similarly, the Turkey Geothermal Resources Strategy Report indicates that the total installed thermal capacity for direct-use applications in Turkey has reached 5,113 MWt, of which approximately 24.1% is allocated to greenhouse heating purposes [21].

III. HEATING STRATEGIES AND USE OF GEOTHERMAL ENERGY IN AGRICULTURAL GREENHOUSES

The growing global demand for food has made controlled-environment agriculture a strategic production model that enables year-round cultivation. Greenhouses, as the most widespread example of such systems, require maintaining environmental parameters such as carbon dioxide concentration, relative humidity, lighting, and temperature within optimal ranges to ensure healthy plant growth. However, due to their structural characteristics typically constructed from lightweight materials and exhibiting relatively low energy efficiency greenhouses consume significantly more fossil fuels and generate higher carbon emissions compared to other building types of similar scale. Consequently, greenhouses are regarded as one of the most energy-intensive systems within the agricultural production sector.

Among the various applications of geothermal energy, its use in agricultural production stands out as particularly significant. Greenhouses, depending on the climatic characteristics of the region in which they are located, require different levels of heating, ventilation, shading, and cooling throughout the year. The heating process, which plays a critical role in enhancing yield and quality in plant production, also represents one of the major factors contributing to the overall production costs in greenhouse operations. Acosta-Silva et al. [22] emphasize that energy consumption in greenhouse cultivation is one of the primary factors determining production expenses, accounting for up to 50% of total operational costs in many countries. In this context, heating and cooling processes constitute approximately 65-85% of the total energy demand, making them among the most critical components of energy management and sustainability in greenhouse operations [23].

In a study conducted by Çaylı et al. [24], the annual heating energy requirements of greenhouses located in different climatic regions of Turkey were comparatively analyzed. The results revealed that the highest annual heating energy demand was observed in Kahramanmaraş with 179.7 kWh m^{-2}, while the lowest was recorded in Mersin with 65.9 kWh m^{-2}. In addition, regarding the variability of average annual energy demand, the largest fluctuation was found in Antakya (-24.5%), whereas the smallest variation occurred in Osmaniye (-12.2%). These findings clearly indicate that regional climatic conditions play a decisive role in determining the heating energy requirements of greenhouses. Similarly, Baytorun et al. [25] reported that greenhouse heating costs vary between 20% and 60% of the total operating expenses, depending on factors such as structural characteristics, technological equipment used, and regional climatic differences. Energy balance analyses conducted by Kurpaska et al. [26] revealed that heat consumption in Venlo-type greenhouses varies significantly depending on sidewall height and local climatic conditions. According to the study findings, increasing the greenhouse height from 4 m to 6 m results in an approximately 13% increase in total heat consumption. This rise is associated with the larger air volume and greater heat losses due to the expanded surface area. Moreover, it was determined that around 50% of the total annual heat demand occurs during the winter months, 40% during spring and autumn, and 10% during the summer season. These results emphasize that greenhouse energy management strategies should be optimized based on regional climatic conditions and structural design parameters.

The use of geothermal energy in greenhouse heating systems can reduce primary energy consumption by more than 20%, thereby contributing significantly to the reduction of operational costs. It is estimated that if renewable energy sources are more widely adopted in greenhouse cultivation, fossil fuel consumption could decrease by approximately 40%, leading to a substantial reduction in greenhouse gas emissions [27]. In this context, Turkey, Iceland, Italy, and Japan are among the leading countries in geothermal energy-assisted greenhouse heating applications. In Turkey, particularly in the provinces of Afyon, Aydın, and Denizli, project reports indicate that the use of geothermal energy provides 25-40% energy savings compared to conventional heating systems [28]. Studies conducted by Bibbiani et al. [29] support these findings, revealing that maintaining an indoor greenhouse temperature between 15-20 °C requires an average of 5-6 kg/m² of fossil fuel consumption per year. The same study reported that the combustion of approximately 4 million tons of oil equivalent results in 11.3 million tons of CO_2 emissions, emphasizing the significant impact of fossil fuel use in greenhouse heating on total greenhouse gas emissions.

Similarly, Tomarov and Shipkov [20] highlighted the global environmental benefits of energy efficiency practices, reporting that such measures have prevented the consumption of approximately 596 million barrels (around 81.0 million tons) of oil equivalent per year. This conservation corresponds to an estimated reduction of 78.1 million tons of carbon and 252.6 million tons of CO_2 emissions released into the atmosphere. These values also encompass the energy efficiency gains achieved by geothermal heat pumps operating in cooling mode, which have increasingly replaced fuel-oil-based electricity generation. Collectively, these findings demonstrate that the utilization of geothermal and other renewable energy sources in greenhouse heating systems holds substantial potential in terms of both energy efficiency and carbon mitigation.

IV. ENERGY MANAGEMENT, DIGITAL INTEGRATION, AND SUSTAINABILITY IN SMART GREENHOUSES

In recent years, smart greenhouse technologies and automation-based control systems have become fundamental components of the digital transformation in controlled-environment agriculture. These systems are designed to enhance production efficiency, reduce energy and water consumption, and promote environmental sustainability. At the same time, the increasing cost of energy and the growing need to mitigate the environmental impacts of greenhouse operations have made the integration of renewable energy sources such as photovoltaic (PV) panels, wind turbines (WTs), and geothermal energy systems increasingly important. The use of these renewable systems significantly reduces the carbon footprint of greenhouses and decreases their dependence on fossil fuels. Integrating renewable energy technologies with advanced control, monitoring, and automation infrastructures holds great potential for optimizing energy management, enhancing production efficiency, and ensuring sustainability in resource utilization [30]. The model developed by Ghiasi et al. [30] presents a comprehensive approach to the integration of renewable energy sources into smart greenhouse systems. The overall structure of this integrated system is illustrated in Figure 5.

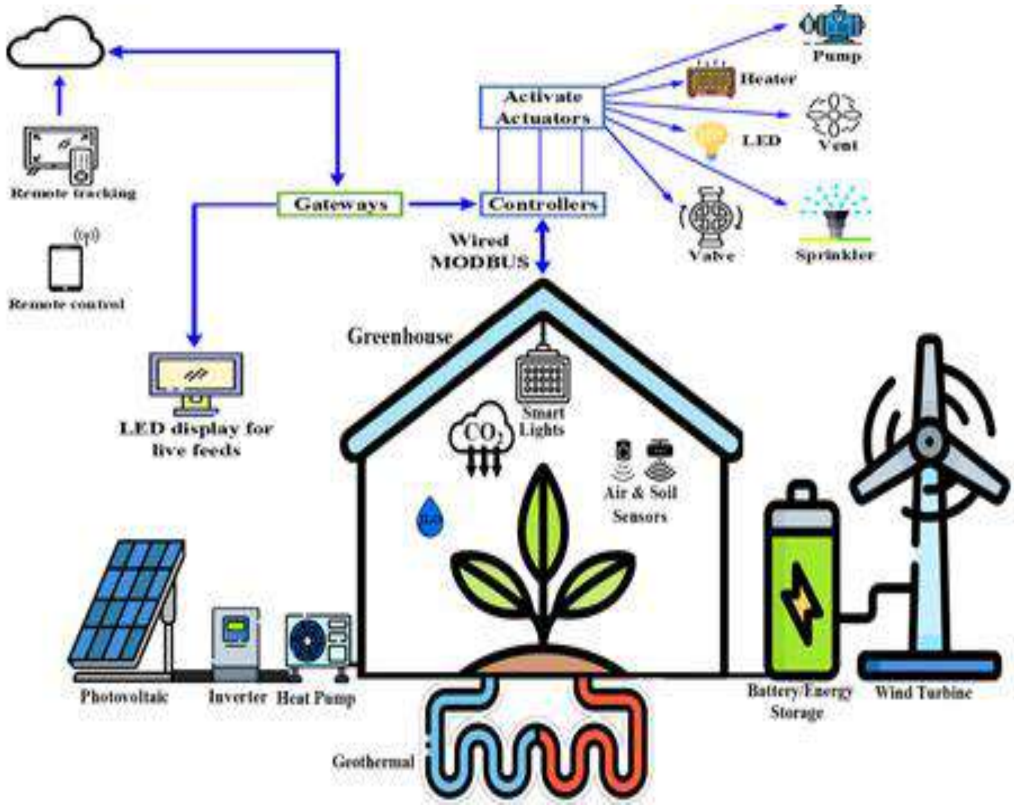

FIGURE 5: Conceptual model of the integration of renewable energy sources into smart greenhouse systems [30].

Automation-based heating and cooling systems, which constitute one of the fundamental components of climate control in smart greenhouses, automatically regulate the indoor temperature using data obtained from sensors and allow remote access through internet connectivity. With Wi-Fi-based control modules, users can monitor and manage the system via tablets or smartphones. This approach offers significant advantages in terms of optimizing energy consumption, reducing operational costs, and enhancing production efficiency [31], [32]. Consequently, smart automation systems emerge as an effective technology that supports both economic sustainability and energy efficiency in modern greenhouse production.

The integration of Internet of Things (IoT) technology into agricultural production systems has fundamentally transformed the operational principles of traditional greenhouses, paving the way for data-driven, automated, and interactive production environments. IoT-based greenhouse systems rely on sensor networks that continuously monitor key environmental variables such as temperature, relative humidity, carbon dioxide (CO_2) concentration, pH, light intensity, and water usage. Data collected from these sensors are analyzed by central control units, enabling irrigation, fertilization, ventilation, and heating operations to be activated automatically and only when required. This intelligent control mechanism reduces energy and water consumption, optimizes resource utilization, and lowers operational costs. Furthermore, IoT-enabled automation systems minimize pesticide use, thereby mitigating environmental impacts and contributing to the protection of plant health against sudden climatic fluctuations. In this regard, IoT technology plays a strategic role in the development of sustainable, energy-efficient, and environmentally friendly agricultural production models [33].

The schematic representation of the IoT-based smart greenhouse model developed by Rayhana et al. [34] is presented in Figure 6. This model represents an intelligent energy management system in which sensor-based monitoring, data collection infrastructure, control algorithms, and artificial intelligence (AI)-driven decision-making mechanisms operate in an integrated framework. The digitalization of energy management in greenhouses through such systems enables the continuous monitoring of environmental variables including temperature, humidity, solar radiation, CO_2 concentration, and soil moisture and allows the analysis of collected data to optimize energy consumption patterns. Consequently, heaters, fans, pumps, and other energy-consuming devices are activated only, when necessary, thereby minimizing energy losses [35].

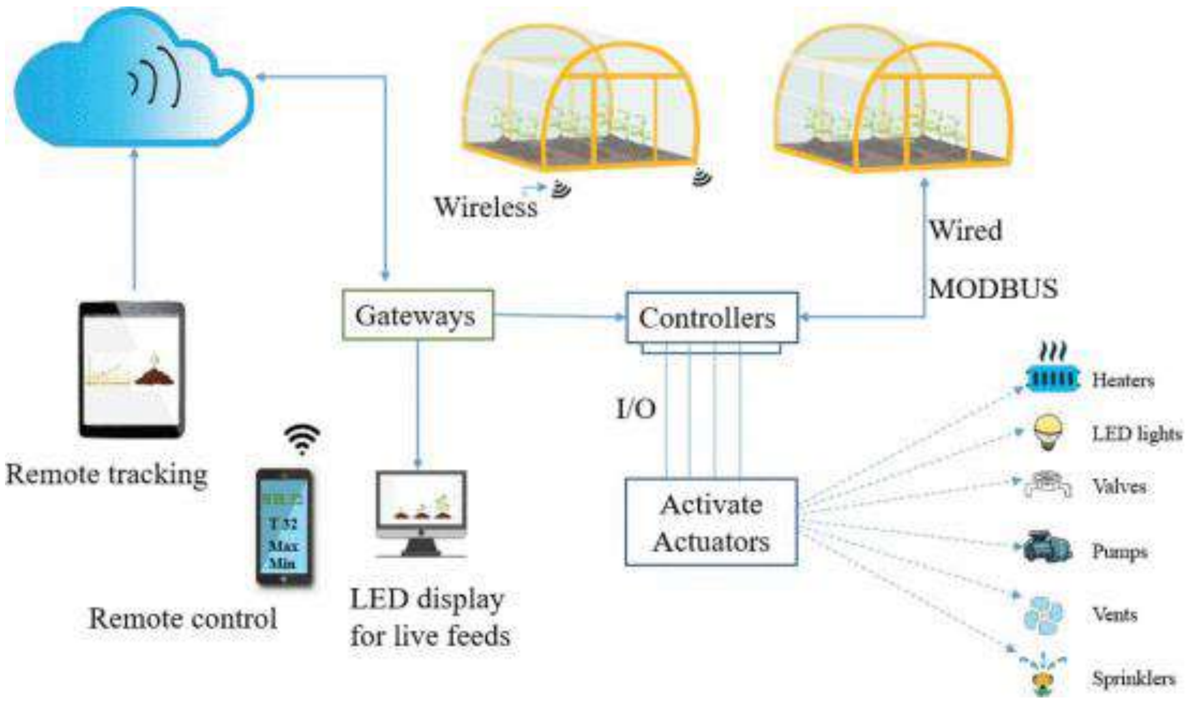

FIGURE 6: IoT-enabled smart greenhouse model [34].

When supported by artificial intelligence (AI) algorithms, this digital transformation process is expected to give rise to highly autonomous and self-learning smart greenhouse systems. The next generation of smart greenhouses will operate through the seamless integration of IoT-based sensor networks and AI-driven analytical systems, enabling the real-time monitoring and analysis of environmental parameters such as light intensity, temperature, relative humidity, carbon dioxide (CO_2) concentration, soil moisture, and wind speed. This integrated structure will not only optimize energy consumption but also ensure that plant growth is maintained under the most favorable microclimatic conditions [36], [37].

In addition, the integration of digital twin technology enables the creation of a virtual model parallel to the physical greenhouse environment, establishing a bidirectional data flow between the physical and digital systems. This dynamic interaction not only enhances energy efficiency but also allows for the predictive identification of potential system failures and the implementation of more planned and proactive maintenance processes [38]. Therefore, the holistic integration of Internet of Things (IoT), artificial intelligence (AI), and digital twin technologies in smart greenhouse systems not only enhances production efficiency and resource management, but also establishes the foundation for an innovative production paradigm centered on sustainability, environmental awareness, and energy efficiency in agricultural production. This integrated approach unites the goals of energy optimization, climate adaptation, and resource conservation within the broader context of agriculture's digital transformation, thereby introducing a new framework for the smart farming ecosystems of the future.

Azaza et al. [39] developed a fuzzy logic-based control (FLC) system aimed at optimizing temperature and humidity balance within greenhouse environments. In this system, ventilation and heating rates were used as control variables, resulting in a 22% reduction in energy consumption and a 33% reduction in water use. Similarly, studies conducted by Bevilacqua [40] reported that smart energy management systems can reduce energy consumption in greenhouse applications by 20-40%, while significantly improving overall system efficiency.

Azaizia et al. [41] reported that in such smart systems, energy conversion efficiency is approximately 35-45% higher compared to traditional climate control methods. In line with these findings, research conducted by Mohamed et al. [42] demonstrated that the implementation of IoT-based energy management systems led to a 35% reduction in energy consumption and a 12% increase in crop yield in greenhouse operations. These results clearly demonstrate the potential of digital and intelligent control-based energy management approaches in greenhouses to simultaneously enhance energy efficiency and improve production performance. In another study conducted by Asibeluo and Ekruyota [43], it was determined that the integration of sensor-based systems with Internet of Things (IoT) technology enabled greenhouse automation units to operate with high accuracy levels. According to the research findings, the accuracy rates were measured as 85% for the irrigation unit, 90% for the heating unit, 90% for the cooling unit, and 85% for the fertigation (nutrient solution application) unit. These findings indicate that IoT-assisted control systems possess significant potential in greenhouse management, both for enhancing energy efficiency and for the precise regulation of environmental parameters.

Castaneda-Miranda and Castano [44] employed a multi-layer perceptron (MLP) model to accurately predict frost conditions inside greenhouses and reported that the system could forecast temperature variations with 95% accuracy. Similarly, a study conducted by Tzounis et al. [45] demonstrated that the implementation of IoT-based climate control systems could reduce greenhouse energy consumption by up to 30%. Collectively, these studies highlight the substantial potential of digital technologies and AI-assisted control systems in greenhouse climate management to optimize energy and water use, enhance production efficiency, and strengthen environmental sustainability.

V. RESULT AND DISCUSSION

In this study, the potential use of geothermal energy in agricultural greenhouses, as well as its advantages in terms of energy efficiency and sustainable production, have been comprehensively evaluated. The findings indicate that global dynamics such as climate change, population growth, and rising energy costs are rapidly increasing the need for renewable energy solutions in agricultural production systems. Particularly, greenhouse cultivation has become a strategic production model due to its ability to enable year-round production; however, it is also one of the most energy-intensive agricultural activities in terms of energy consumption and carbon emissions. Therefore, the importance of geothermal-based heating systems that enhance energy efficiency and reduce environmental impacts is increasingly emphasized.

Geothermal energy can reduce primary energy consumption in greenhouses by more than 20%, leading to significant reductions in operating costs. Geothermal greenhouse applications implemented particularly in the Turkish provinces of Afyon, Aydın, and Denizli have demonstrated energy savings of between 25% and 40% compared to conventional heating systems. This provides substantial benefits in terms of both economic sustainability and the reduction of carbon emissions. Furthermore, energy analyses have shown that greenhouse design parameters (such as sidewall height) and local climatic conditions have a direct impact on energy requirements. These findings highlight the necessity of planning energy management strategies in accordance with regional conditions.

With the integration of digital transformation into agricultural production systems, smart greenhouse technologies have ushered in a new era of energy management. Internet of Things (IoT), Artificial Intelligence (AI), and digital twin-based systems monitor in real time the internal climate parameters of greenhouses (such as temperature, humidity, light, CO_2 concentration, and soil moisture), thereby optimizing energy and water consumption. Research has shown that through the integration of these technologies, energy consumption can be reduced by 20-40%, water use by up to 30%, and system accuracy rates can reach 85-90% [39], [40], [42], [43]. Moreover, these systems enhance production performance by increasing crop yield by approximately 10-15%.

The findings indicate that greenhouse systems based on digital and renewable energy technologies possess a high potential not only in terms of energy savings but also regarding environmental sustainability, resource efficiency, and climate change adaptation capacity. Smart greenhouse models that holistically integrate geothermal energy with IoT and artificial intelligence technologies constitute key components of both economic and ecological sustainability in the agricultural systems of the future. Consequently, the integrated utilization of Türkiye’s geothermal energy potential with digital technologies will reduce energy dependency in agricultural production, lower the carbon footprint, and strengthen food security. In this context, the widespread adoption of geothermal energy-supported smart greenhouse systems should be regarded as a strategic priority for implementing sustainable agricultural development policies at the national level.

Geothermal energy resources are among the most prominent renewable energy options for greenhouse heating applications due to their high energy efficiency and low carbon emissions. By directly utilizing heat extracted from underground, these resources reduce fossil fuel consumption, thereby lowering greenhouse gas emissions and achieving significant savings in operating costs. In addition, the stable and reliable heat supply provided by geothermal systems supports continuous year-round production, contributing to the energy sustainability of modern greenhouse cultivation. However, the regional variability of geothermal resources, the high costs associated with drilling and infrastructure investment, and issues such as corrosion and mineral precipitation caused by the chemical composition of geothermal fluids are considered major technical and economic constraints limiting the widespread adoption of these technologies.

VI. CONCLUSION

Geothermal energy-integrated smart greenhouse systems represent an innovative approach that enhances energy efficiency, reduces carbon emissions, and supports the sustainable use of resources in agricultural production. Through the integration of IoT, artificial intelligence (AI), and digital twin technologies, these systems optimize energy and water consumption, leading to significant improvements in production efficiency. However, high drilling and infrastructure costs, technical challenges arising from the chemical properties of geothermal fluids, and limited financial resources remain the main factors constraining the widespread adoption of these technologies.

Therefore, establishing organized geothermal greenhouse zones in regions with high geothermal potential, increasing investment incentives, and promoting the development of domestic technologies are of great importance. The hybrid use of geothermal energy with photovoltaic and biomass systems, along with the widespread adoption of heat storage and recovery technologies, offers effective solutions for strengthening energy supply security.

In conclusion, geothermal energy-supported smart greenhouse systems represent a significant opportunity and a forward-looking strategic engineering approach for Türkiye to achieve its goals of sustainable agriculture, energy independence, and low-carbon production.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Sequestering Carbon in Agriculture: Innovations for Climate Mitigation

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Abstract— *Carbon sequestration plays a crucial role in addressing climate change by lowering the concentration of carbon dioxide (CO_2) in the atmosphere. With the rapid increase in greenhouse gas (GHG) emissions, the Earth's climate is undergoing significant transformations, making it essential to adopt strategies that counteract these emissions. Among various solutions, soil carbon sequestration stands out as an effective method, particularly because degraded and agricultural soils hold substantial capacity for storing additional carbon. Globally, soils are capable of storing nearly twice as much carbon as the atmosphere and terrestrial vegetation combined. The amount of carbon held in soil is influenced by both climatic conditions and soil characteristics. Agricultural practices—including land-use changes, crop residue handling and soil management—play a major role in determining soil carbon levels. Improving these practices not only enhances soil carbon stocks but also supports food security and promotes sustainable farming systems. The development of carbon sequestration technologies is increasingly important. Abiotic approaches such as CO_2 injection into oceans, geological formations, and mineral carbonation offer long-term storage solutions, while biotic approaches rely on natural processes and tend to be more affordable and faster to implement. Together, these methods complement each other and contribute to reducing the risks associated with climate change. Human activities, especially the burning of fossil fuels, have significantly increased atmospheric CO_2 concentrations, resulting in global warming and a range of environmental challenges. Therefore, it is essential to adopt strategies that both limit emissions and actively remove CO_2 from the atmosphere. This chapter provides an in-depth examination of carbon sequestration—its definition, processes, benefits, and challenges—along with its importance in mitigating climate change and enhancing our understanding of its overall potential.*

Keywords— Carbon sequestration, climate change mitigation, greenhouse gas emissions, soil carbon sequestration, geological sequestration, terrestrial sequestration, and oceanic sequestration.

I. INTRODUCTION

Carbon is an essential component for maintaining soil biological processes, ecosystem productivity, soil biodiversity, and overall environmental quality (Gaikwad, 2021). Atmospheric carbon enters land-based ecosystems primarily through photosynthesis, while it returns to the atmosphere through various respiration processes (Gaikwad, 2021). Even slight imbalances between the amount of carbon captured from the atmosphere and the amount released back can produce noticeable shifts in climate patterns over decades. In recent years, the excessive emission of carbon has negatively affected air, water, soil, and human well-being (Gaikwad, 2021).

Since the late 19th century, global surface temperatures have increased by approximately 0.88°C, with 11 of the 12 warmest years occurring after 1995 (IPCC, 2007). Projections indicate that Earth's average temperature could rise by 1.5–5.8°C by the end of the 21st century (IPCC, 2001). The warming trend has accelerated since 1975, with an estimated increase of 0.158°C per decade. These temperature shifts have also contributed to major ecological changes (Greene & Pershing, 2007) and a rise in both the frequency and severity of wildfires (Running, 2006; Westerling et al., 2006). Much of this climate change is attributed to greenhouse gas (GHG) emissions produced by human activities—including land-use conversion, deforestation, biomass burning, drainage of wetlands, soil disturbance, and the combustion of fossil fuels.

Since the Industrial Revolution around 1850, concentrations of GHGs and their radiative forcing have steadily increased alongside human population growth. Carbon dioxide (CO_2) levels, for example, climbed from 280 ppmv in 1850 to 380 ppmv in 2005, and continue rising by roughly 1.7 ppmv (or 0.46%) each year (WMO, 2006; IPCC, 2007). Methane (CH_4) and nitrous oxide (N_2O) show similar long-term upward trends (IPCC, 2001, 2007; Prather et al., 2001; WMO, 2006). Altogether, the total radiative forcing resulting from all greenhouse gases since 1850 is estimated at 2.43 W m^{-2} (IPCC, 2001, 2007).

To mitigate climate change and reduce CO_2 emissions, several strategies have been proposed (Schrag,2007):

1) Lowering global energy demand,
2) Developing energy sources that are low-carbon or carbon-neutral, and
3) Utilizing both natural and technological methods to capture and store CO_2 from emission sources or directly from the atmosphere.

Between 1850 and 1998, fossil fuel use emitted an estimated 270 ± 30 Pg of carbon, while land-use change, deforestation, and soil cultivation released an additional 136 ± 30 Pg (IPCC, 2001). At present, fossil fuel combustion contributes about 7 Pg C per year (Pacala & Socolow, 2004), and land-use change contributes another 1.6 Pg C annually. Of the total anthropogenic emissions of roughly 8.6 Pg C each year, about 3.5 Pg accumulates in the atmosphere, 2.3 Pg is absorbed by the oceans, and the remainder goes into an unidentified terrestrial sink—likely situated in the Northern Hemisphere (Tans et al., 1990; Fan et al., 1998).

The purpose of this chapter is to examine the processes and technological pathways for long-term CO_2–C sequestration in major global carbon reservoirs. While presenting a broad overview of CO_2 sequestration, particular attention is directed toward soil-based (terrestrial) carbon sequestration and its role in reducing the rate of atmospheric CO_2 accumulation.

II. WHAT IS CARBON SEQUESTRATION?

Carbon sequestration is the process of capturing carbon dioxide (CO_2) from the atmosphere and storing it in forms that prevent its return to the air. This storage can take place through natural ecological pathways or through human-developed technologies. The concept includes both naturally occurring mechanisms and deliberate interventions that remove CO_2 from the atmosphere or prevent it from being emitted in the first place. These approaches store carbon in different reservoirs, such as oceans, terrestrial ecosystems (including soils, vegetation, and sediments), and deep geological formations.

Before human activities began significantly increasing CO_2 emissions, the global carbon cycle (Figure 1) maintained a stable balance between the absorption and release of carbon. Today, however, the natural carbon sinks responsible for CO_2 uptake cannot keep pace with the rapid and continuous emissions generated by human actions. As a result, the planet's natural systems are no longer able to offset the accelerated rise in atmospheric CO_2.

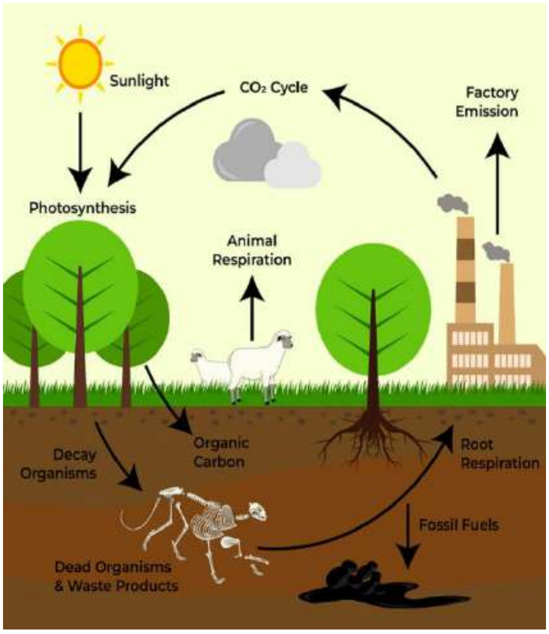
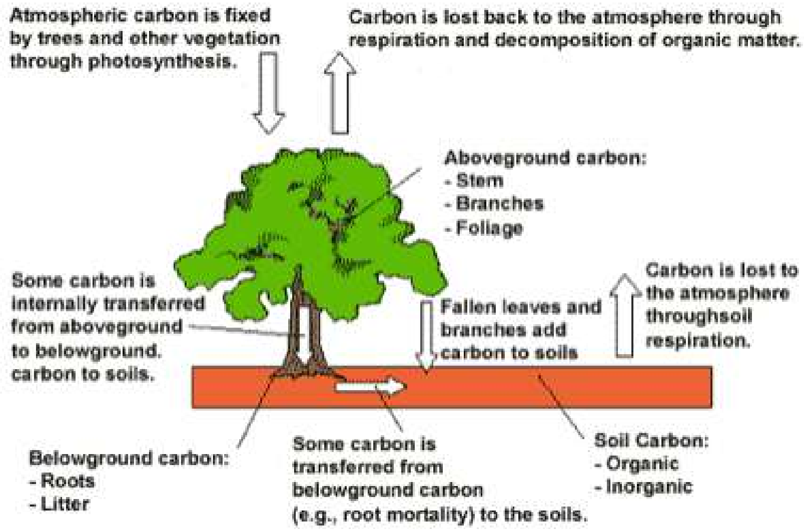


FIGURE 1: The global carbon cycle

III. CARBON SEQUESTRATION APPROACHES

3.1 Terrestrial Sequestration:

Terrestrial carbon sequestration refers to the uptake of atmospheric carbon dioxide (CO_2) by vegetation—such as trees, crops, and other plants—through the process of photosynthesis. The absorbed carbon is then stored in plant biomass, including trunks, branches, leaves, roots, as well as in soil organic matter. Forests, agricultural lands, and grazing areas are often described as “carbon sinks” because of their capacity to capture and retain carbon. However, these same systems can also emit CO_2 through various agricultural and forestry operations. A landscape functions as a carbon sink only when the amount of carbon it captures exceeds the amount it releases over a specific period.



Source: https://www.projectguru.in/carbon-sequestration-to-prevent-global-warming/

3.1.1 Terrestrial Activities for CO_2 Sequestration:

Carbon sequestration in terrestrial ecosystems can be increased through strategic land-use practices and management decisions that enhance carbon storage in soils, croplands, and forests. Practices such as diversified crop rotations, no-till farming, reducing summer fallow periods, planting cover crops (e.g., wheat, rye) or high-residue crops (e.g., corn, grain sorghum), and establishing vegetative buffer zones all contribute to carbon accumulation in cropland soils.

Additional measures include converting underutilized or marginal agricultural lands into grasslands or forests, selecting crop varieties with higher carbon storage potential, and adopting land management techniques that limit soil disturbance, erosion, and the removal of organic carbon from the land. These approaches collectively strengthen the role of terrestrial ecosystems as effective carbon sinks.

3.2 Geologic Sequestration

Geologic sequestration of CO_2 involves three main stages: capturing the CO_2, transporting it, and storing it in deep underground formations.

3.2.1 Capture:

CO_2 produced by power plants is captured using several techniques, including flue-gas separation, oxy-fuel combustion, and pre-combustion methods:

- **Flue-gas separation**: CO_2 is removed from exhaust gases using solvents. The CO_2 is then released from the solvent using steam, producing a concentrated CO_2 stream that can be commercially utilized.
- **Oxy-fuel combustion**: Fuel is burned in pure or oxygen-enriched air, producing flue gas that primarily contains CO_2 and water vapor.
- **Pre-combustion capture**: CO_2 is removed before fuel combustion, often as part of a gasification process.

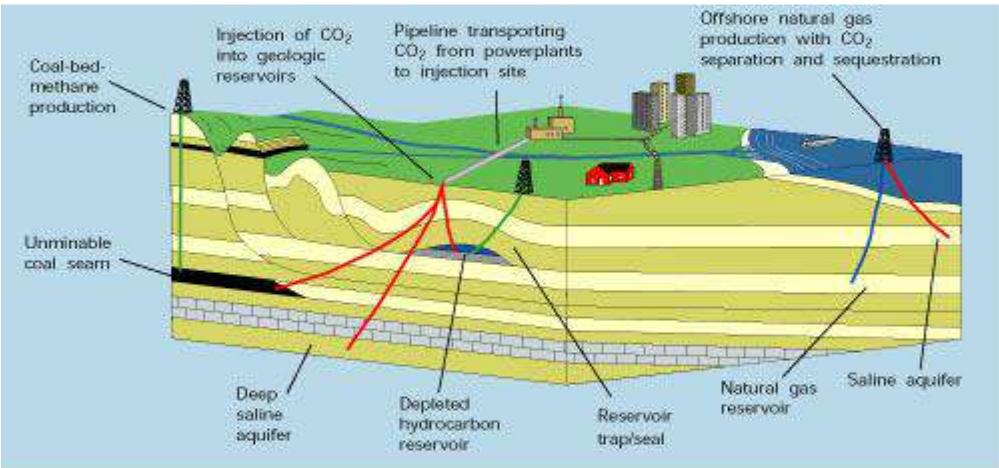
3.2.2 Transportation:

Once captured, the CO_2 is transported—typically via pipelines—to a designated storage site. Selection of the site involves input from geologists, engineers, project managers, and other specialists.

3.2.3 Storage:

The CO_2 is injected into deep underground rock formations with high porosity and permeability. Porosity refers to the volume of pore spaces in the rock where CO_2 can reside, while permeability describes how well these pores are interconnected, allowing the CO_2 to flow efficiently during injection.

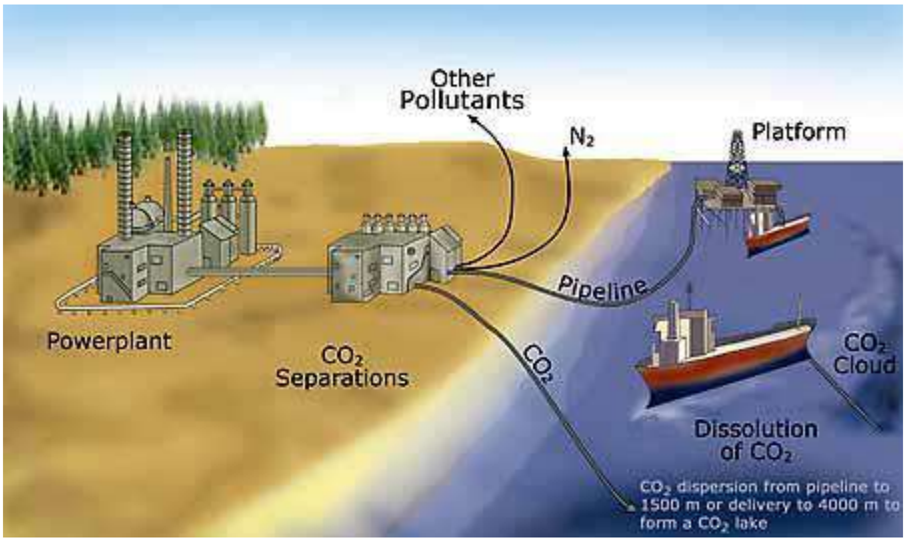
The storage formation, called the **reservoir**, must be capped by a low-permeability layer known as the **cap rock**, which prevents CO_2 from escaping. Suitable reservoirs include deep saline aquifers, depleted oil and gas fields, and unmineable coal seams. After injection, wells are sealed properly, and the site is monitored over the long term to ensure that no CO_2 leaks occur.



Source: https://pubs.usgs.gov/fs/fs026-03/fs026-03.html

3.3 Carbon Sequestration in the Oceans:

Enhancing the removal of carbon from the atmosphere by oceans can be achieved through methods such as fertilizing phytoplankton with nutrients or injecting CO_2 into ocean depths exceeding 1,000 meters. These processes, along with terrestrial and geologic approaches, are commonly referred to as carbon "sinks."



Source: https://www2.lbl.gov/Science-Articles/Archive/sea-carb-bish.html

Farmers who demonstrate that their practices have sequestered more carbon in soils than they emitted through machinery and other activities can earn **carbon credits**. The carbon stored in soils can then be used to offset emissions from activities such as fossil fuel combustion, cement production, and other industrial processes. In addition to reducing atmospheric CO_2, these practices enhance soil health and promote long-term agricultural productivity. It is estimated that globally, farmlands have the potential to offset up to 30% of annual CO_2 emissions from fossil fuels.

Establishing soil carbon offset credits for the market requires clear governance, including determining ownership of the carbon (e.g., landowners, operators, or government), identifying buyers of carbon offsets, defining contract durations, establishing verification procedures, and setting penalties for fraud or breaches.

Monitoring, verification, and accounting (MVA) are critical components of carbon sequestration. MVA ensures the permanence and safety of stored CO_2 by measuring the amount of carbon stored at specific sites, tracking its underground location, detecting potential leaks, and verifying that storage methods are secure and environmentally safe. Mitigation strategies are also essential, enabling a response to risks such as CO_2 leakage or environmental harm in the unlikely event of a storage failure.

IV. PRINCIPLES AND MECHANISMS OF CARBON SEQUESTRATION:

Several technological approaches exist for capturing atmospheric CO_2 and storing it in various global reservoirs. Choosing the appropriate methods is essential for designing energy policies that support sustainable economic growth and development at both national and international levels. These approaches are generally grouped into two main categories: **abiotic** and **biotic** carbon sequestration (Lal, 2008).

4.1 Abiotic carbon sequestration: Non-biological carbon capture

Abiotic sequestration refers to the capture and storage of carbon using physical, chemical, and engineering methods, without relying on living organisms such as plants or microbes. The concept of storing carbon in oceanic and geological formations has received considerable attention (Freund and Ormerod, 1997) because of its potential to hold larger amounts of CO_2 compared to biological methods. Significant progress is being made in developing and testing technologies for capturing, transporting, and injecting CO_2 into these reservoirs (Kerr, 2001).

4.1.1 Deep sea carbon injection or oceanic injection:

The injection of pure CO_2 into the deep ocean has been explored by engineers for nearly three decades, with gradual advancements in techniques and understanding. For long-term stability and to prevent CO_2 from returning to the atmosphere, injections must be carried out at substantial ocean depths. Several methods have been proposed for oceanic CO_2 sequestration (Lal, 2008):

1. **Injection below 1,000 meters from an ocean floor manifold**: Liquefied CO_2, being less dense than seawater, rises to around 1,000 meters, forming a plume of droplets.
2. **Injection of a CO_2-seawater mixture at depths of 500–1,000 meters**: The denser mixture sinks into deeper ocean layers.
3. **Discharge from a large pipe towed behind a vessel**: CO_2 is released directly into the water column.
4. **Pumping CO_2 into depressions on the seafloor**: This forms a localized “CO_2 lake” on the ocean bottom.

Studies suggest that liquefied CO_2 injected at depths near 3,000 meters can remain stable over long periods (O’Connor et al., 2001). The ocean has a tremendous capacity to store carbon, estimated at 5,000–10,000 Pg C, which exceeds the total carbon content of known fossil fuel reserves (Herzog et al., 2002).

However, potential impacts on deep-sea organisms must be considered (Seibel & Walsh, 2001). The long-term stability of CO_2 injections also depends on ocean stratification and natural circulation processes. Beyond ecological concerns, economic factors and technical feasibility play a critical role in evaluating the practicality and sustainability of oceanic CO_2 sequestration.

4.1.2 Subsurface carbon storage or geological injection:

Geological carbon storage, also called subsurface carbon storage or geological injection, involves capturing CO_2 from industrial sources, converting it to a liquid state, transporting it, and injecting it into deep underground formations. Suitable formations include depleted coal seams, abandoned oil and gas fields, stable rock layers, or saline aquifers (Tsang et al., 2002; Klara et al., 2003; Baines & Worden, 2004; Gale, 2004).

Saline aquifers are porous sedimentary layers filled with brackish water located beneath freshwater reservoirs and separated from them by impermeable strata. Injected CO_2 is stored in these aquifers through a combination of physical trapping and chemical reactions that can form stable carbonates. Additionally, injecting CO_2 into underground reservoirs can be used as a cost-effective approach for **enhanced oil recovery (EOR)**, where it displaces remaining oil or gas and boosts production from mature or declining fields (Klusman, 2003).

4.1.3 Chemical scrubbing and carbon mineralization:

Mineral carbonation is a process that mimics natural reactions in which CO_2 is transformed into stable mineral forms, such as calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$). The process typically involves two main steps: **scrubbing** and **mineral carbonation**. Scrubbing captures CO_2 chemically using solvents like amines or carbonates, a widely used technique in carbon capture. The purified CO_2 is then converted into solid carbonates through mineral carbonation, permanently storing the carbon.

Ultramafic minerals are considered ideal feedstocks for mineral carbonation, providing long-term potential for industrial CO_2 emissions management (Goff et al., 1997, 2000). However, these geological reactions naturally occur at a slow pace. Methods to accelerate the reaction include reducing particle size, increasing temperature and pressure, and employing catalysts. These enhancements, however, require additional energy and can be costly (Fan & Park, 2004).

4.2 Biotic carbon sequestration: biological carbon capture-

Biotic carbon sequestration involves the active management of plants and microorganisms to capture CO_2 from the atmosphere. This approach emphasizes strategies that extend beyond simply reducing emissions or offsetting them. Improving the efficiency of resources such as water and energy also plays a role in managing carbon storage within terrestrial ecosystems. Some of the key methods for biotic carbon sequestration are briefly discussed below (Lal, 2008):

4.2.1 Marine carbon storage: Oceanic carbon sequestration-

Biological processes play a crucial role in oceanic carbon sequestration through photosynthesis. Phytoplankton, in particular, are responsible for capturing an estimated 45 Pg C per year (Falkowski et al., 2000). Some of the organic matter produced by these microscopic organisms sinks to the ocean floor, effectively storing carbon for long periods (Raven & Falkowski, 1999).

The growth of phytoplankton is often limited by the availability of iron (Fe), which has led to studies on the effects of iron fertilization on enhancing biotic CO_2 sequestration in marine environments (Martin et al., 2002; Boyd et al., 2004). However, the ecological consequences of ocean fertilization remain uncertain, and its potential impacts on marine ecosystems are still widely debated (Chisholm et al., 2001). Additionally, there is ongoing discussion about the possibility of trading the extra carbon sequestered through ocean fertilization as carbon credits in global markets. Despite these considerations, ocean fertilization remains a controversial approach due to limited scientific understanding and unresolved environmental risks (Johnson et al., 2002).

4.2.2 Terrestrial carbon capture: Soil, forest and wetlands carbon sequestration-

Terrestrial carbon sequestration is the process of capturing atmospheric CO_2 and storing it in organic matter and soil carbon pools within land-based ecosystems. Of the 8.6 Pg C released annually into the atmosphere, about 3.5 Pg C, or roughly 40% of anthropogenic CO_2, is absorbed by terrestrial carbon sinks, which are not fully specified but play a vital role in regulating the global carbon cycle.

Terrestrial ecosystems act as major carbon sinks by using photosynthesis to capture CO_2 and store it in living biomass and decomposing organic matter. Beyond mitigating climate change, terrestrial carbon sequestration provides additional benefits, including improved soil fertility, enhanced water quality, restoration of degraded lands, and increased agricultural productivity. For these reasons, it is often described as a **win-win** or **no-regrets strategy** (Lal et al., 2003), offering multiple advantages even if climate change were not a concern.

The primary components of terrestrial carbon sequestration include:

1. **Soils**
2. **Forests**
3. **Wetlands**

4.2.3 Soil carbon sequestration:

Soil carbon sequestration involves enhancing the levels and storage of both **soil organic carbon (SOC)** and **soil inorganic carbon (SIC)**, including secondary carbonates, through various land management practices and land-use changes in agricultural, pastoral, and forest ecosystems. It also encompasses the rehabilitation of degraded or heavily disturbed soils. One approach includes the production of **charcoal** and the application of **biochar** as a soil amendment to improve fertility and store carbon (Fowles, 2007).

Unlike geological sequestration, which stores CO_2 deep underground at depths of 1–2 km, SOC sequestration focuses on carbon storage in the **topsoil**, typically within 0.5–1 m, through natural humification processes. In many managed ecosystems, SOC levels are lower than in natural ecosystems due to carbon depletion in cultivated soils. The most substantial SOC losses generally occur within the first 20–50 years following the conversion of natural ecosystems to agricultural lands in temperate regions, and within 5–10 years in tropical regions (Lal, 2001). On average, cultivated soils retain only 50–75% of their original SOC content. This depletion is mainly driven by processes such as **oxidation/mineralization, leaching, and soil erosion**.

4.2.4 Forest ecosystem: Carbon sinks-

Forest ecosystems serve as important carbon reservoirs due to the presence of lignin and other resistant polymeric compounds in vegetation. The current net carbon sequestration rate in forests, excluding areas affected by deforestation, is estimated at around 1.7 ± 0.5 Pg C per year (Fan et al., 1998). Carbon is stored not only in harvestable timber but also in woody debris, wood products, and woody plants encroaching into grasslands (Wofsy, 2001).

Rising atmospheric CO_2 levels have not yet saturated terrestrial **net primary productivity (NPP)** and may even enhance it through the **CO_2 fertilization effect** (Krishnamurthy & Machavaram, 2000). However, NPP saturation is predicted to occur at CO_2 concentrations of approximately 800–1,000 ppm (Falkowski et al., 2000), with the CO_2 fertilization effect on forest carbon uptake expected to peak around the mid-21st century. Nevertheless, further increases in CO_2 may be limited by nutrient constraints, including nitrogen, phosphorus, and water availability. Managing the interactions between carbon, nitrogen, phosphorus, and water cycles can help maximize terrestrial carbon sequestration.

Afforestation is recognized as an effective approach for sequestering carbon in terrestrial ecosystems (IPCC, 1999; Fang et al., 2001; Lamb et al., 2005). It is one of the 15 strategies proposed to stabilize atmospheric CO_2 at 550 ppm by 2050 (Pacala & Socolow, 2004). Modeling studies suggest that halting clear-cutting of primary tropical forests over the next 50 years could prevent approximately 0.5 Pg C emissions. Additionally, reforesting or afforesting around 250 million hectares in the tropics or 400 million hectares in temperate regions could sequester an additional 0.5 Pg C per year.

However, large-scale afforestation can have unintended consequences, such as reduced streamflow, soil salinization, and acidification (Jackson et al., 2005). The impacts on water availability must therefore be carefully evaluated when planning large-scale projects. Biodiversity loss is another concern, particularly when monoculture plantations are established, which can negatively affect ecosystem services (Bunker et al., 2005). Implementing regulatory frameworks, including carbon credit trading systems and permit processes, is essential. The overall costs of carbon sequestration, including opportunity costs, should also be considered in policy planning (McCarl & Schneider, 2001).

4.2.5 Wetlands: Carbon reservoirs-

Wetlands play a crucial role in carbon storage and sequestration, making them important ecosystems for mitigating greenhouse gas emissions and addressing climate change. Wetlands and their associated soils, often referred to as **histosols**, represent a major soil carbon pool, estimated at around 450 Pg C (Gorham, 1991; Warner et al., 1993). The carbon content in wetland soils can be up to 200 times higher than that of the aboveground vegetation (Milne & Brown, 1997; Garnett et al., 2001).

Since the post-glaciation period, wetlands and peat soils have sequestered carbon at an average rate of roughly 0.1 Pg C per year (Gorham, 1991; Kobak et al., 1998). However, human activities such as drainage and agricultural or forestry conversion have turned many peatlands into net sources of CO_2. Draining wetlands accelerates decomposition and soil subsidence, primarily due to oxidation, at rates of 1–2 cm per year (Rojstaczer & Deverel, 1995).

Restoration of wetlands can reverse these effects and re-establish them as effective carbon sinks. Nevertheless, it can take considerable time after restoration for the ecosystem processes to return to levels comparable to those of natural wetlands.

4.2.6 Secondary carbonates:

Soil carbon sequestration can occur not only through soil organic carbon (SOC) but also via **secondary carbonates (SIC)** and the leaching of bicarbonates into groundwater. Secondary carbonates appear in a variety of forms, including films, threads, concretions, pedants, laminar caps, caliche, and calcrete (Gile, 1993). In gravel-rich soils, they may coat the lower surfaces of stones and pebbles.

There are four primary mechanisms for secondary carbonate formation (Monger, 2002; Mermut & Landi, 2006). Marion et al. (1985) proposed that carbonates form when CO_2 dissolves in the soil surface, followed by the downward movement and re-precipitation of $CaCO_3$ and $MgCO_3$ in the subsoil. Sobecki and Wilding (1983) suggested that capillary rise of $CaCO_3$ from shallow groundwater can lead to re-precipitation in the surface layer. Rabenhorst and Wilding (1986) described a mechanism involving in situ dissolution and re-precipitation, while Monger (2002) observed that some secondary carbonates are **biogenic**, produced through the activity of soil organisms such as termites.

Secondary carbonates typically form in soils with pH values between 7.3 and 8.5, provided there is sufficient $CaCO_3$ and $MgCO_3$. Precipitation is favored by decreasing soil water content, reduced CO_2 or HCO_3^- partial pressure in soil air, and increasing concentrations of $CaCO_3$ or HCO_3^- in the soil. Compared to SOC, the formation of secondary carbonates occurs at a slower rate. For example, in the deserts of southwestern USA, Pleistocene-era deposition rates ranged from 1.2 to 6 kg C/ha/yr (Marion et al., 1985; Schlesinger, 1985). Other studies in the same region reported rates of 1.2–4.2 kg C/ha/yr (Schlesinger, 1985) and 1–14 kg C/ha/yr (Monger & Gallegos, 2000). In Saskatchewan, Canada, secondary carbonate deposition rates were estimated at 9.9–13.4 kg C/ha/yr (Landi, 2002). Non-calcareous soils generally exhibited lower deposition rates of 1.7–6.1 kg C/ha/yr (Machette, 1985), indicating higher formation in calcareous soils.

Another pathway for SIC sequestration is the **leaching of bicarbonates (HCO_3^-) into groundwater**, particularly in irrigated soils using high-quality water (Nordt et al., 2000). In such soils, HCO_3^- leaching can reach 0.25–1.0 Mg C/ha/yr (Wilding, 1999). With approximately 250 million hectares of irrigated land worldwide, the potential global contribution of bicarbonate leaching to carbon sequestration is estimated at 62.5–250 Tg C/yr.

While technological options to accelerate secondary carbonate formation are limited, the use of **organic amendments**—such as crop residue mulch, manure, and biosolids—can enhance the activity of soil fauna, promoting biogenic carbonate formation. In irrigated soils, the application of high-quality irrigation water can also help increase HCO_3^- leaching, further contributing to long-term carbon storage.

4.2.7 Biofuels:

Producing ethanol from biomass-derived sugars and converting plant oils and fats into biodiesel is an effective approach to decrease dependence on fossil fuels and promote sustainable energy alternatives (Himmel et al., 2007; Stephanopoulos, 2007; Wald, 2007). In 2004, the global primary energy supply totaled 11.2 Pg of oil equivalent, with oil contributing 35.03%, coal 24.6%, natural gas 20.44%, nuclear energy 6.33%, and renewable sources 13.61% (Goldemberg, 2007). Within renewables, traditional biofuels such as crop residues, wood products, and animal dung accounted for 2.48%, while modern biofuels represented 1.91%. Other renewable sources, including hydro, solar, wind, and geothermal energy, collectively supplied only 3.22% of global primary energy.

Biofuels play a significant role in both scientific and policy discussions and are linked to carbon sequestration in two main ways. First, converting degraded or marginal agricultural soils into energy plantations helps restore soil organic carbon (SOC) pools, enhancing soil carbon storage. Second, biofuel production cycles atmospheric CO_2 back into biomass, contributing to carbon mitigation. By selecting suitable plant species and applying careful management practices, energy plantations with dedicated crops such as poplar, willow, switchgrass, miscanthus, karnalgrass, Andropogon, and Pennisetum can sequester carbon in soils, offset fossil fuel emissions, and slow the accumulation of atmospheric CO_2 and other greenhouse gases (GHGs).

Despite these advantages, concerns remain about potential competition for land and water resources required to establish energy plantations, highlighting the need for sustainable planning and management.

V. ADVANTAGES AND DISADVANTAGES OF CARBON SEQUESTRATION

5.1 Biotic Carbon Sequestration:

- Involves the removal of atmospheric CO_2 through natural processes like photosynthesis.

- Woody plants and managed ecosystems are expected to sequester more CO_2 in the future due to the CO_2 fertilization effect.
- Can be enhanced through proper nutrient management (N, P, K, Ca, Mg, S, Zn, Cu, Mo) and efficient water management.
- Offers multiple co-benefits, including:
  - Improved soil and water quality
  - Reduced nutrient losses
  - Decreased soil erosion
  - Enhanced wildlife habitat
  - Increased water conservation
  - Restoration of degraded soils
  - Improved efficiency of agricultural inputs

5.1.1 Soil carbon sequestration includes both:

- Soil Organic Carbon (SOC)
- Secondary Inorganic Carbon (SIC)

5.1.2 Benefits of SOC sequestration:

- Enhanced soil structure and fertility
- Greater plant-available water
- Increased nutrient storage
- Detoxification of pollutants
- Climate moderation
- Higher agricultural productivity and food security
- Increased aesthetic and economic value of land

5.1.3 Recommended management practices (RMPs) for agricultural and forest soils exist for most ecoregions (IPCC, 1999).

5.1.4 Limitations:

- Total terrestrial capacity is relatively low (estimated 50–100 Pg C over 25–50 years) (Lal, 2004a,b).
- Carbon can be re-released due to soil management changes (e.g., ploughing) or land-use changes (e.g., deforestation).

5.2 Abiotic Carbon Sequestration:

- An engineered process involving technologies for CO_2 capture and storage.
- Includes deep injection of CO_2 into:
  - Oceans
  - Geological formations
  - Coal seams
  - Oil wells
- Current challenges:
  - High costs of implementation

- Risks of CO_2 leakage
- Need for careful monitoring and measurement
- Potential ecological impacts
- Regulatory and legal requirements

5.2.1 Advantages:

- Enormous storage capacity, potentially exceeding fossil fuel carbon reserves (thousands of Pg C).

5.2.2 Complementary to biotic sequestration:

- Biotic methods provide immediate, cost-effective mitigation
- Abiotic methods offer long-term, large-scale carbon storage potential
- Ecosystem-specific approaches may utilize both methods together.

5.3 Integration:

- Biotic sequestration is already accessible and can be implemented immediately.
- Abiotic sequestration, combined with carbon-neutral energy production, will become a viable alternative in the near future.
- Together, these strategies can reduce atmospheric CO_2 and mitigate climate change impacts effectively.

VI. CONCLUSION

Natural terrestrial and oceanic carbon sinks currently absorb roughly 60% of the 8.6 Pg C emitted annually. However, these sinks alone are insufficient to offset anticipated anthropogenic CO_2 emissions. Increasing the carbon storage capacity of managed ecosystems—such as forests, soils, and wetlands—requires careful land-use planning and the adoption of Resource Management Practices (RMPs). Effective biotic or terrestrial carbon sequestration depends on managing biological processes and understanding the interactions between carbon, water, and other nutrient cycles.

Abiotic sequestration techniques, including direct injection of CO_2 into oceans or geological formations and mineral carbonation to form stable carbonates, provide significant potential for long-term storage. While these engineering-based methods are under development and may become widely available by 2026, further research is needed to make them cost-efficient, minimize leakage risks, and reduce environmental impacts.

Human dimensions, such as policy frameworks, regulatory oversight, measurement, monitoring, carbon residence time, and carbon credit systems, are critical considerations for implementing both biotic and abiotic sequestration strategies. Alongside carbon sequestration, reducing emissions through carbon-neutral technologies is essential. This includes adopting energy-efficient production and consumption practices and exploring renewable fuels, such as bioethanol, biodiesel, methane from anaerobic digesters, and hydrogen derived from biomass.

Carbon sequestration offers multiple benefits: mitigating climate change, enhancing soil health to support plant growth, and improving food security. Environmental factors—such as temperature, precipitation, and elevated atmospheric CO_2—affect soil organic matter (SOM) decomposition, while soil texture significantly influences the accumulation of soil organic carbon (SOC). Agricultural practices impact SOC differently depending on soil characteristics, including physical and biological properties. Conservation tillage, combined with suitable crop rotations and the inclusion of legumes, can improve soil organic content and boost SOC storage.

Overall, carbon sequestration strategies contribute to sustainable agriculture by enhancing soil health, reducing pollutant loads, and lowering atmospheric CO_2 concentrations.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Effect of Compost and Fertilizer on Growth, Yield and Quality of Broccoli

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Abstract— *The aimed of the investigation was to evaluate the impact of various organic and inorganic treatments on the growth and yield of broccoli. The experiment utilized a Randomized Complete Block Design (RCBD) with three replications. Five treatment setups were employed: T_1 = Control (Recommended doses of fertilizers: Urea: 250; TSP: 150; MoP: 200; and Boric acid: 12 kg/ha); T_2 = Vermicompost (5 t/ha) + ¼ RDF; T_3 = Vermicompost (3 t/ha) + ¼ RDF; T_4 = Trichocompost (5 t/ha) + ¼ RDF; T_5 = Trichocompost (3 t/ha) + ¼ RDF. The results revealed significant differences across treatments. Vermicompost (T_2) consistently produced the highest values. For all 30, 45 and 60 DAT, T_2 had the tallest plant height (48.18, 63.80 and 64.00 cm), the most leaves (12.60, 15.60 and 15.62), the largest stem diameter (2.14, 2.40 and 2.62 cm), the longest leaf length (43.32 and 52.98 cm), and the greatest leaf breadth (17.58, 21.26 and 22.38 cm). T_2 achieved the highest yield (4.32 kg/plot; 21.33 t/ha), outperforming all other treatments, while T_1 produced the lowest (3.20 kg/plot; 15.80 t/ha). TSS was recorded the highest in T_2 (9.83°Brix), with high ascorbic acid content (88.32 mg/100 g), maximum protein (4.34%), iron content in T_2 (1.44 mg/100 g) and calcium content (47.60 mg/100 g). These findings demonstrated the potential of T_2: Vermicompost (5 t/ha) with 1/4 of the recommended doses of fertilizers (RDF) to be a recommendable fertilizer management practice to boost broccoli productivity and also demonstrate its significance in reducing production cost for farmers.*

Keywords— ***Vermicompost, Trichocompost, Organic, Yield, Broccoli.***

I. INTRODUCTION

About 2.82% of the total land area of Bangladesh is usually involved for vegetable production with a yield of 3.73 million tonnes of vegetables (BBS, 2024). Broccoli (*Brassica oleracea* L. var. *italica*) has become a high-value vegetable crop of growing attention in Bangladesh. It is a member of the Brassicaceae family, involving such products as cabbage, cauliflower and kale (Rabbee *et al*., 2020). Broccoli is a Mediterranean crop, and it is appreciated for its healthy value. It is rich in vitamins A, C, and E and minerals (calcium, iron, and zinc) (Hamza and Al-Taey, 2020). China is the biggest producer of broccoli globally, and it produces approximately 43% of the total (FAO, 2022). In Bangladesh approximate production of cauliflower and broccoli rose 16.2% to 342000 tonnes in the year 2022 (FAOSTAT, 2022). In Bangladesh, production and productivity levels, as well as quality, are highly dependent on the soils and their management. To boost the harvest, farmers regularly use excessive levels of chemical fertilizers, which harm the environment and degrade the soil health (Singh *et al*., 2021).

The effect of compost and fertilizer on the growth and yield of broccoli has been extensively studied, revealing significant benefits from both organic and inorganic amendments; compost usually enhances soil chemical properties, leading to increased nitrogen content, which is crucial for broccoli's growth (Aouass & Kenny, 2022). It has been observed that organic and chemical fertilizers used in a proper balance contribute to sustainable output and lower the degradation of the environment (Al-Taey *et al*., 2019).

Excessive use of chemical fertilizers in broccoli fields has raised concerns about overall soil health and environmental sustainability, causing a shift toward organic fertilizer management practices (Islam *et al.*, 2024; Meem *et al.*, 2024). Vermicompost is produced through the decomposition of organic matter by earthworms. Among available organic fertilizers, vermicompost has gained attention for its ability to enhance soil fertility, microbial activity, and plant growth, leading to improved yield and quality in broccoli and other crops (Rehman *et al.,* 2023; Blouin *et al.,* 2019). Studies consistently report that vermicompost application improves plant height, leaf number, and biomass in broccoli due to enhanced nutrient availability and improved soil structure (Rabbee *et al.,* 2020). Vermicompost improves soil structure, microbial activity, and nutrient supply (Manzoor *et al.,* 2024). Yield increases are attributed to better root development and increased nutrient uptake, with some studies noting up to 20-30% higher yields in vermicompost-treated plots (Alkobaisy *et al.,* 2021). Trichocompost, generated by incorporating *Trichoderma* species in the composting process, supplements nutrients and also acts as a natural biocontrol agent, and *Trichoderma* helps resistance against soil-borne pathogens and promotes plant vigour (Tarafder *et al.,* 2022). Trichocompost can enhance broccoli growth parameters and yield, often by improving disease resistance and stimulating root growth (Islam *et al.,* 2024).

Both vermicompost and trichocompost can be used as key growth promoters, such as for plant height, leaf number, curd initiation, and marketable yield in broccoli, often outperforming conventional fertilizers and other organic manures (Tarafder *et al.,* 2022; Alkobaisy *et al.,* 2021). The integration of these organic manures helps to promote sustainable agriculture, supporting soil health, reducing environmental impact, and achieving the growing consumer demand for organic vegetables (Rehman *et al.,* 2023). Given the increasing demand for organic vegetables and sustainable soil management practices in Bangladesh, optimizing fertilizer management practices for broccoli is important. This study aims to assess the effect of vermicompost on broccoli growth and yield, evaluate the effect of trichocompost on broccoli growth and yield and examine the combined impact of compost and inorganic fertilizer on broccoli growth and yield.

II. MATERIALS AND METHODS

2.1 Site Description:

The research was carried out at the Horticulture Farm, Sher-e-Bangla Agricultural University, Dhaka, Bangladesh, located at 23.074° N latitude and 90.035° E longitude, 8.2 meters above sea level, and was conducted during the rabi season, from October 2022 to March 2023. The field belongs to the Modhupur Tract Agro-Ecological Zones (AEZ-28), characterized by red clay loam soils developed over Modhupur clay with small hillocks surrounded by floodplains. The soil was sandy loam with moderate fertility and a pH of 6.3.

2.2 Experimental Design:

The experiment followed a Randomized Complete Block Design (RCBD) with five replications and five treatments. The total number of plots was 25. Each plot measured 1.5 m × 1.35 m, with 0.5 m spacing between plots and 1.0 m spacing between blocks. Plant spacing was 50 cm between rows and 45 cm between plants (9 plants per plot).

2.3 Seedbed, Field Preparation and Sowing:

The broccoli variety *Gloria F1 Hybrid* was used. A seedbed (3 m × 1 m) was prepared on October 1, 2022. Soil was treated with Sevin 50 WP (5 kg/ha) to control soil insects. Seeds were sown on October 12, 2022, at a depth of 2 cm with 5 cm line spacing. The seedbed was covered with thin polythene to maintain moisture. Seeds were treated with Provax 200 WP at 3 g/kg to prevent fungal diseases such as blight and anthracnose. Seedlings were watered regularly and kept weed-free without chemical inputs. 30-day-old healthy seedlings were transplanted to the main field on November 17, 2022. The field was ploughed, harrowed, and levelled for good tilth. It was exposed to sunlight for a week to reduce soil-borne pathogens. Basal fertilizers were applied during the final ploughing.

2.4 Fertilizer Application:

Fertilizers were applied following the Bangladesh Agricultural Research Institute (BARI, 2025) recommendation. The nutrient doses were: Urea: 250 kg/ha; TSP: 150 kg/ha; MoP: 200 kg/ha; and Boric acid: 12 kg/ha. Full TSP and boric acid were applied at final land preparation. Urea and MoP were applied in two equal splits at 15 and 35 days after transplanting (DAT).

2.5 Treatments:

T_1= Control (Recommended doses of fertilizers: Urea: 250; TSP: 150; MoP: 200; and Boric acid: 12 kg/ha); T_2= Vermicompost (5 t/ha) + ¼ RDF; T_3= Vermicompost (3 t/ha) + ¼ RDF; T_4= Trichocompost (5 t/ha) + ¼ RDF; T_5= Trichocompost (3 t/ha) + ¼ RDF.

2.6 Vermicompost and Trichocompost Application:

Vermicompost was prepared using cowdung, crop residues, and organic wastes through *Eisenia fetida* earthworms at the Horticulture Farm. It was applied before transplanting at the prescribed rates. Trichocompost was collected from ACI Biotech, Dhaka. It was prepared using *Trichoderma harzianum* mixed with cowdung, poultry litter, and plant residues.

2.7 Crop Management and Harvesting:

Seedlings with 5/6 true leaves were transplanted in the afternoon in the main field. Intercultural operations included weeding, earthing-up, irrigation, and pest control. Hand weeding was done at 15, 30, 45, and 60 DAT. Irrigation was applied as needed to maintain soil moisture. Harvesting of broccoli heads began at 70 DAT when they reached marketable size and firmness.

2.8 Data Collection:

2.8.1 Growth characteristics:

- **Plant height (cm) at 30, 45, and 60 DAT:** Plant height was observed from 30 days after transplanting (DAT) to 60 DAT at intervals of 15 days. The height of broccoli plants was measured by starting from the ground to the tip of the longest stem for 9 plants, and the average value was then calculated and recorded in centimeters.
- **Number, length, and breadth of leaves at 30, 45, and 60 DAT:** The number of leaves on each plant was counted and recorded. The lengths of plant leaves from the base of the leaves to the tip and the breadth of leaves on each plant were measured from the widest part of the leaf; the average value was then calculated and recorded in centimeters. The data was collected by averaging the counts from nine plants in each plot. This process was carried out at intervals of 15 days, from 30 days after transplanting (DAT) to 60 DAT.
- **Stem diameter (cm) at 30, 45, and 60 DAT:** Stem diameter was measured at the point where the central head was cut off. The diameter of the stem was recorded with slide calipers and the average of nine values was taken into account and was expressed in centimeters (cm).

2.8.2 Yield and yield contributing characteristics:

- **Head length, breadth and head stem diameter (cm):** Heads from each plant, the length and breadth and the stem diameter of the head were measured and recorded in centimeters.
- **Head weight (g):** The weight of the central head was recorded, excluding the weight of all secondary curds, and expressed in grams.
- **Dry matter content of heads (%):** The fresh weight of the head was recorded, and 100 g of head were taken from the central portion of each head and dried in an oven at 70°C for 72 hours after sun drying for two days. The final weight of the sample was taken and expressed as percent dry matter content.

$$\text{Percent dry matter content (DMC)} = \frac{\text{Oven dry weight of head (g)}}{\text{Fresh weight of head (g)}} \times 100 \quad (1)$$

- **Yield per plant (kg), per plot (kg), and per hectare (t):** The yield per plant was calculated by averaging the weights of nine harvested heads and expressed in kilograms (kg). The yield per unit plot was calculated by adding the yields of all plants of each plot and expressed in kilograms (kg). The yield of head per hectare was calculated by conversion of the weight per plot and recorded in tonnes (t/ha).

2.8.3 Quality characteristics:

- **Total soluble solid (°Brix):** For estimation of TSS content of broccoli, a digital refractometer (MA871; Romania) was used. A drop of broccoli grind was obtained by dropper and placed on the refractometer prism. The refractometer showed a reading of total soluble solids. The refractometer readings were recorded for nine samples, and the average value was recorded in °Brix.

- **Ascorbic acid (mg/100 g):** For the determination of vitamin C content, 10 g of broccoli was ground and homogenized in 100 ml of cold metaphosphoric acid (HPO_3) using a blender for two minutes and filtered through Whatman filter paper No. 2. The clear supernatant was collected for assaying ascorbic acid content by the 2, 6-dichlorophenolindophenol titration method (AOAC, 2005). The vitamin C content of the sample was calculated using the following formula:

$$\text{Vitamin C content (mg/100g)} = \frac{(T \times d \times V1)}{(V2 \times W)} \times 100 \tag{2}$$

Where, T = Titre value (ml), d = Dye factor, V1 = Volume to be made (ml), V2 = Volume of extract taken for titration (ml) and W = Weight of sample taken for estimation (g)

- **Protein (%):** Protein content was determined using the AOAC (2005) method. The protein content of the sample on a percentage basis was calculated by using the following formula:

$$\text{Nitrogen (\%)} = \frac{(C-b) \times p \times 0.014 \times d}{\text{Sample weight}} \times 100 \tag{3}$$

Where, c = reading of the sample, b = blank reading, p = strength of the HCL solution, d = conversion factor (6.25 for vegetables)

Nitrogen percentage was converted into protein by multiplying with a factor 6.25.

- **Iron (mg/100 g) and Calcium (mg/100 g):** Iron and calcium were measured by using the Atomic Absorption Spectroscopy method by hollow cathode lamp at wavelengths of 248.3 nm and 422.7 nm, respectively, using an air acetylene flame, and the measurement results must be within the concentration range of the series solution of standard iron and calcium. The treatment for each sample was repeated five times (AOAC, 2005).

$$\text{Iron/Calcium content (mg/100g)} = \frac{\text{Total concentration} \times \text{dilution factor}}{10 \times \text{sample weight} \times \text{dry factor (D.F)}} \times 100 \tag{4}$$

Where, Drying factor (D.F) = Fresh wt./Dry wt.

2.9 Statistical Analysis:

Data were analyzed using Statistix software (version 10). The mean differences among treatments were tested using ANOVA, and the LSD test was used at a 5% significance level.

III. RESULTS

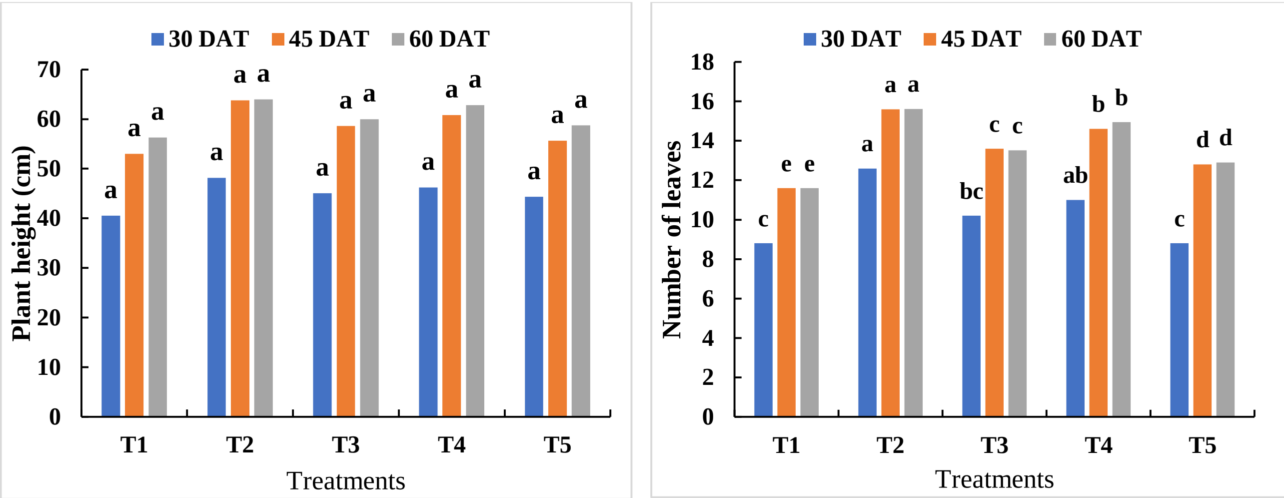
3.1 Growth Characteristics:

3.1.1 Plant height (cm):

Plant height was non-significant among treatments at 30, 45, and 60 DAT (Figure 1A). Although no statistical separation was observed, broccoli plants treated with vermicompost at 5 t ha^{-1} with ¼ RDF (T_2) resulted in the highest plant height (48.18, 63.80, and 64.00 cm) at all growth stages, followed by trichocompost-based treatments (T_4 and T_5). The slight improvement in vegetative growth under organic amendments aligns with earlier reports that showed vermicompost enhances soil nutrient availability and root activity, thereby improving plant stature in *Brassica* crops (Singh *et al.*, 2021).

3.1.2 Number of leaves:

The number of leaves showed significant differences at 30, 45, and 60 DAT ($p < 0.05$). T_2 produced the highest number of leaves at 30, 45, and 60 DAT (12.6, 15.6, and 15.62 leaves), followed by T_4 and T_3 (Figure 1B). The control (T_1) produced the lowest leaf numbers. The higher leaf production under vermicompost and trichocompost treatments supports previous studies that showed organic amendments improve leaf initiation and canopy expansion through enhanced nitrogen mineralization (Kumar *et al.*, 2023). Increased leaf area and number are linked to improved photosynthetic capacity in broccoli (Syed *et al.*, 2023).



(A) **(B)**

FIGURE 1: Impact of recommended doses of fertilizers (RDF), vermicompost, trichocompost on (A) height of plants (B) number of leaves of broccoli at different days after transplanting (DAT). Different letters within a trait indicate significant differences ($p < 0.05$)

3.1.3 Leaf length (cm):

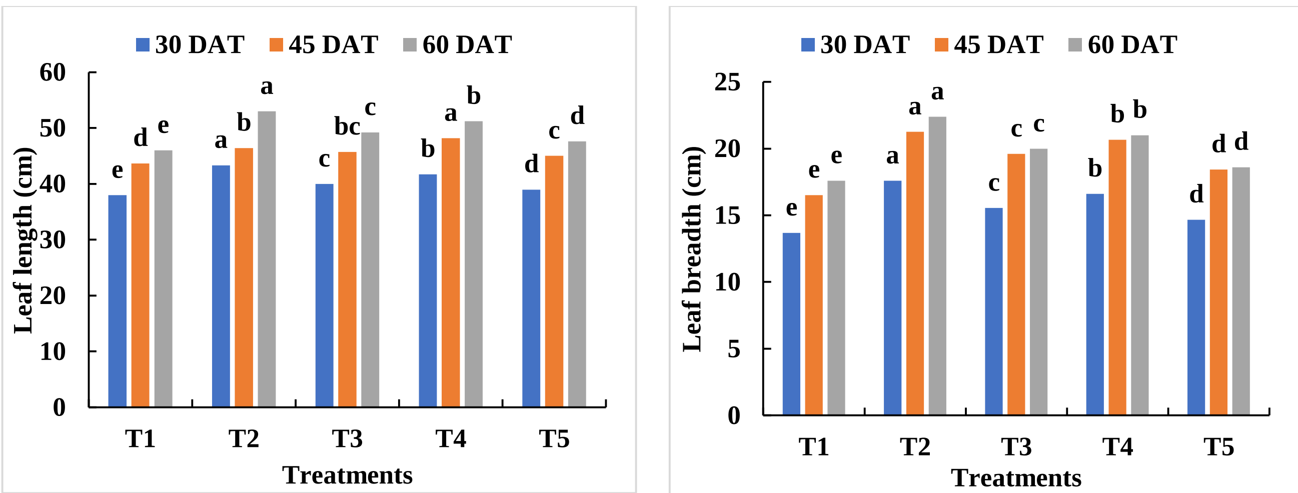
Leaf length resulted in a significant difference at 30, 45, and 60 DAT ($p < 0.05$). T_2 produced the longest leaves at 30 and 60 DAT (43.32 and 52.98 cm), followed by T_4 and T_3, whereas T_1 and T_5 recorded the shortest leaves (Figure 2A). The results indicate that organic fertilizers with partially subsidized RDF enhance vegetative vigour of broccoli. Previous studies show that vermicompost improves leaf expansion through increased cytokinin-like activity and better soil moisture retention (Ievinsh, 2020).

3.1.4 Leaf breadth (cm):

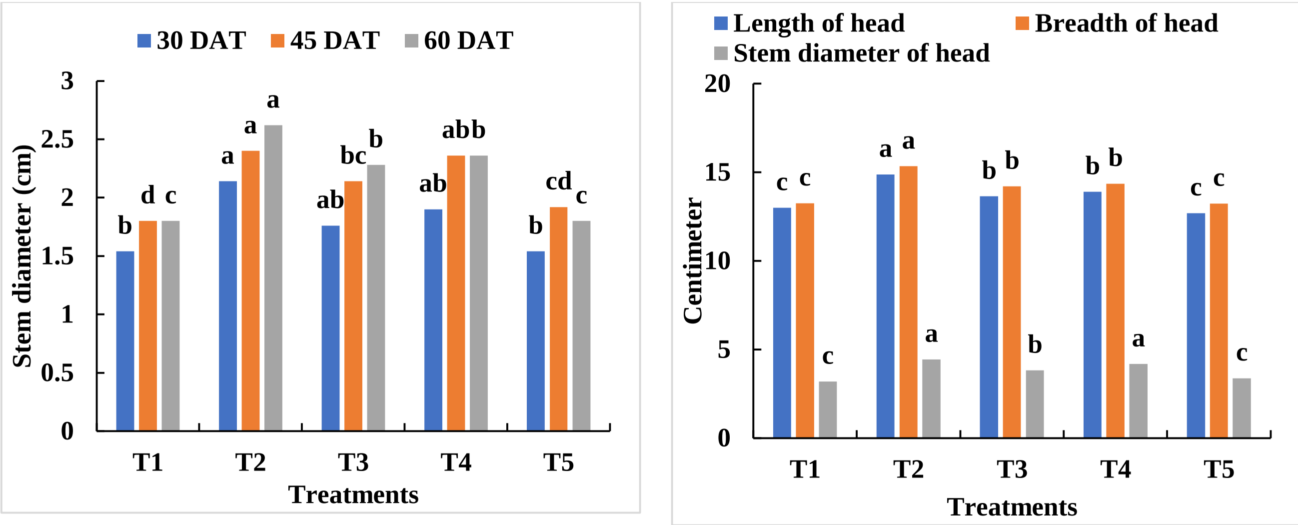
The widest leaves were recorded in T_2 across 30, 45, and 60 DAT (17.58, 21.26, and 22.38 cm), followed by T_4 and T_3 (Figure 2B). The control exhibited the narrowest leaves. Vermicompost treatments ensured wider leaf surfaces were consistent with previous reports indicating improved chlorophyll synthesis due to enhanced soil biological activity and nutrient availability (Suruban *et al.*, 2022; Ievinsh, 2020).

3.1.5 Stem diameter (cm):

Stem diameter varied significantly among treatments at 30, 45, and 60 DAT (Figure 2C). T_2 achieved the thickest stem (2.14, 2.40, and 2.62 cm) at 30, 45, and 60 DAT, followed by the treatment of T_4 and T_3. The control and the trichocompost treatment (T_5) recorded the lowest stem diameters for all 30, 45, and 60 DAT. A better stem diameter is suitable for nutrient transport and structural support in broccoli plants. Vermicompost plays a vital role in increasing stem diameter is well recorded, as its microbial activity stimulates cell division and stem tissue development (Aman *et al.*, 2022).



(A) **(B)**



(C) (D)

FIGURE 2: Impact of recommended doses of fertilizers (RDF), vermicompost, trichocompost on (A) leaf length (B) leaf breadth (C) stem diameter (D) length of head, breadth of head, stem diameter of head of broccoli at different days after transplanting (DAT). Different letters within a trait indicate significant differences ($p < 0.05$)

3.2 Yield and Yield Components:

3.2.1 Length of head (cm):

T_2 achieved the greatest head length (14.88 cm), followed by T_4 and T_3, whereas T_1 and T_5 produced shorter heads (Figure 2D). The improvement in head morphology under vermicompost is similar to the findings of Ievinsh (2020), who mentioned that vermicompost improves plant vigour and reproductive organ development through enhanced enzymatic and hormonal activity.

3.2.2 Breadth of head (cm):

Head breadth also varied significantly among all treatments, with T_2 producing the widest heads (15.34 cm), followed by T_4 and T_3, while T_1 and T_5 showed the narrowest heads (Figure 2D). These findings are consistent with observations of organic amendments improving chlorophyll content, leaf expansion, and assimilate allocation, key drivers of head enlargement in broccoli (Ievinsh, 2020).

3.2.3 Stem diameter of head (cm):

Stem diameter showed a significant response to treatment ($p < 0.05$). T_2 and T_4 produced the largest diameters (4.44 cm and 4.18 cm, respectively), while T_1 and T_5 had significantly lower values (Figure 2D). Improved stem diameter after vermicompost and trichocompost application enhanced cell division and structural tissue development supported by humic substances and microbial metabolites (Aman *et al*., 2022).

3.2.4 Head weight (g):

The highest head weight was recorded in T_2 (478.8 g), followed by T_4 (443.6 g) and T_3 (424.4 g), while the control (T_1) produced the lowest value (357.2 g) (Table 1). The superior performance of vermicompost at 5 t ha^{-1} + ¼ RDF is consistent with earlier studies reporting improved nutrient mineralization and soil microbial activity that enhance biomass and head development in broccoli (Kumar *et al*., 2023; Aman *et al*., 2022). The enhanced nutrient uptake associated with vermicompost application has also been shown to increase curd formation and overall yield in *Brassica* crops.

3.2.5 Dry matter content of head (%):

Dry matter content (DMC) of heads was significantly different ($p < 0.05$), with T_2 producing the highest DMC (14.72%), followed by T_4 and T_3. The lowest DMC was observed in T_1 (11.12%) (Table 1). Higher dry matter resulted from organic nutrient sources, drawing a parallel with findings that indicate improved carbohydrate synthesis and soil nutrient accumulation when vermicompost is applied (Suruban *et al*., 2022).

3.2.6 Yield per plant (kg):

Yield per plant increased significantly under all organic treatments ($p < 0.05$). T_2 recorded the highest yield (0.48 kg), followed by T_4 and T_3, while T_1 produced the lowest yield (0.36 kg) (Table 1). Yield improvements with vermicompost followed the results of Aman *et al*. (2022), who showed that integrated organic and inorganic nutrient management enhances nutrient uptake efficiency.

3.2.7 Yield per plot (kg) and yield (t/ha):

Yield per plot and per hectare followed a similar trend, with T_2 achieving the highest yield (4.32 kg/plot; 21.33 t/ha), significantly outperforming all other treatments (Table 1). The second highest yields were recorded in T_4 and T_3, while T_1 produced the lowest (3.20 kg/plot; 15.80 t/ha). Similar findings in broccoli yield treated with vermicompost have been reported by Singh *et al*. (2021), who found that organic nutrient sources enhance soil structure, cation exchange capacity and long-term fertility, which eventually contribute to higher yields in broccoli.

TABLE 1
Effect of recommended doses of fertilizers (RDF), vermicompost, trichocompost on head weight (g), dry matter content of head (%), yield/plant (kg), yield/plot (kg) and yield (t/ha) of broccoli

Treatment	Head weight (g)	Dry matter content of head (%)	Yield/Plant (kg)	Yield/Plot (kg)	Yield (t/ha)
T_1	357.20 e	11.12 d	0.36 e	3.20 b	15.80 b
T_2	478.80 a	14.72 a	0.48 a	4.32 a	21.33 a
T_3	424.40 c	13.42 b	0.43 c	3.86 ab	19.06 ab
T_4	443.60 b	13.66 b	0.45 b	4.22 a	20.84 a
T_5	396.00 d	12.70 c	0.40 d	3.6 ab	17.78 ab
Level of Sig.	**	**	**	**	**
LSD (0.05)	3.76	0.37	0.05	0.73	3.6
CV (%)	0.67	2.07	0.48	14.16	14.16

[Values in the column with distinct letters showed significant differences according to the LSD at a 5% level of significance. Here, T_1= Control (Recommended doses of fertilizers: Urea: 250; TSP: 150; MoP: 200; and Boric acid: 12 kg/ha), T_2= Vermicompost (5 t/ha) + ¼ RDF, T_3= Vermicompost (3 t/ha) + ¼ RDF, T_4= Trichocompost (5 t/ha) + ¼ RDF, T_5= Trichocompost (3 t/ha) + ¼ RDF]

3.3 Quality Characteristics:

3.3.1 Total soluble solid (°Brix):

TSS recorded significant differences under all treatments ($p < 0.05$) and demonstrated that T_2 (vermicompost 5 t/ha + ¼ RDF) produced the highest °Brix (9.83), noticeably higher than the control treatment (T_1, 6.35) (Table 2). Findings suggest that organic fertilizer management with vermicompost is likely to improve the total soluble solid content of broccoli heads (Tiwari *et al.*, 2024).

3.3.2 Ascorbic acid (mg/100 g):

T_2 resulted in high ascorbic acid content (88.32 mg/100 g), significantly different from the control treatments (83.62 mg/100 g) (Table 2). This finding supports previous studies showing integrated nutrient management, combining vermicompost and biofertilizers in broccoli, led to increased ascorbic acid compared to control or full chemical fertilization (Tiwari *et al.*, 2024).

3.3.3 Protein (%):

Protein (%) showed a significant difference in T_2 (4.34%) compared to the control treatment (2.80%) (Table 2). This indicates that reduced chemical fertilizer plus vermicompost supports better nitrogen assimilation into proteins (Wadmare *et al.*, 2019).

3.3.4 Iron (mg/100 g):

Iron content in T_2 (1.44 mg/100 g) resulted in approximately 1.6 times the control treatment (0.87) (Table 2). This indicates vermicompost strongly improves iron uptake or accumulation (Mashkey *et al.*, 2024).

3.3.5 Calcium (mg/100 g):

Calcium content increased significantly for T_2 (47.60 mg/100 g) compared with the control treatment (31.20 mg/100 g) (Table 2). Results indicate that vermicompost application enriched Ca accumulation. The general effect of organic manures on mineral enrichment was observed as the organic matter improves cation exchange capacity and root growth (Mashkey *et al.*, 2024).

TABLE 2
Effect of recommended doses of fertilizers (RDF), vermicompost, trichocompost on total soluble solid (°Brix), ascorbic acid (mg/100 g), protein (%), iron (mg/100 g) and calcium (mg/100 g) content of broccoli

Treatment	Total soluble solid (°Brix)	Ascorbic acid (mg/100 g)	Protein (%)	Iron (mg/100 g)	Calcium (mg/100 g)
T_1	6.35 c	83.62 b	2.80 c	0.87 b	31.20 e
T_2	9.83 a	88.32 a	4.34 a	1.44 a	47.60 a
T_3	7.88 bc	86.48 a	3.61 b	0.90 b	42.00 c
T_4	8.02 b	88.29 a	4.01 ab	1.02 b	45.00 b
T_5	7.85 bc	87.67 a	3.58 b	0.92 b	37.00 d
Level of Sig.	**	**	**	**	**
LSD (0.05)	1.54	2.7	0.5	0.2	1.4
CV (%)	14.41	2.31	10.13	14.15	2.57

[Values in the column with distinct letters showed significant differences according to the LSD at a 5% level of significance. Here, T_1= Control (Recommended doses of fertilizers: Urea: 250; TSP: 150; MoP: 200; and Boric acid: 12 kg/ha), T_2= Vermicompost (5 t/ha) + ¼ RDF, T_3= Vermicompost (3 t/ha) + ¼ RDF, T_4= Trichocompost (5 t/ha) + ¼ RDF, T_5= Trichocompost (3 t/ha) + ¼ RDF]

IV. DISCUSSION

Vermicompost improves root growth, nutritional availability and water capacity because it has abundant microbial composition and humic compounds (Singh *et al*., 2021). Such mechanisms tend to cause small yet significant vegetation growth even in cases in which the statistical evidence is not striking. Nitrogen is extremely important in the development of chlorophyll and the initiation of leaves, and a gradual degradation of nitrogen in vermicompost promotes the continuous vegetation cover (Kumar *et al*., 2023). These results are consistent in agreement with increasing leaf counts with T_2, and it is evident that there is high-rate nutrient-use efficiency with integrated organic-inorganic nutrient management.

The large growth in the diameter of the stem during T_2, T_3, and T_4 indicates that nutrient sources that were composed of compost enhanced the growth of the structure. Vermicompost contains the humic substances and growth-promoting metabolites that stimulate cell division and tissue differentiation (Aman *et al*., 2022). Moisture trapping of the soil, nutrient uptake and the stimulation of hormones directly affects the growth of the leaf - all of which are enhanced by vermicompost (Ievinsh, 2020). The increased surface area of the leaves helps in supporting elevated assimilate production as the number of the leaves is increased. This is in line with previous results in *Brassica* species that organic inputs stimulate the growth of the leaf and canopy, which are critical in the formation of the head.

The strongest response to treatment was in the case of head weight, where T_2 generated significantly heavier head weight compared to all other treatments. This is because the vermiculite quality, which enhances the nutrient mineralization, microbial enzyme activity, and cation exchange capacity, makes it superior to use (Aman *et al*., 2022). All these mechanisms increase partitioning of assimilates to reproductive structures. According to Kumar *et al*. (2023), the current findings were corroborated by the authors who have noted a comparable increase in the head weight and marketable yield of broccoli in nutrient regimes obtained through vermicompost. The increase of the head length and breadth in T_2, T_3 and T_4 is a factor that shows that T_2, T_3 and T_4 with organic amendments have enhanced morphological development in broccoli curds. The growth of the size of the head in organic treatments indicates that the treatment enhanced the reproduction of the body and the partitioning of nutrients. The larger diameter of the head stem in both T_2 and T_4 was observed under high nutrient status of the compost. The presence of a heavier stem at the junction of the head makes the translocation of water and nutrients easier in making curd. This result is also in line with Aman *et al*. (2022), who discovered that the use of vermicompost enhances the development of vascular tissues in the *Brassica* crops. The enhanced yields of organic-amended armaments can be accounted for by the enhanced stem diameter.

Increased DMC of heads under T_2, T_3, and T_4 suggested superior accumulation of carbohydrates. The property of vermicompost as being able to promote nutrient cycling through microbes leads to better carbon assimilation and location of carbon in edible tissues (Ievinsh, 2020). Better quality, firmness, and storability of broccoli have been linked with increased head DMC, proving that organic sources of the nutrients are better. The content of leaf dry matter resembled exactly head DMC, proving that these amendments enabled better physiological efficiency by organic amendment. The increase in DMC in T_2 and T_3 treatments resulted in better chlorophyll activity and nitrogen uptake (Singh *et al*., 2021).

The head weight per plant was significantly higher under the treatments of vermicompost and trichocompost, with the highest yield per plant being the T_2. Aman *et al*. (2022) proved that vermicompost enhances the efficiency of nutrient utilization and growth of the biomass, which is closely connected with the presented results. The agronomic benefit of partially replacing inorganic fertilizer by organic amendments is indicated by the considerably increased plot and hectare yields of T_2 and T_4. The results are similar to Singh *et al*. (2021), who have stated that soil fertility and long-term productivity increase when there is a combination of vermicompost with a low level of chemical fertilizer. The yield-related traits of head length, breadth, stem diameter, and head weight were highest in T_2, while trichocompost treatments (T_4, T_5) also improved on the control. Yield per plant and yield per hectare were the highest in T_2, which supports the idea that vermicompost helps supply nutrients and supports curd growth when applied along with partial RDF (Hasan *et al.,* 2024; Dhatt *et al.,* 2022). The improved dry matter content and weight further support the notion that organic amendments enhance yield and quality, which is supported by various reports (Meem *et al.,* 2024). The low values for the control group demonstrate the necessity of providing organic nutrients for optimal broccoli production. It is most effective to use vermicompost (5 t/ha) and only 1/4 of the chemical fertilizer recommended to increase several qualities like sugar (°Brix), vitamin C, protein, iron, and calcium content (Mashkey *et al.,* 2024; Kumar *et al.,* 2023; Wadmare *et al.,* 2019). This practice recommends organic fertilizer management combined with low chemical fertilizers to help enhance nutritional values by decreasing synthetic fertilizer use. Vermicompost, particularly when combined with partially recommended fertilizer, delivers superior growth, yield and quality in broccoli, with trichocompost providing significant benefits. These findings are strongly supported by recent research and highlighted the value of integrating organic fertilizer management for sustainable and productive broccoli cultivation.

V. CONCLUSION

The use of trichocompost and vermicompost, with 1/4 of the recommended doses of fertilizers (RDF), has the potential to be a valuable agricultural activity for improving broccoli productivity. While this method demonstrates increases in crop yield, it also provides much-needed assistance to farmers. The use of vermicompost and trichocompost has demonstrated positive and synergistic effects on soil health, nutrient availability, and plant growth, which ultimately led to increases in broccoli yield. Farmers are constantly challenged to ensure food security and sustainability in agricultural practices, and incorporating these types of integrated ideas provides long-term hope for regenerative and productive farming. The improvements experienced from using these types of integrated methods demonstrate why research-based methods are important to discover ways that farmers can implement good techniques to improve crop performance and agriculture as a whole.

CONFLICT OF INTERESTS

The authors declare that there are no conflicts of interest related to this article.

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Floral Calendar of Tree Species associated with Insect Pollinators in Coastal Odisha of India

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Abstract— *Understanding of temporal patterns of tree flowering is essential for assessing the availability of floral resources to sustain the pollinator population throughout the year. The present study examined the flowering phenology of fifteen tree species used as forage of insect pollinators in coastal Odisha during 2024, documenting variations in early, middle, and late flowering phases. Two species such as Moringa oleifera and Santalum album exhibited biannual flowering, with Moringa oleifera flowering for the longest duration (22 weeks), followed by Santalum album (19 weeks). The overall order of flowering duration revealed that a few species substantially dominated the floral calendar, ensuring prolonged resource availability. Month-wise analysis indicated that February, March, and April supported the highest number of insect species (five species each) in their middle flowering phase, reflecting a spring peak in floral abundance. While most species showed middle-phase flowering for two consecutive months, Peltophorum ferrugineum extended to three months. Moringa oleifera and Santalum album again stood out for flowering twice annually and for more than three months in the middle phase, offering extended forage for pollinators. The floral calendar demonstrated distinct species-specific phenological patterns, with eight tree species flowering mainly in spring during February to March and fewer tree species (three each month) flowering during July to December. January, May, and June recorded moderate flowering activity with five, six, and five tree species respectively. The extended flowering periods of Moringa oleifera, Santalum album, Peltophorum ferrugineum, and Tectona grandis contributed significantly to year-round floral resource availability. These overlapping flowering periods, spanning two to four months for many species, play a crucial role in sustaining diverse insect pollinators.*

Keywords— ***Floral Calendar, Insect Pollinators, Coastal Odisha, Tree Species, Biannual Flowering.***

I. INTRODUCTION

Floral calendar plays a crucial role in ecosystem conservation by tracking the phenology of native plant species. Floral calendar, which tracks the phenology of flowering in plants, is essential tool for understanding the dynamics between plant species and insect pollinators. The timing and sequence of flowering events play a critical role in sustaining healthy pollinator populations, as they determine the availability of nectar and pollen, two key resources for insects like bees, butterflies, and other pollinators. These calendars are particularly important for identifying periods of abundance and scarcity of floral resources, which can directly impact pollinator health and, consequently, ecosystem stability. Since flowering times often fluctuate annually with weather conditions, floral calendars help identify main blooming and dearth periods, allowing beekeepers to introduce supplemental plants to bridge forage gaps (Onyango *et al.* 2019). This information can inform strategies for adaptation and mitigation in response to changing environmental conditions. It contributes to biodiversity monitoring by highlighting the presence of different plant species over time. Understanding the timing and sequence of flowering events through floral calendars is crucial for sustainable apiculture, apisilviculture, pollinator management, and ecosystem conservation The timing and sequence of plant flowering events are fundamental to the health and sustainability of pollinator populations and the broader ecosystems they support. Trees serve as a continuous source of forage by offering nectar, pollen, and suitable habitats throughout the year. The type, quantity, and quality of pollen and nectar vary among tree species and influence pollinator preferences (Ahmed *et al.* 2023). Their extended flowering periods ensure a steady food supply, reducing forage shortages and stabilizing insect populations. In recent years, there has been increasing recognition of the role of trees in sustainable agriculture and pollinator management, particularly in agroforestry systems.

Tracking flowering times helps to understand which species are thriving and which are at risk, providing insights into the overall health of an ecosystem. In recent years, there has been increasing recognition of the pivotal role of trees in supporting biodiversity and ensuring food security, especially within agroforestry systems and natural forests (Garibaldi *et al.,* 2014). Trees that flower at different times can provide year-round resources, such as seeds, fruit, or resin, and also help maintain biodiversity. In agroforestry systems, integrating trees with staggered flowering times can improve productivity by supporting multiple income streams and optimizing the use of land throughout the year. It are therefore essential tools for efficient apiary management, helping to determine periods of abundance and scarcity of forage, and enabling proper colony management of bees. (Singh *et al.* 2023). They also provide valuable data for future studies on climate change impacts and promote the use of beekeeping as a tool for conserving native flora (Onyango et al. 2019). A floral calendar outlines the approximate timing and duration of flowering for major nectar and pollen-producing plants in a given area (Onyango *et al.* 2019). The flowering period of plant species varies across different locations and times. Each landscape possesses its own unique composition of honeybee flora and experiences specific periods of floral abundance and scarcity. (Bhattarai *et al.*, 2023).

Such records are valuable for studying plant–pollinator relationships, biodiversity conservation, and the influence of climate change. The systematic monitoring of plant phenology provides critical data for numerous scientific and applied fields, including predicting forest productivity, modeling global carbon cycles, managing agricultural systems and most critically understanding the cascading consequences of climate warming on species interactions (Wolkovich *et al.*,2017).

Coastal Odisha, located along India's eastern coastline, experiences a tropical monsoon climate, characterized by distinct wet and dry seasons, as well as fluctuating temperatures and humidity levels. These climatic conditions significantly influence the phenology of plants, determining the timing of flowering. Despite the acknowledged importance of phenology and the environmental sensitivity of the region, systematic and quantitative data on the floral dynamics of forest tree species in coastal Odisha remain critically limited in published literature

This study aims to document the floral calendars of selected tree species in coastal Odisha that are associated with insect pollinators, contributing to the growing body of research on floral phenology in tropical coastal regions. By examining the seasonal flowering patterns of key tree species, this research seeks to identify periods of nectar scarcity, assess their implications for pollinator populations, and propose strategies for enhancing pollinator conservation in both natural and agricultural landscapes. Ultimately, the findings will provide valuable insights into the role of trees in sustaining pollinators, promoting biodiversity, and supporting the livelihoods of local communities dependent on these ecosystems

II. MATERIALS AND METHODS

2.1 Study area:

The present study was carried out in and around Bhubaneswar which is aerially 35km away from east coast of India along Bay of Bengal. The experimental site is located between 20025' - 20035' N latitude and 85080' - 85085' E longitude with elevation 30-60m above mean sea level. The google map of the experimental area is given in Fig 1.

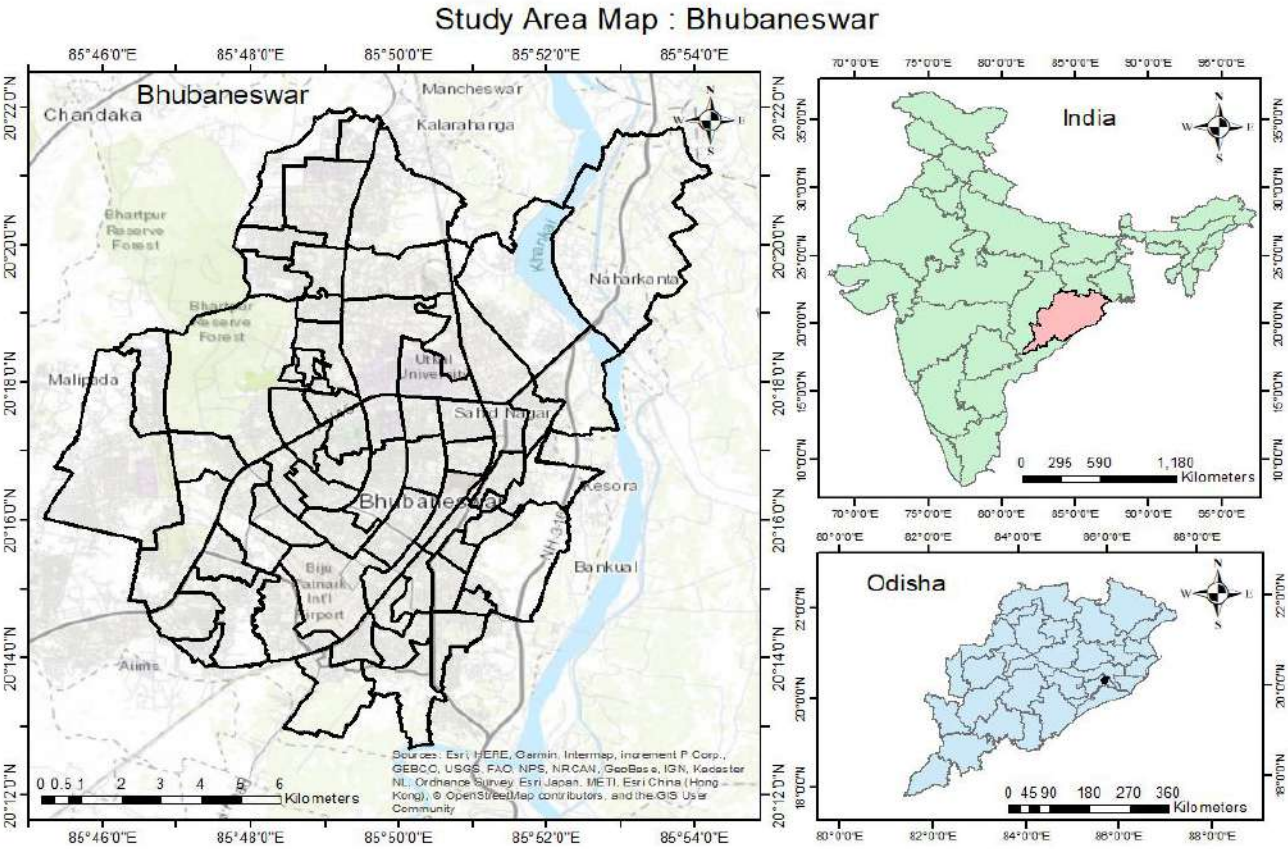

FIGURE 1: The google map of the experimental area

2.2 Climate and Weather

The study area comes under tropical climate. It has a warm and moist climate characterized by humid summer and mild winter. In general, the climate of Bhubaneswar comes under the group of moist and hot climate. The area receives an average annual rainfall of 1495 mm major portion during June to October from south-west monsoon.

2.3 Treatments

For preparation of floral calendar, fifteen number of tree species which have strong association with insects in coastal Odisha condition were considered such as: (a) *Mangifera indica,* (b) *Gliricidia sepium,* (c) *Moringa oleifera,* (d) *Litchi chinensis,* (e) *Cinnamomum zeylanicum,* (f) *Pongamia pinnata,* (g) *Peltophorum ferrugineum,* (h) *Lagerstroemia speciose* (i) *Caesalpinia coriaria,* (j) *Tectona grandis,* (k) *Santalum album,* (l) *Ziziphus mauritiana,* (m) *Alstonia scholaris,* (n) *Sapindus mukorossi* and (o) *Anacardium occidentale.*

2.4 Floral calendar for selected tree species

To develop floral calendars for selected tree species, systematic field observations were carried out over a period of 12 months. Regular survey was carried out in Bhubaneswar and adjoining areas during the early flowring, middle flowering and late flowering. Each selected tree species was studied in three different locations of at least 1 km away from one another as per availability. For each selected tree species two trees will be considered from each location. The floral calendar included the names of tree species in Latin along with their local names and flowering period. According to the range of blooming period, the particular trees got entry to the defined months.

2.5 Observations recorded

Time of flowering: For determining the flowering period of different tree species, systematic observations were carried out at on weekly basis through the blooming period.

Early, middle and late of flowering phases: The early phase of flowering was considered when the flowers cover one third of the canopy. Like-wise middle phase was considered when the flowering covered half of the canopy and late phase was considered as the last two third part of the canopy.

III. RESULTS

3.1 Flowering time of different tree species associated with insect pollinators:

The flowering time of different tree species associated with insect pollinators in coastal Odisha is presented in Table 1. In the year 2024, it was found that there were 15 number of major tree species associated with insect pollinators such as *Mangifera indica, Gliricidia sepium, Moringa oleifera* (Flowering 1 & 2), *Litchi chinensis, Cinnamomum zeylanicum, Pongamia pinnata, Santalum album* (Flowering 1 & 2), *Peltophorum ferrugineum, Lagerstroemia speciosa, Caesalpinia coriaria, Tectona grandis, Ziziphus mauritiana, Alstonia scholaris, Sapindus mukorossi* and *Anacardium occidentale*. Different tree species witnessed flowering at different time of the year. Further, there was a difference of time within the flowering period as early, middle and late phase of flowering of the tree. *Moringa oleifera* and *Santalum album* flowered twice in a year. *Moringa oleifera* flowered for maximum period of 22 weeks followed by *Santalum album* (19 weeks). The order of flowering period in terms of week in a year was observed to be: *Moringa oleifera >Santalum album > Peltophorum ferrugineum =Tectona grandis> Mangifera indica = Pongamia pinnata = Lagerstroemia speciose> Gliricidia sepium= Litchi chinensis = Caesalpinia coriaria = Ziziphus mauritiana> Cinnamomum zeylanicum =Alstonia scholaris= Sapindus mukorossi > Anacardium occidentale.*

Mangifera indica started flowering in the 1st week of January to the 3rd week, reached its middle phase during the 4th week of January and continued till 4th week of February and late flowering occurred in march 1st week to 3rd week. *Gliricidia sepium* initiated flowering in the 4th week of January to 1st week of February and closed flowering in March 3rd week to 1st week of April with a middle flowering during February 2nd week to March 2nd week. *Moringa oleifera* began first flowering in the 4th week of January to the 2nd week of February and reached middle phase during February 3rd week till March 4th week. It closed flowering during the 3rd week of April. Further, it flowered in May 4th week reached, its mid- flowering in June 3rd week to July 3rd week and late flowering occurred in the 4th week of July to August 1st week.

Litchi chinensis started flowering in the 1st week of February and continued until the 2nd week of February, middle phase occurred between 3rd week of February and 3rd week of March. The last phase lasts from the 4th week of March to the 2nd week of April. The early flowering of *Cinnamomum zeylanicum* extended from the 4th week of February to 2nd week of March and its middle flowering took place from the 3rd week of March until the 2nd week of April. The late Flowering phase continued from 3rd week to 4th week of April.

Santalum album displayed two cycles of flowering, the first began in the 4th week of February to the 2nd week of March, middle phase of took place from the 3rd week of March to April 2nd and had a late flowering phase from the 4th week of April to 1st week of May. The second cycle started from the 1st week of August to 2nd week of August and concluded its late phase from the 4th week of September to 1st of October with middle flowering from the 3rd week of August to September 3rd week.

In *Pongamia pinnata,* flowering began during the 2nd week of March and continues until the 4th week of March. The middle flowering period is from the 1st week of April to 2nd week of May, after which it closes flowering in the 3rd to 4th week of May. *Peltophorum ferrugineum* commenced flowering from the 4th week of March to the 1st week of April, middle phase was observed from the 3rd week of April up to June 1st week, and ended its late phase from the 2nd week to 4th week of June. *Lagerstroemia speciosa* floral initiation took place from the 1st week of April to the 3rd week April, had its middle flowering from the 4th week of April to the 4th week May and ended flowering in the 1st week to 3rd week of June.

Caesalpinia coriaria set into flowering from the 3rd week to 4th week of May, peaked from the 1st week of June to the 2nd week of July and the late phase was from the 3rd week to 4th week of July. *Tectona grandis* initiated flowering in the 3rd week of June to the 1st week of July, and ceased flowering from the 1st to the 3rd week of September. It had mid flowering in July 2nd week which continued up to August 4th week. *Ziziphus mauritiana* started flowering phase from the 1st week of September to the 3rd week and closed flowering from the 1st week to 2nd week of November with a middle phase of flowering from the 4th week of September to 4th week of October.

TABLE 1
FLOWERING TIME OF DIFFERENT TREE SPECIES ASSOCIATED WITH INSECT POLLINATORS

<table>
<tr><th rowspan="2">Sl.No</th><th rowspan="2">Name of tree species (Scientific name)</th><th rowspan="2">Common Name of tree</th><th rowspan="2">Family</th><th colspan="3">Flowering time</th><th rowspan="2" colspan="2">Total number of weeks of flowering</th></tr>
<tr><th>Initial phase</th><th>Middle flowering phase</th><th>Late phase</th></tr>
<tr><td>1</td><td>Mangifera indica</td><td>Mango</td><td>Anacardiaceae</td><td>January 1st week- January 3rd week</td><td>January 4th week- February 4th week</td><td>March 1st week - 3rd week</td><td colspan="2">11</td></tr>
<tr><td>2</td><td>Gliricidia sepium</td><td>Gliricidia</td><td>Fabaceae</td><td>January 4th week- February 1st week</td><td>Feb 2nd week- March 2nd week</td><td>March 3rd week- April 1st week</td><td colspan="2">10</td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">Moringa oleifera</td><td rowspan="2">Drumstick</td><td>Moringaceae</td><td>January 4th week- February 2nd week</td><td>February 3rd week – March 4th week</td><td>April 1st week- 3rd week</td><td>12</td><td rowspan="2">22</td></tr>
<tr><td></td><td>May 4th week- June 2nd week</td><td>June 3rd week - July 3rd week</td><td>July 4th week - Aug 1st</td><td>10</td></tr>
<tr><td>4</td><td>Litchi chinensis</td><td>Litchi</td><td>Sapindaceae</td><td>February 1st- February 2nd week</td><td>Feb 3rd week- March 3rd week</td><td>March 4th week-April 2nd week</td><td colspan="2">10</td></tr>
<tr><td>5</td><td>Cinnamomum zeylanicum</td><td>Dalchini</td><td>Lauraceae</td><td>February 4th week – March 2nd week</td><td>March 3rd week- April 2nd week</td><td>April 3rd week – 4th week</td><td colspan="2">9</td></tr>
<tr><td rowspan="2">6</td><td rowspan="2">Santalum album</td><td rowspan="2">Sandal</td><td>Santalaceae</td><td>February 4th week – March 2nd week</td><td>March 3rd week – April 3rd week</td><td>April 4th week- May 1st week</td><td>10</td><td rowspan="2">19</td></tr>
<tr><td></td><td>August 1st week – 2nd week</td><td>August 3rd week – September 3rd week</td><td>September 4th week- October 1st week</td><td>9</td></tr>
<tr><td>7</td><td>Pongamia pinnata</td><td>Karanj</td><td>Fabaceae</td><td>March 2nd week- 4th week</td><td>April 1st week – May 2nd week</td><td>May 3rd week – 4th week</td><td colspan="2">11</td></tr>
<tr><td>8</td><td>Peltophorum ferrugineum</td><td>Radhachuda</td><td>Fabaceae</td><td>March 4th week- April 2nd week</td><td>April 3rd week- June 1st week</td><td>June 2nd week- 4th week</td><td colspan="2">13</td></tr>
<tr><td>9</td><td>Lagerstroemia speciosa</td><td>Pride Of India tree</td><td>Lythraceae</td><td>April 1st week- 3rd week</td><td>April 4th week- May 4th week</td><td>June 1st week – June 3rd week</td><td colspan="2">11</td></tr>
<tr><td>10</td><td>Caesalpinia coriaria</td><td>Divi divi</td><td>Fabaceae</td><td>May 3rd week - 4th week</td><td>June 1st week - July 2nd week</td><td>July 3rd week- 4th week</td><td colspan="2">10</td></tr>
<tr><td>11</td><td>Tectona grandis</td><td>Teak</td><td>Lamiaceae</td><td>June 3rd week- July 1st week</td><td>July 2nd week- August 4th week</td><td>September 1st week- 3rd week</td><td colspan="2">13</td></tr>
<tr><td>12</td><td>Ziziphus mauritiana</td><td>Ber</td><td>Rhamnaceae</td><td>September 1st week- 3rd week</td><td>September 4th week - October 4th week</td><td>November 1st week – 2nd week</td><td colspan="2">10</td></tr>
<tr><td>13</td><td>Alstonia scholaris</td><td>Devil’s tree</td><td>Apocynaceae</td><td>October 1st week- 2nd week</td><td>October 3rd week- November 3rd week</td><td>November 4th week- December 1st week</td><td colspan="2">9</td></tr>
<tr><td>14</td><td>Sapindus mukorossi</td><td>Reetha</td><td>Sapindaceae</td><td>November 2nd week -3rd week</td><td>November 4th week- December 4th week</td><td>Jan 1st week-2nd week</td><td colspan="2">9</td></tr>
<tr><td>15</td><td>Anacardium occidentale</td><td>Cashewnut</td><td>Anacardiaceae</td><td>December 4th week- January 1st week</td><td>January 2nd week – February 1st week</td><td>February 2nd week- 4th week</td><td colspan="2">8</td></tr>
</table>

Alstonia scholaris commenced flowering from the 1st week to the 2nd of October, mid flowering was evident from October 3rd week to November 3rd week. It had a late phase from 4th week of November to the 1st week of December. *Sapindus mukorossi* set into flowering from the 2nd to 3rd week of November and reached at mid flowering during November 4th week to December 4th week and finished flowering in the 1st and 2nd week of January. *Anacardium occidentale* initiated flowering from the 4th week of December to the 1st week January and middle phase was noted in the 2nd week of January to 1st week of February and late flowering took place from the 2nd to 4th week of February.

3.2 Month-wise middle flowering of different tree species:

A perusal of data in Table 2 indicates that different months of the year 2024 recorded middle flowering of different tree species having an association with insect pollinators. January 2024 registered the middle flowering of species like *Anacardium occidentale* and *Mangifera indica* which were associated with insect pollinators. The month of February 2024 witnessed middle flowering of *Anacardium occidentale, Mangifera indica*, *Gliricidia sepium, Moringa oleifera* (Flowering 1) and *Litchi chinensis.* In the month of March 2024, middle phase of flowering of *Gliricidia sepium, Moringa olifera* (Flowering 1), *Litchi chinensis, Cinnamomum zeylanicum* and *Santalum album* (Flowering 1) was noticed. In April 2024 various tree species which were linked with pollinators that witnessed their middle flowering were *Cinnamomum zeylanicum, Santalum album* (Flowering 1)*, Pongamia pinnata, Peltophorum ferrugineum* and *Lagerstroemia speciosa*. The month May 2024 also registered flowering of *Pongamia pinnata, Lagerstroemia speciosa* and *Peltophorum ferrugineum* which flowered in the previous month. June 2024 experienced middle flowering of *Moringa oleifera* (Flowering 2) and *Caesalpinia coriaria* in addition to *Peltophorum ferrugineum* which continued middle flowering from the previous flowering. In the month of July of the same year recorded the continued flowering of *Moringa oleifera* (Flowering 2), *Caesalpinia coriaria* in addition to *Tectona grandis.* August 2024 which falls in the peak rainy season got flowering of only *Tectona grandis* and *Santalum album* (Flowering 2) having insect pollinator association. September 2024 also recoded continued flowering of *Santalum album* (Flowering 2) and middle flowering of *Ziziphus mauritiana.* October month of the same year received flowering *Alstonia scholaris* tree along with *Ziziphus mauritiana* which had flowering in the previous month also. November 2024 exhibited middle flowering of *Alstonia scholaris* and *Sapindus mukorossi.* December 2024 which is the winter month of the year recorded the continued flowering of *Sapindus mukorossi* which was associated with insect pollinators.

The Table 2 revealed that flowering of all the tree species mentioned above is more than one month. Most of the species showed flowering for 2 months. Species like *Peltophorum ferrugineum* flowered for 3 months. Some tree species like *Moringa olifera* and *Santalum album* showed middle flowering twice in the same year and covered more than 3 months which can provide forage for sustaining the insect pollinators for longer period of time. The overlapping of flowering time of different tree species observed for two to four months helps in the sustenance of the life of the various insect pollinators.

TABLE 2
MONTH-WISE FLOWERING OF SELECTED TREE SPECIES ASSOCIATED WITH INSECT POLLINATORS

Sl No.	Month	Name of the tree species
1	Jan-24	*Anacardium occidentale, Mangifera indica*
2	Feb-24	*Anacardium occidentale, Mangifera indica, Gliricidia sepium, Moringa oleifera* (Flowering 1), *Litchi chinensis*
3	Mar-24	*Gliricidia sepium, Moringa olifera* (Flowering 1), *Litchi chinensis, Cinnamomum zeylanicum, Santalum album* (Flowering 1)
4	Apr-24	*Cinnamomum zeylanicum, Santalum album* (Flowering 1), *Pongamia pinnata, Peltophorum ferrugineum, Lagerstroemia speciosa*
5	May-24	*Pongamia pinnata, Lagerstroemia speciosa, Peltophorum ferrugineum,*
6	Jun-24	*Peltophorum ferrugineum, Moringa oleifera* (Flowering 2), *Caesalpinia coriaria*
7	Jul-24	*Moringa oleifera, Caesalpinia coriaria, Tectona grandis*
8	Aug-24	*Tectona grandis, Santalum album* (Flowering 2)
9	Sep-24	*Santalum album* (Flowering 2), *Ziziphus mauritiana,*
10	Oct-24	*Ziziphus mauritiana, Alstonia scholaris*
11	Nov-24	*Alstonia scholaris, Sapindus mukorossi*
12	Dec-24	*Sapindus mukorossi*

3.3 Floral calendar of different tree species:

The floral calendar of the different tree species associated with different insect in coastal Odisha for the year 2024 has been prepared and depicted in tabular form in Table 3. In this calendar three phases of flowering such as early, middle and late phase have been included. January witnessed flowering of 5 tree species interacting with insect pollinators such as *Sapindus mukorossi*, *Anacardium occidentale*, *Mangifera indica*, *Gliricidia sepium* and *Moringa olifera* (Flowering 1). The calendar accommodates 7 tree species in the month of February which are *Anacardium occidentale, Mangifera indica, Gliricidia sepium, Moringa oleifera, Litchi chinensis, Cinnamomum zeylanicum* and *Santalum album* (Flowering 1). This month recorded two more species compared to previous month. In the month of March, flowering of 8 tree species such as *Mangifera indica, Gliricidia sepium, Moringa olifera* (Flowering 1), *Litchi chinensis, Cinnamomum zeylanicum, Santalum album* (Flowering 1), *Pongamia pinnata* and *Peltophorum ferrugineum* in the study area having association with insect pollinator were recorded and the number of tree species were higher than January and February. As for to the month of April 2024, the number of tree species (8) remained the same as of the previous month. This month witnessed flowering *Gliricidia sepium, Moringa olifera* (Flowering 1), *Litchi chinensis, Cinnamomum zeylanicum, Santalum album* (Flowering 1), *Pongamia pinnata, Peltophorum ferrugineum* and *Lagerstroemia speciosa* that have association with insect pollinator. May in the floral calendar of the 2024 registered 6 tree species such as *Santalum album* (Flowering 1) *Pongamia pinnata, Lagerstroemia speciosa, Peltophorum ferrugineum, Moringa oleifera* (Flowering 2) and *Caesalpinia coriaria w*hich was comparatively less than the previous month. June exhibited 5 number of tree species which were relatively lesser from the previous month that included the species such as *Peltophorum ferrugineum, Lagerstroemia speciosa, Caesalpinia coriaria, Moringa oleifera* (Flowering 2) and *Tectona grandis.* The next month July accommodated 3 number of tree species associated to inset pollinators which were *Caesalpinia coriaria Moringa oleifera* and *Tectona grandis.* Similar trend was observed in month of August, September, October, November and December in which 3 tree species been registered in each month. However, August exhibited a different set of the species such as *Moringa oleifera* (Flowering 2), *Tectona grandis* and *Santalum album,* while in September tree species were *Tectona grandis, Santalum album* (Flowering 2) and *Ziziphus mauritiana.* October, 2024 recorded flowering of *Santalum album* (Flowering 2), *Ziziphus mauritiana* and *Alstonia scholaris.* November included flowering of *Ziziphus mauritiana, Alstonia scholaris* and *Sapindus mukorossi.* December had also 3 number of species that were *Alstonia scholaris, Sapindus mukorossi* and *Anacardium occidentale.*

TABLE 3
FLORAL CALENDAR OF DIFFERENT TREE SPECIES ASSOCIATED WITH INSECT POLLINATORS IN COASTAL ODISHA OF INDIA

Tree Species	Month																																															
	Jan				Feb				Mar				April				May				June				July				Aug				Sept				Oct				Nov				Dec			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Mangifera indica (T_1)																																																
Gliricidia sepium (T_2)																																																
Moringa oleifera (Flowering 1) (T_3)																																																
Litchi chinensis(T_4)																																																
Cinnamomum zeylanicum(T_5)																																																
Santalum album (Flowering 1) (T_6)																																																
Pongamia pinnata(T_7)																																																
Peltophorum ferrugineum(T_8)																																																
Lagerstroemia speciosa(T_9)																																																
Caesalpinia coriaria(T_{10})																																																
Moringa oleifera (Flowering 2) (T_{11})																																																
Tectona grandis(T_{12})																																																
Santalum album (Flowering 2) (T_{13})																																																
Ziziphus mauritiana(T_{14})																																																
Alstonia scholaris(T_{15})																																																
Sapindus mukorossi(T_{16})																																																
Anacardium occidentale(T_{17})																																																

IV. DISCUSSION

4.1 Flowering time of different tree species associated with insect pollinators:

The flowering time of different tree species associated with insect pollinators in coastal Odisha varied remarkably from one another (Table 1 & Fig 2). In this research effort it has been observed that among the 15 selected tree species in coastal Odisha, the onset of flowering ranged from the month of January to December, with varying middle flowering periods. Species like *Moringa oleifera* and *Santalum album* flowered twice in the year 2024. Flowering time is controlled by an interplay of environmental cues (light/ photoperiod, temperature/chill/heat, water availability, nutrients) and endogenous signals (hormones, carbohydrate status, gene regulatory networks). Singh and Kushwaha (2006) have reported diversity of flowering and fruiting phenology in Indian dry-tropical trees having five flowering types relative to leaf flush; time lag between vegetative and reproductive phases correlated with leafless period. Suresh and Krishnamurthy (2014) have also observed variation of flowering and phenology patterns in dry deciduous forest at Bhadra Wildlife Sanctuary, Southern India and found flowering peaks in summer; leafing, fruit-bud etc. correlated with monsoon, temperature, rainfall etc. Bhol and Parida (2022, 2024) have also reported the variation of flowering time of different tree species. They have mentioned similar flowering time of *Tectona grandis* and *Santalum album*. Wang *et al.* (2020) showed that the flowering phenology among the trees relates to the tree height, flowering and fruit type and growth rate to optimise their reproductive success. Wang and Ding (2023) revealed that molecular mechanism have impact on the flowering of the tree species. Alves-de-Lima *et al.* (2023) documented the difference in flowering of same species to reduce overlapping of the pollinator usage. Onyango *et. al.* (2019) also reported that the months of April and May had highest forage availability and lowest was in December.

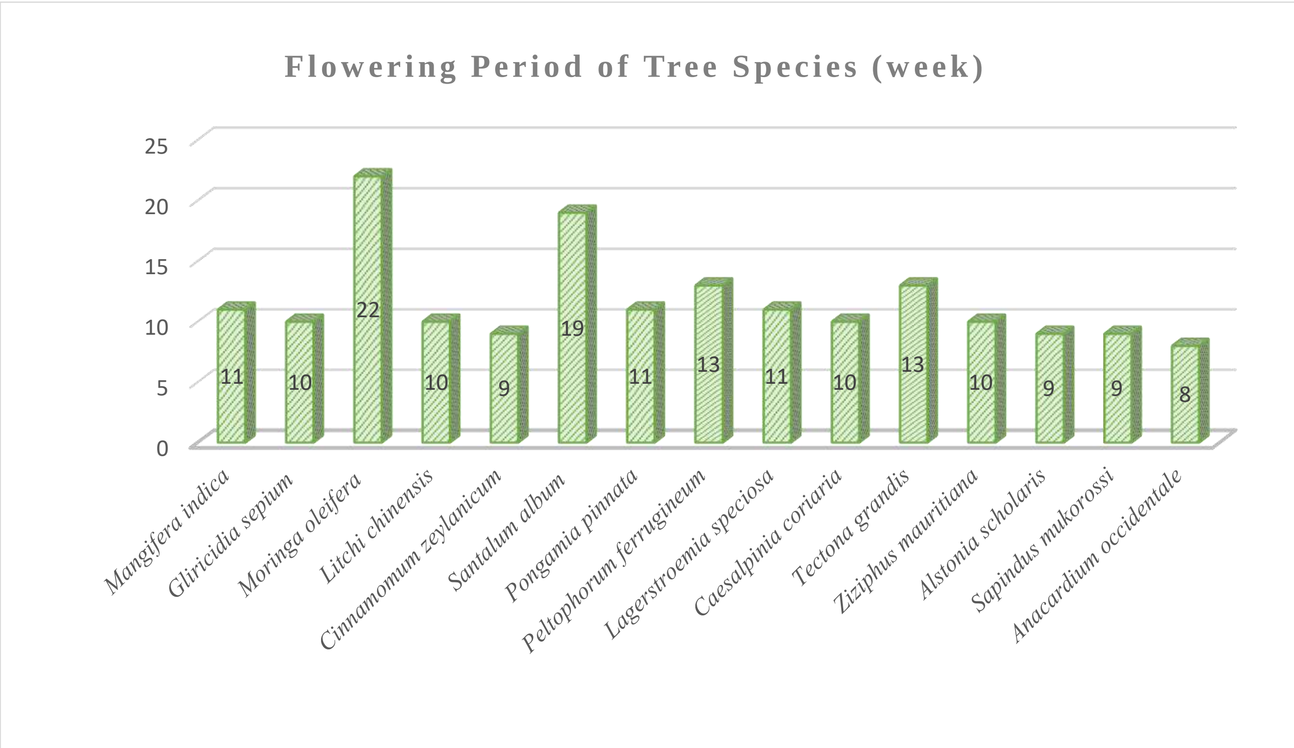

FIGURE 2: Flowering period of different tree species

4.2 Month-wise middle flowering of different tree species

The data on month-wise middle flowering of different tree species (Table 2) revealed that the middle flowering of different tree species occurred in the month of February, March and April suggesting that this period as the principal reproductive season for many tree species. Similar observations were made by Pande and Ramakrushna (2018), who found that March had the greatest percentage of bee flora abundance and highest bee flora availability. Essien (2020) also demonstrated that the highest level of flowering activity was recorded during the month February and March. Neupane *et al.* (2024) also reported that the maximum number of flowerings of the plant species were during the month of April and sufficient number of flowerings was observed in the month of February and March. Panigrahi *et al.* (2020) observed that the main flowering and honey flow period extended from November to April, supporting bee colony development and honey production, while the remaining months showed limited floral activity. Certain species such as *Moringa oleifera* and *Santalum album* had two flowering peaks and the bimodal pattern of flowering reflects the adaptive plasticity for the purpose of reproductive active which may be due climatic or genetic factor. These results align with findings of Thakur *et al.* (2024) who reported similar biannual pattern on *Santalum album* and Jyothi *et al.* (1990) who observed the similar sequence biannual flowering in *Moringa oleifera.*

4.3 Floral calendar of different tree species associated with insect pollinators

The floral calendar of different tree species associated with insect pollinator in coastal Odisha which comes under tropical climate, for the year 2024 has been depicted as Table 3 and Fig 3. It was observed that the calendar continuous throughout the year starting from January to December 2024. Among the 15 tree species studied in every month more than one species contributed forage to different insect pollinators. However, the number of tree species was different in different months of the year. The period of February, March and April was prominent with respect to flowering of maximum number of trees (8 numbers) which supported as good as 11 numbers of insect pollinators. The flowering abundance was maximum during this period because in coastal Odisha condition climate is tropical and maximum tree species exhibit flowering during this period. Prior to this time usually winter occurs and with approach spring season (Feb to April) major species flower in this region. Nanda *et al.* (2014) showed that flowering activities occur in the summer or pre-monsoon and flower bud initiates in January with a peak in April and May. Pao *et al.* (2016) stated that middle flowering occurred in the month of March and April. Rijial *et al.* (2018) found that most bee forage was available from February to September, whereas flowering declined between November and January.Hosamani *et al*. (2018) observed that peak honey flow occurred during June to October and January to March, while a dearth period extended from mid-April to mid-June, indicating two distinct foraging seasons linked to climatic patterns. In contrast to the findings, Waykar and Baviskar (2015) reported distinct seasonal flowering patterns, noting that 15 wild species flowered in summer, 18 in winter, and 21 during the monsoon, their study identified mid-October to mid-December as the major honey flow period, while mid-May to mid-August represented a critical dearth period.

The flowering phenology of 8 tree species such as *Mangifera indica, Gliricidia sepium, Moringa oleifera, Litchi chinensis, Cinnamomum zeylanicum, Pongamia pinnata, Peltophorum ferrugineum* and *Lagerstroemia speciosa* coincides in the month of February to April in coastal Odisha ecosystem. The meteorological data that have been given in the Table 3.1 can suggest that the weather condition may be helpful for the blooming of the tree species. This floral calendar gradually became narrow from the month of May to December. This may be attributed to start of vegetative phase of majority tree species in coastal Odisha agroclimatic condition as monsoon shower started in May and continued strongly upto October, even to some extent in November and December 2024. The rainfall data has been given in table 3.1. Number of tree species with flowering phase varied from 3 months to 5 months as shown in Table 4.3. In January the floral calendar was further wider because tropical tree like *Sapindus mukorossi, Anacardium occidentale, Mangifera indica, Gliricidia sepium* and *Moringa oleifera* flowered in this time. Jaswal *et al.* (2022) observed that late summer and the rainy season were marked as critical dearth periods for honey bees due to less availability of bee flora. Singh and Kushwaha (2006) stated that predominance of summer flowering with summer leaf flushing is a unique adaptation in trees to survive under a strongly seasonal tropical climate.

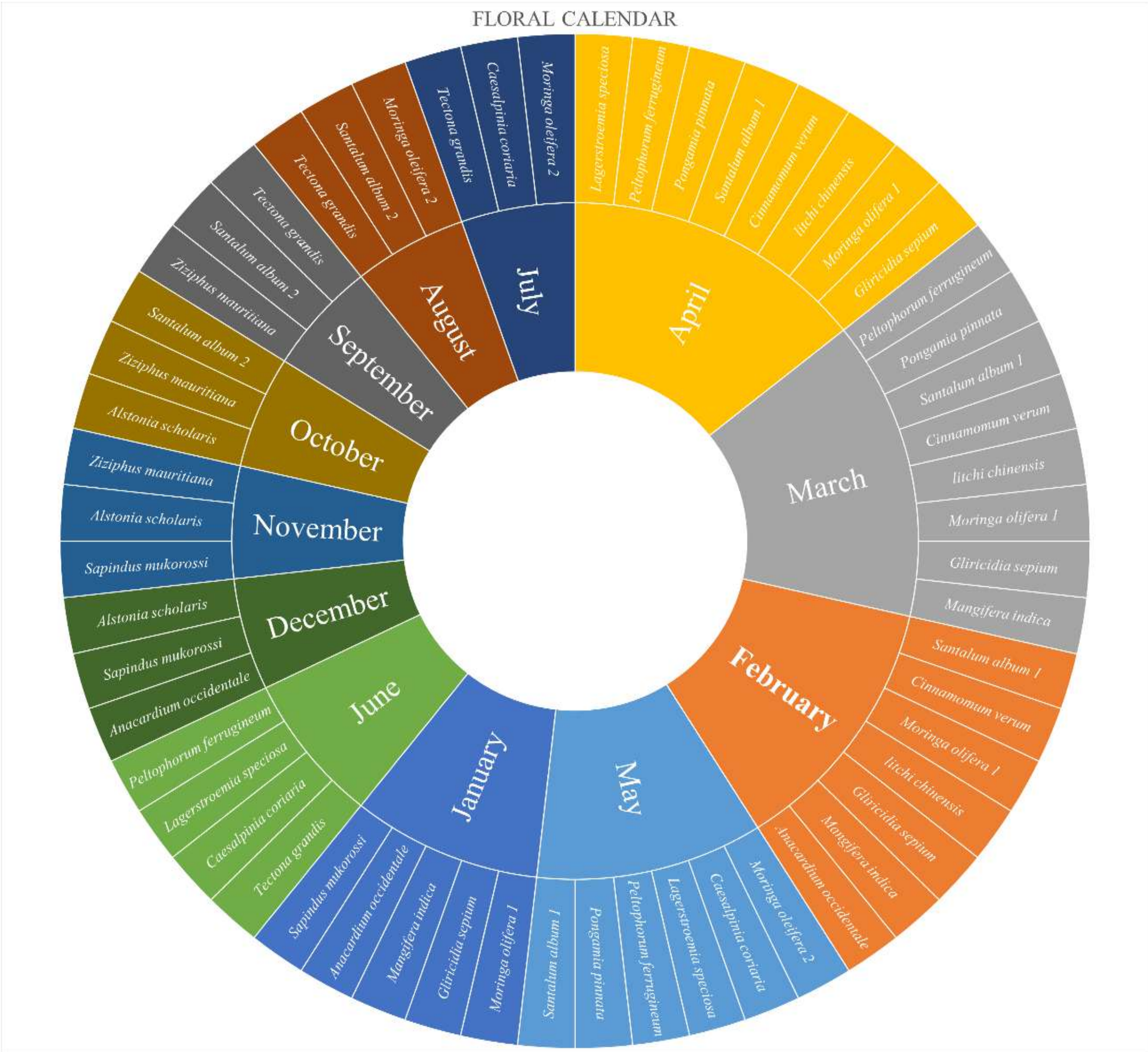

FIGURE 3: Floral colander of different tree species associated with insect pollinators in coastal Odisha of India

V. CONCLUSION

The flowering phenology of the fifteen tree species examined in coastal Odisha during 2024 revealed clear temporal variation across early, middle, and late flowering phases, contributing to a diverse and extended floral resource base. Species such as *Moringa oleifera* and *Santalum album* demonstrated biannual and prolonged flowering durations, making them particularly important for sustaining pollinator activity over extended periods. The concentration of middle-phase flowering during February to April, along with multi-month flowering in several species, highlights a strong spring peak supported by the region's tropical climate. At the same time, the presence of at least a few flowering species in all months of the year indicates a continuous, though variable, supply of nectar and pollen vital for insect pollinators. The floral calendar constructed from these observations underscores the ecological significance of flowering overlap among species, which enhances pollinator survival and stabilizes ecosystem functioning throughout the year. Future studies should explore how climate variability and long-term climate change may further influence flowering patterns and pollinator dynamics, enabling better conservation planning and adaptive management.

ETHICAL STANDARDS

All authors declare that the submission is original, unpublished, and not under consideration elsewhere.

Explanation of any issue relating to journal policies

There is no issue relating to journal policies.

Declaration of any competing interest

There is no competing interest.

Confirmation that all authors have approved the manuscript for submission

All authors declare that they have approved the manuscript for submission.

Data availability

Data will be made available on request.

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Authors have not received fund for this work from any source.

AUTHOR CONTRIBUTIONS

Sushree Rojalina Mahapatra made data collection, analysis, review of literature and writing of manuscript. Nirakar Bhol designed the research work, guided manuscript writing and made critical review of the manuscript. Pravasini Behera identified insect pollinators and guided insect related studies. Prajnashree Mallick assisted in data collection, analysis of data and collected reviews of works done. Subhasmita Parida guided in data collection, contributed to manuscript writing and made critical review of the manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Native Orchids of the Western Ghats: Ecology, Cultivation, and Microhabitat Restoration

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***Abstract*—** *The Western Ghats of India, recognized as one of the world's most critical biodiversity hotspots, hosts an exceptional diversity of orchids, many of which are endemic and highly sensitive to environmental change. However, rapid habitat degradation, climate instability, and the erosion of microhabitat complexity have placed these native orchids at increasing risk of decline. This 3.5-year interdisciplinary study examines species diversity, ecological requirements, mycorrhizal specificity, and habitat-based cultivation and restoration strategies for wild orchids across various forest ecosystems in Wayanad, Kerala.*

Through systematic field surveys, phenological observations, microclimate monitoring, and topographic assessments, the research documented ***54 native orchid species*** *across diverse elevations and forest types. Six distinct microhabitat classes were identified as critical determinants of orchid success, characterized by variations in host tree bark texture, moss and litter depth, canopy cover, humidity gradients, slope orientation, and associated microbial communities.*

Symbiotic seed germination and fungal isolation trials revealed strong and consistent mycorrhizal associations with ***Tulasnellaceae*** *and* ***Ceratobasidiaceae****, highlighting their essential role in seedling development and early-stage survival. Controlled cultivation experiments conducted under semi-natural conditions demonstrated that microhabitat-sensitive propagation significantly improves growth performance. Artificial microhabitat reconstruction—incorporating bark roughness, moisture-retentive substrates, and stable humidity—achieved a* ***68% survival rate****, outperforming conventional cultivation methods. Furthermore,* ***semi-wild reintroduction trials*** *recorded a* ***54% survival rate*** *after one year, confirming the effectiveness of habitat-mimicking restoration protocols.*

The findings underscore that successful orchid conservation in tropical forest landscapes requires a fine-scale understanding of microhabitat conditions, symbiotic fungal associations, and ecologically informed propagation techniques. This study provides a replicable, science-based restoration framework integrating cultivation research, field ecology, and community-based conservation. The methodologies and insights generated here offer valuable guidance for long-term orchid recovery efforts in the Western Ghats and other biodiversity-sensitive regions worldwide.

Keywords*— *Western Ghats; native orchids; microhabitat replication; mycorrhizal symbiosis; ecological restoration; reintroduction biology; conservation horticulture.

I. INTRODUCTION

Orchids represent one of the most evolutionarily advanced, ecologically intricate, and taxonomically diverse plant families on Earth. Their extraordinary specialization in pollination biology, seed dispersal mechanisms, and symbiotic interactions with mycorrhizal fungi makes them exceptional indicators of ecosystem health. The Western Ghats of India—recognized as a **UNESCO World Heritage Site** and one of the world's eight "hottest" biodiversity hotspots—harbor an exceptional richness of orchid species. This mountain chain supports a complex mosaic of microclimates, altitudinal gradients, and habitat niches that allow orchids to flourish in forms ranging from delicate terrestrial species to epiphytes anchored high on ancient forest canopies.

Despite this botanical wealth, the orchid flora of the Western Ghats faces unprecedented challenges. **Deforestation, habitat fragmentation, land-use change, climate variability, and degradation of forest microhabitats** pose serious threats to long-term orchid survival. Many species depend on extremely specific combinations of humidity, shade, host trees, soil composition, and symbiotic fungi. Even slight disturbances—such as canopy opening, stream diversion, or temperature shifts—can disrupt their survival cycles. Native orchids, unlike cultivated hybrids bred for resilience, have narrow ecological amplitudes, making both in-situ and ex-situ conservation scientifically demanding.

Although several taxonomic and floristic studies have catalogued the orchid diversity of the Western Ghats, **major gaps remain** in understanding the ecological processes that govern their persistence. Existing literature has primarily focused on species lists, morphological descriptions, and distribution records, while comparatively few studies address the **integration of ecology, conservation horticulture, microhabitat reconstruction, and long-term ecological monitoring**. Without such a holistic approach, restoration efforts risk being incomplete or ineffective.

This study seeks to bridge these gaps by undertaking a comprehensive evaluation of **ecophysiological traits, microhabitat dependencies, and long-term adaptation patterns** of selected endemic orchids of Wayanad, one of the most ecologically rich districts of the Northern Western Ghats. By integrating field-based ecological observations, controlled cultivation trials, and microhabitat reconstruction experiments, the study aims to identify the environmental variables most critical for orchid survival, growth, and successful reintroduction.

Furthermore, the research adopts a **restoration ecology framework**, emphasizing the reconstruction of microhabitats that mimic natural forest conditions. This includes the revival of humus-rich substrates, moisture-retaining canopy layers, host-specific phorophytes for epiphytes, and compatible mycorrhizal fungi essential for seed germination. Recognizing the cultural and traditional ecological knowledge of local communities, the study also integrates community-driven conservation practices, promoting sustainable protection and long-term stewardship.

Ultimately, this research contributes to the growing need for actionable conservation strategies. By coupling scientific insights with community engagement and habitat revitalization, the study aims to support the **sustainable reintroduction, long-term resilience, and ecological persistence** of native Western Ghats orchids. Such an integrated approach provides a replicable model for conserving orchid species globally, particularly in regions threatened by rapid environmental change.

II. MATERIALS AND METHODS

2.1 Study Site:

This study was conducted across **19 ecologically diverse forest sites** in the Wayanad district of the Western Ghats, India, distributed between **700 and 1,700 meters above sea level**. These locations were selected to represent the major vegetation types of the region, including **moist deciduous forests, semi-evergreen forests, mid-elevation evergreen forests**, and **shola–grassland ecotones**. Each habitat type supports a distinct assemblage of native orchids, microclimatic gradients, and host tree communities, making them ideal for evaluating species-specific ecological requirements and adaptive responses.

Microclimatic parameters—**air temperature, relative humidity (RH), light intensity**, and **substrate moisture content**—were monitored continuously throughout the study period using automated dataloggers placed at standardized heights. Canopy cover was assessed using hemispherical photography, while rainfall data were obtained from local forest department weather stations. To examine seasonal variation, data were collected across the **southwest monsoon, northeast monsoon, winter**, and **pre-summer flowering season**. This allowed detailed profiling of environmental fluctuations influencing epiphytic, lithophytic, and terrestrial orchid assemblages. Soil pH, organic carbon, and nutrient composition were analysed for terrestrial habitat plots.

2.2 Ecological Surveys (Months 1–24):

Ecological field surveys were conducted for two years using a **monthly stratified sampling framework**, ensuring consistent representation of all major forest types. Orchid populations were located through systematic transects (100 m × 20 m), and each individual or clump recorded was **geotagged using a handheld GPS** with sub-meter accuracy. Population attributes—including plant density, life stage (seedling, juvenile, adult), and phenological state—were documented.

For epiphytic orchids, host tree characteristics were assessed, including **bark texture, exfoliation pattern, moisture retention capacity, pH**, and presence of naturally accumulated biofilm. Bark roughness was quantified using standardized roughness index scoring. The presence and percentage cover of **mosses, liverworts, and lichens** were measured using a 10 cm × 10 cm quadrat placed directly on host substrates.

During peak flowering months, detailed observations of **pollinator activity** were conducted. Flower-visiting insects were photographed, and visitation rates, behavior, and contact with reproductive structures were noted. Pollinators were not collected to minimize disturbance, but identification was attempted using visual field guides and macro-photography.

Microhabitat parameters around each orchid—such as canopy openness, vapor pressure deficit, and bark moisture—were recorded. This dataset helped determine environmental thresholds essential for orchid establishment and survival.

2.3 Mycorrhizal Isolation and Symbiotic Germination:

To understand fungal associations supporting orchid seed germination, root segments from **32 native orchid species**—including both epiphytes and terrestrials—were collected from healthy individuals. Samples were cleaned, surface-sterilized using 1% sodium hypochlorite, and inoculated on **Oatmeal Agar (OMA)** and **Potato Dextrose Agar (PDA)** under aseptic conditions. Emerging fungal pelotons were isolated and cultured for further study.

Fungal identification was performed using both **morphological microscopy** and **molecular characterization**, focusing on the internal transcribed spacer (ITS) region. DNA extraction, amplification, and sequencing followed standard protocols, and sequences were compared with those in public databases to confirm identity.

Symbiotic germination trials were conducted to assess compatibility between isolated fungi and orchid seeds. Seeds were sown on symbiotic media co-inoculated with fungal isolates, and germination stages—swelling, protocorm formation, rhizoid emergence, and leaf initiation—were monitored. Seedling vigor, biomass accumulation, and survival rates were quantified to determine optimal plant–fungus pairings.

2.4 Cultivation Trials (Months 12–32):

Controlled cultivation experiments were established to evaluate the influence of microhabitat variables on orchid growth and development. These trials included both **epiphytic** and **terrestrial** species.

2.4.1 Epiphytic Orchid Trials:

Experiments tested the effect of:

- **Bark slabs** of varying roughness (smooth, moderately rough, highly rough)
- **Moss layer thickness** (0 cm, 1 cm, 3 cm)
- **Light regimes** ranging from **300 lux to 1,200 lux**
- **Relative humidity (RH)** treatments between **70–92%**

Plants were cultivated in semi-controlled shade-net environments, and environmental conditions were monitored using multi-parameter sensors. Growth performance was measured through:

- **Leaf initiation rate**
- **Pseudobulb development**
- **Root elongation and branching**
- **Chlorophyll fluorescence (Fv/Fm)**
- **Time to spike formation and flowering**

These metrics allowed comparative evaluation of the influence of substrate and microclimate on physiological performance.

2.4.2 Terrestrial Orchid Trials:

Different substrate compositions were tested, including:

- Loamy soil + decomposed forest leaf litter
- Cocopeat + perlite + forest humus
- Sand + lateritic soil + organic compost

Soil moisture retention, aeration, and nutrient parameters were monitored weekly. Both above-ground and below-ground growth parameters were recorded.

2.5 Microhabitat Reconstruction and Reintroduction (Months 30–42):

A major component of the study involved designing and testing artificial microhabitats to support orchid restoration. These microhabitats were engineered using a combination of:

- **Decomposed wood matrices** mimicking natural trunk cavities
- **Moss and bio-layered moisture-retaining substrates**
- **Bark sheets** fashioned from naturally shed tree bark
- **Controlled humidity modules** that maintained RH above 80% during dry months
- **Shaded canopy structures** replicating forest understory light conditions

Orchids propagated through symbiotic germination and ex-situ cultivation were selected for reintroduction. Sites were chosen in **partially restored forest patches** within community-managed and state forest zones. Reintroduction followed a soft-release method: plants were acclimatized in field chambers before being fixed onto host trees or planted in forest soil.

Long-term monitoring was conducted every three months and included:

- Survival rate
- New root attachment
- Leaf and pseudobulb progression
- Flowering and reproductive success
- Mycorrhizal re-colonization, checked via root peloton analysis

The monitoring helped assess the ecological feasibility of large-scale orchid restoration and identify critical parameters for successful reintroduction.

III. RESULTS

3.1 Species Richness and Habitat Distribution:

A total of **54 native orchid species** were recorded across the study landscape, revealing significant diversity within a relatively small geographic range. Epiphytic orchids formed the majority, accounting for **59.3%**, followed by **terrestrial species (25.9%)** and **lithophytes (14.8%)**. Epiphytes were predominantly associated with mid-elevation forest canopies, where stable humidity and diffused light created optimal growth conditions. Evergreen forest patches supported the highest species richness due to consistent canopy cover, reduced temperature fluctuations, and a well-developed layer of moss and organic debris. Fragmented or semi-open areas showed markedly lower diversity, indicating the sensitivity of orchids to microclimatic disruptions.

3.2 Microhabitat Determinants:

Six distinct microhabitat categories were identified, ranging from shaded lower canopies to semi-exposed rocky outcrops. Statistical analysis revealed strong correlations between orchid survival and specific microenvironmental factors. Relative humidity exhibited a high predictive value (**$r^2 = 0.81$**), highlighting its importance in maintaining leaf turgor, preventing desiccation, and supporting mycorrhizal activity. Host tree bark properties—including roughness and water-holding capacity—played a critical role in epiphytic establishment, as rough bark retained moisture and provided anchorage. Moss depth between **1.3 and 2.1 cm** emerged as the optimal substrate for root stability and moisture regulation. Light intensity thresholds varied by guild, with epiphytes preferring 200–500 lux and terrestrials thriving at slightly higher levels. Additionally, the density of fungus-root colonization strongly influenced seedling establishment, particularly in shaded forest interiors.

3.3 Mycorrhizal Findings:

Mycorrhizal analysis revealed that fungi belonging to **Tulasnellaceae** and **Ceratobasidiaceae** were dominant across most sampled species. Symbiotic interactions significantly enhanced early developmental stages of orchids. In controlled environments, fungal inoculation improved seed germination by **2.4 times** compared to asymbiotic controls. Seedling vigor, measured through leaf expansion rate and root biomass, increased by **1.9 times**, demonstrating the critical role of fungal partners in nutrient acquisition, stress resistance, and survival under fluctuating moisture conditions. These findings reinforce the ecological dependency of native orchids on their mycorrhizal counterparts.

3.4 Cultivation Success:

Under semi-controlled nursery conditions, epiphytic orchids displayed a **76% survival rate**, attributed to their ability to withstand short-term humidity fluctuations. Terrestrial species achieved **62% germination** in fungal-assisted trays, with symbiotic cultures outperforming conventional methods. Species possessing pseudobulbs exhibited noticeably higher resilience, owing to their internal water-storage capacity and adaptive traits that buffer against moisture variability.

3.5 Reintroduction Outcomes:

Reintroduction experiments yielded encouraging results. Artificially created microhabitats—designed to mimic natural forest conditions—recorded a **68% survival rate**, while semi-wild forest sites achieved **54%**. Survival was strongly influenced by three key factors: effective root anchorage, stable moisture regimes, and successful mycorrhizal colonization. Orchids that established early fungal associations showed markedly improved adaptation and long-term stability, highlighting the need for integrated ecological restoration approaches.

IV. DISCUSSION

This study demonstrates that **microhabitat fidelity** is one of the most critical determinants of orchid establishment, survival, and long-term persistence. Traditional cultivation approaches—often based on generic horticultural practices—fail to capture the fine-scale ecological requirements that orchids depend on in the wild. These methods overlook essential **ecological filters**, such as obligate fungal symbiosis, species-specific bark microtextures, narrow humidity ranges, and the moisture-buffering capacity provided by bryophytes and epiphytic moss layers. Such filters operate simultaneously in natural habitats, creating microconditions that cannot be replaced by standard potting methods or conventional greenhouse environments.

By integrating ecological field data with controlled cultivation techniques, this study highlights how **ecologically informed habitat replication** can significantly enhance orchid survival. Artificial habitats designed to mimic natural microconditions—including bark roughness, pH, temperature gradients, mycorrhizal associations, and canopy-filtered light—resulted in survival and growth rates comparable to those observed in intact forest patches. This suggests that orchids respond more strongly to microhabitat quality than to the broader landscape context, reinforcing the importance of fine-scale habitat design in ex-situ conservation.

These findings advocate for a paradigm shift toward **conservation horticulture**, where cultivation is not merely a method of propagation but a scientifically grounded extension of restoration ecology. By treating cultivation as a form of **rewilding support**, conservation strategies can bridge the gap between nursery-based propagation and successful reintroduction in natural habitats. Such a framework aligns with global efforts to restore ecological function, enhance genetic resilience, and support threatened species recovery.

Furthermore, the implications of this research extend beyond the Western Ghats. Many tropical montane ecosystems—characterized by high humidity, steep environmental gradients, and narrow species niches—face similar biodiversity threats. The principles demonstrated here are therefore widely applicable across orchid-rich landscapes in Southeast Asia, tropical Africa, and Latin America, where microhabitat-driven species decline is accelerating due to habitat fragmentation and climate instability.

In summary, this study underscores the necessity of integrating **microhabitat science** into every stage of orchid conservation, from propagation to reintroduction. By aligning horticultural practice with ecological reality, conservationists can achieve more predictable, resilient, and ecologically meaningful outcomes for some of the world's most threatened plant species.

V. CONCLUSION

This 3.5-year study clearly demonstrates that the long-term survival and ecological resilience of native orchids depend on a precise understanding and replication of fine-scale microhabitat conditions, coupled with the preservation of essential orchid–mycorrhizal fungal relationships. Orchids, being highly sensitive bioindicators, respond quickly to even subtle environmental variations; therefore, effective conservation cannot rely on general habitat protection alone. Instead, it requires a scientific, site-specific approach grounded in microclimatic profiling, soil chemistry evaluation, moisture regulation, and canopy-light interactions.

By integrating ecological field assessments, controlled ex-situ cultivation trials, and microhabitat restoration experiments, this study establishes a practical, evidence-based framework for orchid conservation across fragmented landscapes. Reintroduction trials further revealed that successful establishment is significantly enhanced when the associated fungal partners are present, confirming that symbiotic compatibility is a non-negotiable element in species recovery programs.

The framework developed through this research is not limited to Wayanad or the Western Ghats. Its principles are transferable and offer a scalable model for tropical orchid conservation worldwide. Forest departments, botanical gardens, NGOs, and community conservation groups can adopt this model to design climate-resilient restoration programs, especially for threatened and endemic taxa.

Importantly, this study highlights the role of community involvement, traditional ecological knowledge, and participatory monitoring in strengthening conservation outcomes. When scientific methodology is paired with local stewardship, the speed and success of restoration efforts dramatically increase.

Overall, the research contributes a holistic, climate-smart, and ecologically grounded conservation strategy that supports biodiversity enhancement, strengthens ecosystem integrity, and provides a pathway for safeguarding orchid diversity in a rapidly changing world.

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CONFLICT OF INTEREST

The author declares no conflict of interest.

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