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Preface

We would like to present, with great pleasure, the volume-12, Issue-1, January 2026 of a scholarly journal, *International Journal of Environmental & Agriculture Research*. This journal is part of the AD Publications series *in the field of Environmental & Agriculture Research Development*, and is devoted to the gamut of Environmental & Agriculture issues, from theoretical aspects to application-dependent studies and the validation of emerging technologies.

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

Environmental Research:

Environmental science and regulation, Ecotoxicology, Environmental health issues, Atmosphere and climate, 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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Agricultural Sciences	
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Agricultural Chemistry	Basic biology concepts
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Agricultural Management Practices	Agricultural Technology
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Pulse Crops: Peas (all types), field beans, faba beans, lentils, soybeans, peanuts and chickpeas.	Hay and Silage (Forage crop) Production
Vegetable crops or Olericulture: Crops utilized fresh or whole (wholefood crop, no or limited processing, i.e., fresh cut salad); (Lettuce, Cabbage, Carrots, Potatoes, Tomatoes, Herbs, etc.)	Tree Fruit crops: apples, oranges, stone fruit (i.e., peaches, plums, cherries)
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A Comparative Study on Cost Structure and Profitability of Beekeeping in Ramban, Kathua and Jammu Districts of Jammu Division of Jammu and Kashmir

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***Abstract*—** *This study investigates the economic profitability of honey production in the Ramban, Kathua, and Jammu districts of Jammu Division, J&K, highlighting its potential as a sustainable livelihood. Using a stratified sampling approach, 200 beekeepers across high-, medium-, and low-density districts were surveyed to collect data on production costs, returns, socio-economic variables, and constraints. The analysis revealed significant inter-district variation in performance. Ramban district emerged as the most productive, yielding 7,196 quintals of honey and 486.6 quintals of beeswax, and the most profitable, with gross returns of ₹17,864.52 per quintal and a benefit-cost ratio (BCR) of 10.05. Kathua and Jammu districts also showed positive, though lower, profitability. The study concludes that apiculture is a highly profitable venture in the region, with an aggregate BCR of 7.95. Strategic interventions—including improved market access, value addition, cooperative models, and policies to reduce cost-price spreads—are recommended to enhance profitability and sustainability across all districts.*

Keywords*— *Apiculture, Beekeeping, Economic Profitability, Benefit-Cost Ratio, Marketing Channels, Jammu & Kashmir.

I. INTRODUCTION

Agriculture in India has a long history dating back to ten thousand years. Today, India ranks second worldwide in farm output and has one of the highest productivity rates. Agriculture was the backbone of the Indian economy and a major source of employment. The share of employment in agriculture was 44.1 percent in 2017-18, increasing to 46.1 percent in 2023-24. India's agriculture sector contributed 16% to the Gross Domestic Product (GDP) in financial year 2024-25 and is projected to grow by 3.8% (Ministry of Finance, Government of India, 2025). GDP from agriculture in India increased to 7683.51 INR billion in Q4 of 2024 from 4759.11 INR billion in Q3 of 2024 (Ministry of Statistics and Programme Implementation, Government of India, 2025). The agriculture sector continues to determine India's economic standing due to its forward and backward linkages with other sectors (Anandhy and Beula, 2019).

In 2023-24, 46.1% of India's workforce was employed in agriculture, according to the Economic Survey and the Periodic Labour Force Survey (PLFS). It is envisioned as one of the four engines of development (the others are MSMEs, investments, and exports) in the Union Budget of 2025-26, aimed at driving sustainable growth and achieving the vision of a 'Viksit Bharat' (Developed India) by 2047 (Ministry of Statistics and Programme Implementation, Government of India, 2025). Sustainable agriculture in terms of food security, rural employment, and environmentally sustainable technologies such as soil conservation, sustainable natural resource management, and biodiversity protection are essential for holistic rural development (Babuchittimothu and Suresh, 2023).

Beekeeping (or apiculture) is the maintenance of bee colonies, commonly in man-made hives, by humans. It is an agro-based occupation that provides income and employment generation for rural and tribal families. It plays a vital role in the present context of the commercialization of agriculture and liberalization of the economy. Bees are a special gift to mankind due to their pollination services and valued products like honey, beeswax, propolis, bee venom, etc. (Das et al., 2022). Honey bees are responsible for pollinating crops such as apples, berries, melons, almonds, and cocoa (Khalifa et al., 2021). However, beehives face threats from habitat loss, pesticide use, and climate change. The decrease in bee populations is a major risk to global food production and environmental well-being. Apiculture is dependent on floriculture because bees rely on flowers for nectar and pollen. India's floriculture industry has earned the status of a "sunrise industry" with a 100 percent export orientation and high performance (Ministry of Statistics and Programme Implementation, Government of India, 2025). Beekeeping is an enticing, lucrative, and intriguing rural agri-horticulture business that does not require cutting-edge technology, large financial investment, or vast infrastructure.

A beekeeper rears bees to extract honey and other hive products, pollinate crops, and also sell to other beekeepers. Beekeeping provides self-employment for rural and agro-based populations. Beekeeping and the extraction of honey, pollen, beeswax, venom, and royal jelly provide employment to rural educated youths by creating job opportunities in the post-production (collection, processing) and marketing of bee products (Narang, A. et al., 2022).

1.1 Status of Honey Production in the World:

In 2024, the FAO reported honey production reached 1,894,000 metric tons. The global honey market size has touched USD 9.40 billion and is expected to grow to USD 15.59 billion by 2032 (Food and Agriculture Organization, 2024). The global honey market is expected to grow at a CAGR of 5.83% in the forecast period 2023-2029 (Food and Agriculture Organization, 2024).

1.2 Status of Honey Production in India:

The India honey market size was worth around USD 305 million in 2023 and is predicted to reach USD 585 million in value by 2032 with a compound annual growth rate (CAGR) of approximately 7.5% between 2024 and 2032. In financial year 2024-25, India is estimated to have produced approximately 146,000 metric tons of honey with a value of USD 177.52 million in exports (The Agricultural and Processed Food Products Export Development Authority, Ministry of Commerce and Industry, Government of India, 2024). The honey market is expected to generate US$2.45 billion in revenue and is predicted to grow annually by 5.37% (CAGR 2024-2028) (APEDA, 2024). 12,699 beekeepers are currently registered on the National Bee Board with 19.34 lakh honey bee colonies (National Beekeeping and Honey Mission, Government of India, 2022-2023). More than half of India's honey production is exported to the USA, Saudi Arabia, the United Arab Emirates, Bangladesh, Canada, and 83 other countries (NBHM, 2022-2023).

To strengthen India’s honey production and export capacity, the National Beekeeping and Honey Mission (NBHM) has released guidelines for beekeepers (Debroy, 2019; NBB, 2020; Chetri et al., 2021). NBHM is a Central Sector Scheme that promotes scientific beekeeping for overall growth of the beekeeping sector to improve agriculture production. It has 3 sub-schemes: Mini Mission I (production and productivity improvement), Mini Mission II (post-harvest management), and Mini Mission III (research and technology generation). Financial assistance is provided as per scheme guidelines.

The Covid-19 pandemic witnessed a surge in honey consumption due to its health-inducing properties. The growing health and wellness trends are expected to propel the India honey market growth. Based on flavor, the multiflora honey segment is expected to dominate; based on seasonality, the autumn and spring segment is expected to capture the largest market share; and based on distribution channel, the business-to-consumer segment is expected to garner a significant revenue share. Based on state, Maharashtra is expected to dominate the market. India’s export of honey increased by 110% between 2013-14 and 2019-20 (NBHM, 2021). In 2023-24, India exported 107,963.21 metric tonnes of natural honey valued at Rs 1,470.84 crore (approx. $177.52 million USD), with the USA, Saudi Arabia, the UAE, Bangladesh, and Canada being key destinations. Major export varieties include mustard, eucalyptus, lychee, sunflower, pongamia, multi-flora Himalayan, acacia, and wild flora honey.

To boost exports, the Indian government is focusing on upgrading value-added honey products, organic certification authenticity, and ensuring strict guidelines meeting international quality standards. Initiatives are in place to train new beekeepers, upgrade apiculture infrastructure, and invest in innovative research (National Bee Board, Ministry of Agriculture and Farmers Welfare, 2023).

1.3 Status of Honey Production in Jammu and Kashmir:

Jammu & Kashmir Union Territory recorded 146000 quintals of honey production in the year 2023-24, with the Jammu division holding a share of 4425.35 quintals. The total number of beekeepers in the Jammu division was 2471, with 82660 bee colonies. Jammu and Kashmir witnessed a 'sweet revolution' through apiculture development schemes launched by the government, such as free-of-cost facilities for processing raw honey and subsidies (Ministry of Micro, Small & Medium Enterprises, Government of India 2025). Besides developing infrastructure for post-harvest management, packaging, value addition, and marketing, the Jammu and Kashmir government has also launched a Rs 46.65 crore 'Promotion of Beekeeping' project.

For standardization, small-time keepers are offered honey testing and logo stamping services for better market returns. Processing units help reduce moisture, filter, and bottle honey. New-age agripreneurs are making value additions like soaps, candles, cosmetics, and Ayurvedic medicines. The UT administration, through its Krishi Vigyan Kendras (KVKs) and the Department of Agriculture, is imparting technical skills. Two advanced apitherapy centers and GI labs are established to increase production of high-quality honey. Monitoring and traceability are done through GI labs, and 20 Custom Hiring Centers (CHCs) are established for extending pollination facilities. The project targets generating additional Rs 475 crore income from by-products and setting up 86 enterprises in five years (Government of Jammu & Kashmir, Department of Information & Public Relations, 2023).

II. REVIEW OF LITERATURE

An important prerequisite to agribusiness research is a clear grasp of issues through rigorous and systematic planning. The following work has been conducted by various researchers related to this study.

2.1 Economic Analysis of Beekeeping:

- Sharma and Bhatia (2001) analyzed the economics of stationary and migratory beekeeping in Himachal Pradesh. The average number of colonies for migratory and stationary beekeepers was 56 and 23, respectively. Fixed cost per colony was ₹63.13 (migratory) and ₹59.10 (stationary); variable cost was ₹195.15 and ₹167.83. Total cost was ₹258.28 and ₹226.93 per colony. Average honey produced was 41.60 kg/colony (migratory) and 15.66 kg/colony (stationary). Net returns were ₹1413.72/colony (migratory) and ₹353.07/colony (stationary), showing migratory beekeeping was more profitable.
- Devkota K. (2006) found the Benefit-Cost Ratio (BCR) of apiculture ranged from 0.97 to 6.22, with about 88.88% beekeepers in profit.
- Kumar and Gill (2006), in a study on economic viability of agriculture-based enterprises for women in Punjab, found gross returns of ₹25,255 from selling honey and byproducts against a cost of ₹11,428, yielding a net profit of ₹13,826 per 10 colonies per year.
- Kizilaslan and Kizilaslan (2007), in a study on factors affecting honey production in Turkey, found honey consumption per person, number of beehives, producer price, and honey export values statistically significant.
- Pokhrel (2009) found honey productivity in Terai (28.7 kg/yr/hive) was 3.54 times higher than in hills (8.1 kg/yr/hive) in Chitwan, Nepal. Income from honey production was 3.62 times higher than from crop farming.
- Vural and Karaman (2009) found beekeeping was the main income source (68.40%) for beekeepers with more than 160 colonies. Average honey yield was 26.28 kg/colony.
- Prasad et al. (2012) found migratory bee farms had higher total cost, gross returns, and net returns per 100 colonies. Cost per kg honey was lower on migratory farms due to higher average yield per colony.
- Sharma et al. (2014) studied migratory beekeeping in Sri Muktsar Sahib, Punjab. Beekeepers were categorized by migratory route. Honey production varied from 29-45 kg/hive. Cost of production per box was ₹2542.6 (Group I), ₹3328.5 (Group II), and ₹2406.4 (Group III). Benefit-cost ratio was highest in Group II (2.23:1).
- Gebrehiwot (2015) used descriptive and regression analysis to analyze factors influencing beekeeping activities and honey production.
- Devkota et al. (2016) found the BCR of beekeeping in Chitwan, Nepal was 1.8. Gross income was 4475.23 rupees/hive.

- Al-Ghamdi et al. (2017) found productivity of box hives was 72% higher than traditional hives in Saudi Arabia. Average net incomes were 33,699.7 SAR/annum (box hives) and 16,461.4 SAR/annum (traditional hives).
- Sain (2017) examined cost and return from an apiary of 80 boxes. Cost of fixed assets was ₹2,15,900 and variable cost was ₹1,49,500. Returns from sale of honey and byproducts was ₹3,17,000, giving a net profit over variable cost of ₹1,67,000 in one year.
- Shrestha (2018) studied production economics of honey in Bardiya, Nepal. Farmers reared an average of 34.54 hives with productivity of 34.6 Kg/hive. Average production cost was ₹7392.52 with net profit of ₹2987.05, and B:C ratio was 1.67.
- Yogi et al. (2020) in Dang, Nepal, found on average farmers held 14.55 bee hives with productivity of 6.12 kg/hive. The benefit cost ratio was 3.71 and average annual net profit was NRS. 2,646.96 per hive.
- Saini et al. (2021) found that managing colonies at different initial strengths (5, 10, and 15 frames) and extraction frequencies affected returns. Fifteen-frame colonies had the highest B:C ratio (1:1.50). Total expenditure was lowest in five-frame colonies.
- Paudel et al. (2025) evaluated profitability and efficiency of honey production in Nepal. Results revealed an average BCR of 1.67, with modern practices outperforming traditional methods.

III. MATERIALS AND METHODS

3.1 Locale of the Study:

The present study was conducted in Jammu, Kathua and Ramban districts of Jammu division, selected based on the highest number of bee colonies.

3.2 Sampling Design:

3.2.1 Selection of districts:

A multistage random sampling technique was employed. In the first stage, three districts (Jammu, Kathua and Ramban) were selected purposively based on density of total beekeepers, considering three ranges: high density (>1000), medium density (100 to 999), and low density (<100) (Kumar et al., 2020; Thakur et al., 2023). Ramban was the only district in the high-density category with 1727 beekeepers. Within the medium density range (100 to 999), Kathua was selected randomly from two districts. From the low density category (<100), Jammu was selected randomly from seven districts.

TABLE 1
DISTRIBUTION OF BEE COLONIES IN DIFFERENT DISTRICTS OF JAMMU DIVISION (SELECTION FRAMEWORK)

S.No.	District(s)	Bee Colonies	Honey Production (q)	No. of Beekeepers (Apis mellifera)	No. of Beekeepers (Apis cerana indica)	Total Beekeepers
1	Ramban	41486	2451.95	477	1250	1727
2	Doda	11067	754.02	135	67	202
3	Kathua	4999	300.25	75	107	182
4	Udhampur	4764	228.35	94	0	94
5	Jammu	5000	317.3	80	0	80
6	Reasi	635	11.4	65	0	65
7	Kishtwar	6092	90.5	40	0	40
8	Rajouri	4477	111.49	38	0	38
9	Poonch	522	25.62	23	0	23
10	Samba	3618	134.47	20	0	20

3.2.2 Selection of number of beekeepers:

In the second stage, 200 beekeepers were chosen proportionally using the formula:

$$n_i = (N_i / N) * n \quad (1)$$

Where,

n_i = Number of beekeepers sampled in i-th district

N_i = Total number of beekeepers in i-th district density range

N = Total number of beekeepers in Jammu division

n = Total sample size chosen (200)

Therefore, 140 beekeepers were selected from Ramban, 31 from Kathua, and 29 from Jammu.

3.3 Data Collection:

Both primary and secondary data were collected. Primary data were gathered through key informant interviews and personal interviews using a standardized pre-tested questionnaire. The questionnaire captured information on the cost of honey production, production of honey and bee wax, returns, marketing channels, and constraints. A detailed marketing analysis was conducted by mapping the marketing chain. Secondary data were sourced from the Division of Entomology, SKUAST-Jammu, government publications, websites, and KVK reports.

3.4 Statistical Analysis:

The collected data was analysed using suitable economic and statistical tools.

3.5 Socio-economic characteristics:

Variables like age, education, occupation, family size, experience, number of bee colonies, costs of medicine, labour, feed etc. were analysed using descriptive statistics (mean, standard deviation, standard error).

3.6 Economic analysis:

To estimate cost and returns, data on expenses and returns from sale of honey and by-products were analysed. Cost and returns were estimated per quintal/unit hive. Profitability was measured as gross returns, gross margins, net returns and cost-benefit ratio.

3.7 Cost of Beekeeping:

$$\text{Total cost} = \text{Total Fixed Cost (TFC)} + \text{Total Variable Cost (TVC)} \quad (2)$$

3.8 Fixed cost:

Included interest on present value of fixed capital assets and depreciation on equipment and machinery (beehive, bee colony, honey extractor, smoker, gloves, feeder, bee veil). Depreciation was computed using the straight-line method. Interest on fixed assets was computed at 10% per annum.

3.9 Variable costs:

Included:

a) Cost of comb foundation sheets.
b) Cost of feed.
c) Cost of medicines and chemicals.
d) Cost of labour (Hired + owned). Family labour was calculated as per the wage of skilled labour for a day prevailing in the locality.
e) Cost on migration (transportation, land rent, labour for boarding/loading).
f) Cost on honey storage containers.
g) Miscellaneous expenses.

3.10 Returns from Beekeeping:

Gross returns = Quantity of Output × Price per Unit.

Net returns = Gross Returns – Total Cost.

Cost-Benefit Ratio (CBR) = Total Cost of Production / Gross Returns. *(Author's Note: The manuscript uses this formula. Conventionally, BCR = Gross Returns/Total Cost. The results show values >1, indicating the calculation used was likely Gross Returns/Total Cost. This should be clarified.)* A CBR > 1 denotes profit.

IV. RESULTS

4.1 Resource Structure and Social Status of Sampled Beekeepers:

Demographic information is presented in Tables 2-6.

TABLE 2
DISTRIBUTION OF BEEKEEPERS UNDER STUDY ON BASIS OF AGE GROUP

Particulars	Variables	Ramban	Kathua	Jammu			
		f #	%*	f #	% *	f #	% *
Age	18-35 years (Young)	6	3.00%	3	1.50%	4	2%
	35-50 years (Middle)	92	46%	23	11.50%	16	8%
	> 50 years (Old)	42	21%	5	2.50%	9	4.50%

TABLE 3
DISTRIBUTION OF BEEKEEPERS UNDER STUDY ON BASIS OF EDUCATION LEVEL.

Particulars	Variables	Ramban	Kathua	Jammu			
		f	%	f	%	f	%
Education level	Uneducated	36	18%	0	0.00%	1	0.50%
	Up to Primary	15	7.50%	12	6%	11	5.50%
	Matric	55	27.50%	10	5%	10	5%
	Senior Secondary	15	7.50%	2	1%	2	1%
	Graduate	14	7%	6	3%	3	1.50%
	Post Graduate	5	2.50%	1	0.55%	2	1%

TABLE 4
DISTRIBUTION OF BEEKEEPERS UNDER STUDY ON BASIS OF OCCUPATION.

Particulars	Variables	Ramban	Kathua	Jammu			
		f	%	f	%	f	%
Occupation	Agriculture & Beekeeping	82	41%	16	8%	28	14%
	Beekeeping only	57	28.50%	13	6.50%	0	0.00%
	Service	0	0.00%	0	0.00%	0	0.00%
	Housewife	0	0.00%	1	0.50%	1	0.50%
	Student	1	0.50%	1	0.50%	0	0.00%

TABLE 5
DISTRIBUTION OF BEEKEEPERS UNDER STUDY ON BASIS OF FAMILY SIZE.

Particulars	Variables	Ramban	Kathua	Jammu			
		f	%	f	%	f	%
Family size	Up to 4 members	88	44%	21	10.50%	18	9.00%
	5 - 8 members	52	26%	10	5%	11	5.50%
	More than 8 members	0	0.00%	0	0.00%	0	0.00%

TABLE 6
DISTRIBUTION OF BEEKEEPERS UNDER STUDY ON BASIS OF ANNUAL INCOME.

Particulars	Variables	Ramban	Kathua	Jammu			
		f	%	f	%	f	%
Annual income (₹)	Up to 1 Lakh	39	19.50%	1	0.50%	3	1.50%
	1-5 Lakhs	12	6%	8	4%	10	5%
	> 5 Lakhs	89	44.50%	22	11%	16	8%

4.2 Economic Analysis of Honey and Bee products:

4.2.1 Production of honey and hive products:

Production performance is shown in Table 7.

TABLE 7
PRODUCTION OF HONEY AND HIVE PRODUCTS IN STUDY AREA (IN QUINTALS)

District	No. of Beekeepers	No. of Bee colonies	Total Production		Production per colony	
			Honey	Hive products (Bee wax)	Honey	Hive products (Bee wax)
Ramban	140	12166	7196	486.6	0.59	0.04
Kathua	31	5302	1279	41.25	0.24	0.01
Jammu	29	4785	1109	38.25	0.23	0.01
Overall	200	22253	9584	566.1	0.43	0.03

4.2.2 Cost structure of honey production:

Costs are divided into fixed and variable components. Details for each district are in Tables 8, 9, and 10. A summary for the division is in Table 11.

TABLE 8
COST STRUCTURE OF PRODUCTION OF HONEY AND HIVE PRODUCTS IN RAMBAN DISTRICT

Particulars	Ramban	
	For 12166 bee colonies (₹)	Per bee colony (₹)
A. Variable costs		
Honeycomb repair	315000	25.89
Frames replacement	608000	49.97
CF Sheet addition	279810	23
Medicines	1278900	105.12
Feed / nutrition	490000	402.76
Fungicide	1500000	287.68
Temp. labour (extraction)	750000	143.84
Misc. (tools, gear)	912450	75
Interest on variable cost @ 4% p.a.	765766	62.94
Total Variable cost (TVC)	**19144150**	**1573.57**
B. Fixed costs		
Land rent	121660	10
Beehives/colony	1037652	85.29
Permanent labour (hired)	1128400	92.75
Insurance on beehives @12% p.a.	124518.24	10.23
Union fee	0	0
Interest on fixed cost @ 10% p.a.	241223.02	19.8
Total Fixed cost (TFC)	**2471453.26**	**203.14**
Total cost (TVC+TFC)	**21615603.26**	**1776.72**

TABLE 9
COST STRUCTURE OF HONEY AND HIVE PRODUCTS PRODUCTION IN KATHUA DISTRICT.

Particulars	Kathua	
	For 5302 bee colonies (₹)	Per bee colony (₹)
A. Variable costs		
Honeycomb repair	111192	20.9
Frames replacement	157917	29.7
CF Sheet addition	121946	23
Medicines	220000	41.49
Feed / nutrition	65000	119.76
Fungicide	104148	208.25
Temp. labour (extraction)	118122	22.27
Misc. (tools, gear)	111172	20.96
Interest on variable cost @ 4% p.a.	40379	7.61
Total Variable cost (TVC)	**1049876.88**	**198.01**
B. Fixed costs		
Land rent	244499.7	46.11
Beehives/colony	271022	51.11
Permanent labour (hired)	274399	51.75
Insurance on beehives @12% p.a.	32522.64	6.13
Union fee	9300	17.54
Interest on fixed cost @ 10% p.a.	831743.34	15.68
Total Fixed cost (TFC)	**7485690**	**1411.86**
Total cost (TVC+TFC)	**8535566**	**1609.87**

TABLE 10
COST STRUCTURE OF HONEY AND HIVE PRODUCTS PRODUCTION IN JAMMU DISTRICT.

Particulars	Jammu	
	For 4785 bee colonies (₹)	Per bee colony (₹)
A. Variable costs		
Honeycomb repair	91930	19.21
Frames replacement	81200	16.9
CF Sheet addition	110055	23
Medicines	180960	37.81
Feed / nutrition	48840	101.33
Fungicide	70000	181.81
Temp. labour (extraction)	81200	16.96
Misc. (tools, gear)	72500	15.15
Interest on variable cost @ 4% p.a.	138144	28.87
Total Variable cost (TVC)	**1519584**	**317.57**
B. Fixed costs		
Land rent	112230	23.45
Beehives/colony	209455	43.77
Permanent labour (hired)	192792	40.29
Insurance on beehives @12% p.a.	25134.6	5.25
Union fee	5800	12.12
Interest on fixed cost @ 10% p.a.	54541.14	11.39
Total Fixed cost (TFC)	**599953.2**	**125.38**
Total cost (TVC+TFC)	**2119537.2**	**442.95**

TABLE 11
TOTAL COST STRUCTURE OF HONEY AND HIVE PRODUCTS PRODUCTION IN JAMMU DIVISION.

Particulars	Jammu division	
	For 22253 bee colonies (₹)	Per bee colony (₹)
A. Variable costs		
Honeycomb repair	518122	23.28
Frames replacement	847117	38.06
CF Sheet addition	412811	18.5
Medicines	1679860	75.48
Feed / nutrition	6019900	270.52
Fungicide	5474148	245.99
Temp. labour (extraction)	1949322	74.11
Misc. (tools, gear)	1096122	49.25
Interest on variable cost @ 4% p.a.	944289	42.43
Total Variable cost (TVC)	**21713610.88**	**976.5**
B. Fixed costs		
Land rent	478389.7	21.5
Beehives/colony	1695591	76.19
Permanent labour (hired)	1595591	71.7
Insurance on beehives @12% p.a.	182175.24	8.18
Union fee	151000	6.78
Interest on fixed cost @ 10% p.a.	378938.5	17.03
Total Fixed cost (TFC)	**10557096.46**	**474.31**
Total cost (TVC+TFC)	**32270706.46**	**1450.81**

4.2.3 Returns structure of honey and hive products:

Returns are summarized in Tables 12-15.

TABLE 12
RETURNS STRUCTURE OF HONEY AND HIVE PRODUCTS OF RAMBAN DISTRICT.

Particulars	Ramban	
	Total	Per bee colony
Total Production (q.)	7682	0.63
Gross Return (₹)	217339800	17864.52
Net return (₹) (Gross return – Total cost)	195724197	16087.8

TABLE 13
RETURNS STRUCTURE OF HONEY AND HIVE PRODUCTS OF KATHUA DISTRICT.

Particulars	Kathua	
	Total	Per bee colony
Production (q.)	1320.25	0.249
Gross Return (₹)	22506250	7239.22
Net return (₹) (Gross return – Total cost)	29846809	4244.86

TABLE 14
RETURNS STRUCTURE OF HONEY AND HIVE PRODUCTS OF JAMMU DISTRICT.

Particulars	Jammu	
	Total	Per bee colony
Production (q.)	1147.25	0.239
Gross Return (₹)	16749750	3500.47
Net return (₹) (Gross return – Total cost)	14630212.8	3057.51

TABLE 15
TOTAL RETURNS STRUCTURE OF HONEY AND HIVE PRODUCTS OF JAMMU DIVISION.

Particulars	Total (all 3 districts)	
	Total	Per bee colony
Production (q.)	10149.5	0.45
Gross Return (₹)	256595800	11530.84
Net return (₹) (Gross return – Total cost)	224325093.5	10080.66

4.2.4 Cost benefit ratio of study area:

The Benefit-Cost Ratio (BCR) for each district and overall is shown in Table 16.

TABLE 16
BENEFIT COST RATIO OF JAMMU DIVISION.

Particulars	Ramban	Kathua	Jammu	Overall Jammu division
Benefit Cost ratio	10.05	2.64	7.9	7.95

V. DISCUSSION

5.1 Honey production and cost structure:

The study helped enumerate production levels and cost structure. Ramban had the highest number of colonies (12166), followed by Kathua (5302) and Jammu (4785). Collectively, the 200 beekeepers owned 22253 colonies. Ramban was the leading district in honey (7196 q) and beeswax (486 q) production, likely due to favourable environmental factors or greater economic activity.

The average variable cost per hive across Jammu division was ₹976.50, and average fixed cost was ₹474.31. Ramban recorded the highest costs (TVC ₹1573.57, TFC ₹203.14), indicating intensive input use. Jammu had the lowest cost structure (TVC ₹317.57, TFC ₹125.38). Dominant variable costs were feed/nutrition and fungicides; major fixed costs were hive setup and permanent labour.

The total cost per hive averaged ₹1450.81. Ramban was costliest (₹1776.72/hive), followed by Kathua (₹1609.87) and Jammu (₹442.75). These findings align with Kumar and Gill (2006), who emphasized localized practices impact cost variability.

5.2 Returns and profitability:

Gross return per colony was highest in Ramban (₹17864.52), followed by Kathua (₹7239.22) and Jammu (₹3500.47). The overall average was ₹11530.84, showing remarkable disparity in productivity and market access.

Net return averaged ₹10080.66 per colony. Ramban had the highest net return (₹16087.80). These findings align with Sharma and Bhatia (2001) on regional profitability variation.

The overall BCR was 7.95, indicating high profitability. Ramban's BCR was 10.05, Jammu's 7.90, and Kathua's 2.64. A BCR >1 signifies viability. The study concludes beekeeping is financially rewarding, similar to Shrestha (2018) in Nepal and Sharma et al. (2014) in Punjab.

VI. SUMMARY AND CONCLUSION

The study was conducted in Ramban, Kathua, and Jammu districts, selected from high, medium, and low beekeeper density categories. A sample of 200 beekeepers (140, 31, 29 respectively) was selected proportionally. Data on production, costs, and returns were collected via questionnaire and analyzed.

6.1 Key findings:

1. **Number of bee colonies:** Ramban (12166) > Kathua (5302) > Jammu (4785). Total: 22253.
2. **Production:** Total honey production was 9584 quintals, beeswax 566.10 quintals. Ramban was most productive.
3. **Costs:** Average total cost per hive was ₹1450.81. Ramban had highest cost (₹1776.72), Jammu lowest (₹442.75). Major variable costs: feed/nutrition, fungicides. Major fixed costs: beehives, permanent labour.
4. **Returns & Profitability:** Average gross return per colony was ₹11530.84; net return ₹10080.66. Ramban was most profitable (Gross return ₹17864.52/colony, Net return ₹16087.80/colony).
5. **Benefit-Cost Ratio:** Overall BCR was 7.95. Ramban: 10.05, Jammu: 7.90, Kathua: 2.64.

6.2 Conclusion:

Beekeeping is a highly profitable and economically viable enterprise in the Jammu Division, particularly in Ramban district. Variation in profitability is attributed to differences in management practices, input use, and market access.

6.3 Recommendations:

Strategic interventions such as improved market access, value addition (soaps, candles, cosmetics), cooperative models to reduce price spreads, and cost-reduction policies should be implemented. Training, infrastructure development (processing units), and better linkage to schemes like NBHM are essential to harness the full potential of beekeeping in the region.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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APPENDIX

TABLE A1
OPERATION OF BEEKEEPING AND HONEY MISSION PROJECTS IN DIFFERENT STATES AND UTS OF INDIA

S.No	States / UTs	2020-21	2021-22	2022-23	2023-24	2024-25	TOTAL
1	Andhra Pradesh	--	--	1	--	--	1
2	Arunachal Pradesh	--	1	1	3	3	8
3	Assam	1	2	7	3	4	17
4	Bihar	2	--	1	1	2	6
5	Chhattisgarh	--	2	2	--	3	7
6	Gujarat	3	4	--	1	2	10
7	Haryana	--	4	--	3	3	10
8	Himachal Pradesh	2	2	2	--	3	9
9	Jammu & Kashmir	7	--	4	1	6	18
10	Jharkhand	--	--	--	11	1	12
11	Karnataka	7	5	3	2	3	20
12	Kerala	--	4	--	--	1	5
13	Madhya Pradesh	--	4	2	2	2	10
14	Maharashtra	2	--	2	1	9	14
15	Manipur	--	1	2	1	1	5
16	Meghalaya	--	--	--	--	2	2
17	Mizoram	--	--	--	--	--	--
18	Nagaland	--	--	--	2	4	6
19	Odisha	--	1	--	1	1	3
20	Punjab	--	3	1	--	5	9
21	Rajasthan	2	2	1	--	10	15
22	Sikkim	--	1	--	--	1	2
23	Tamil Nadu	5	--	2	1	1	9
24	Telangana	--	1	4	4	4	13
25	Tripura	--	1	--	--	2	3
26	Uttar Pradesh	3	3	12	2	10	30
27	Uttarakhand	2	8	5	1	7	23
28	West Bengal	--	1	1	3	11	16
29	Andaman & Nicobar Islands	--	--	--	--	1	1
30	National/Central Level Agencies	5	2	6	1	--	14
	Grand Total	**41**	**52**	**59**	**44**	**102**	**298**

(Source- National beekeeping and honey mission, Government of India 2025)

TABLE A2
TOP EXPORT COUNTRIES/DESTINATIONS OF INDIAN HONEY IN WORLD (2023-24)

S.No.	Country	Quantity in Metric Tonnes
1	United States of America	89,494.70
2	United Arab Emirates	8,524.01
3	Saudi Arab	1,735.37
4	Qatar	1,030.19
5	Libya	1,125.26
6	Morocco	1,070.18
7	Bangladesh	682.15
8	Nepal	605.48
9	Canada	366.28
10	Portugal	554.4

(Source- Directorate General of Foreign Trade, Government of India, 2024)

TABLE A3
DISTRIBUTION OF BEE-KEEPING UNITS (DISTRICT WISE) AND HONEY PRODUCTION IN JAMMU DIVISION

S. No.	District	Bee Colonies	Honey Production	No. of Bee-keepers (Apis melifera)	No. of Bee-keepers (Apis indica)	Total
1	Ramban	41486	2451.95	477	1250	1727
2	Doda	11067	754.02	135	67	202
3	Kathua	4999	300.25	75	107	182
4	Udhampur	4764	228.35	94	0	94
5	Jammu	5000	317.3	80	0	80
6	Reasi	635	11.4	65	0	65
7	Kishtwar	6092	90.5	40	0	40
8	Rajouri	4477	111.49	38	0	38
9	Poonch	522	25.62	23	0	23
10	Samba	3618	134.47	20	0	20

(Source- SKUAST JAMMU, 2023)

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A Review on Heavy Metal Removal Techniques: A Comparative Study of Physical, Chemical, and Biological Techniques

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Abstract**—** *Contamination of water resources with heavy metals poses serious environmental and public health problems due to their toxic, persistent, and bioaccumulative nature. Common heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), nickel (Ni), and chromium (Cr) are abundant in industrial and municipal wastewater. Effective removal of these metals is essential to ensure water quality, protect aquatic ecosystems, and maintain ecological balance. This review provides a comprehensive comparative analysis of three main categories of heavy metal removal methods: physical, chemical, and biological techniques. Physical methods such as membrane filtration, coagulation-flocculation, and adsorption are widely used for their operational simplicity and efficiency. Chemical methods including precipitation, electrochemical treatment, and solvent extraction are effective but may generate secondary contaminants. Biological approaches such as bioremediation and phytoremediation offer environmentally friendly and sustainable alternatives. Additionally, emerging technologies like nanotechnology-based materials and hybrid processing systems are discussed for their potential to improve removal efficiency and sustainability. The comparative evaluation highlights the advantages and limitations of each method in terms of removal efficiency, cost, environmental impact, and scalability. The analysis concludes that hybrid or integrated treatment systems combining multiple methods provide higher efficiency and represent a promising approach for treating complex wastewaters contaminated with heavy metals.*

Keywords— heavy metal removal, physical methods, chemical methods, biological methods, wastewater treatment, hybrid systems.

Highlights:

- Comprehensive comparative review of physical, chemical, and biological heavy metal removal methods
- Evaluation of removal efficiency, cost-effectiveness, and scalability of various treatment approaches
- Discussion of advanced nanotechnology and hybrid systems for enhanced treatment performance
- Identification of advantages and disadvantages for each method in complex wastewater treatment.

I. INTRODUCTION

Heavy metals are naturally occurring elements that become toxic to living organisms when present in excessive concentrations (WHO, 1993; Sahdev et al., 2024). These elements, characterized by high atomic density and toxicity at elevated levels, pose significant environmental challenges. The toxic effects of heavy metals such as lead, mercury, and arsenic have been recognized since ancient times, with systematic scientific investigation beginning in the late 19th century (Yadav et al., 2023). Heavy metals occur naturally in the Earth's crust and are found in sediments, soil, rocks, water, and living organisms. They are persistent, non-biodegradable, and tend to bioaccumulate in the food chain. Some common heavy metals include copper, silver, zinc, cadmium, gold, and mercury (Mohammed et al., 2011; Yadav et al., 2021).

Water pollution by heavy metals represents one of the most significant environmental challenges of the 21st century. Unlike organic pollutants, heavy metals do not degrade and tend to bioaccumulate in the food chain, creating long-term environmental and health risks. Industrial processes such as mining, electroplating, battery manufacturing, textile processing, leather tanning, and chemical production are primary sources of toxic metals including lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), arsenic (As), and nickel (Ni) in water bodies (Tchounwou et al., 2012). Exposure to heavy metals, even at low concentrations, can cause various health problems including neurodegenerative disorders, renal failure, carcinogenic effects, and reproductive issues. Consequently, effective removal of heavy metals from drinking water and wastewater is essential for public safety and environmental protection (Tchounwou et al., 2012).

Over several decades, numerous methods have been developed for heavy metal removal, broadly categorized into physical, chemical, and biological approaches. These methods vary in their advantages and limitations depending on factors such as target metal species, concentration levels, water matrix characteristics, and treatment scale (Tchounwou et al., 2012). Heavy metal contamination originates from various sources including natural processes, industrial activities, agricultural practices, pharmaceutical operations, domestic wastewater, and atmospheric deposition (Tchounwou et al., 2012; He et al., 2005). Point source pollution from mining operations, foundries, smelters, and other industrial facilities represents particularly significant contributions to environmental contamination (Tchounwou et al., 2012; He et al., 2005; Fergusson, 1990; Bradl, 2005).

This review presents a detailed comparison of these three major categories of heavy metal removal methods, focusing on their operational principles, effectiveness, economic feasibility, environmental sustainability, and recent technological advances. By evaluating the strengths and limitations of each approach, this article aims to identify the most effective and sustainable strategies for removing heavy metals from contaminated water systems.

II. MATERIALS AND METHODS

This review was conducted as a systematic literature analysis to compare the effectiveness of physical, chemical, and biological methods for removing heavy metals from wastewater. Research articles, reviews, and technical reports published between 2010 and 2024 were collected from databases including ScienceDirect, Scopus, SpringerLink, Google Scholar, and ResearchGate. Keywords such as "heavy metal removal," "physical treatment," "chemical treatment," "bioremediation," "phytoremediation," and "hybrid systems" were used to identify relevant studies.

Inclusion criteria required studies focused on metals including Pb, Cd, Hg, As, Ni, and Cr, with clearly described methodologies and reported removal efficiencies. Publications lacking scientific credibility or sufficient data were excluded. Extracted information included treatment principles, performance parameters, removal efficiencies, advantages, limitations, and environmental impacts. The compiled data were systematically compared to assess the performance, cost-effectiveness, and scalability of each method. Emerging technologies, including hybrid approaches and nanotechnology-based systems, were also evaluated for their potential to enhance overall treatment effectiveness.

III. PHYSICAL METHODS FOR HEAVY METAL REMOVAL

3.1 Membrane Filtration:

Membrane filtration represents a widely used method for wastewater treatment and heavy metal removal. This approach includes processes such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), with separation mechanisms based on size exclusion, Donnan exclusion, and adsorption (Peters and Shem, 1993; Abdullah et al., 2019; Yadav et al., 2021). RO and NF have demonstrated particular effectiveness in removing metal ions such as Cu^{2+}, Ni^{2+}, Cr(VI), and As(V) (Chan and Dudeney, 2008; Muthukrishnan and Guha, 2008; Sudilovskiy et al., 2008; Taghizadeh et al., 2013; Yadav et al., 2021). Ultrafiltration, especially when combined with micellar-enhanced (MEUF) or polymer-enhanced (PEUF) techniques, improves removal of smaller metal ions (Verbych et al., 2005; Barakat and Schmidt, 2010; Huang et al., 2016; Yadav et al., 2021). These processes typically achieve removal efficiencies exceeding 90% (Vigneswaran et al., 2004; Sato et al., 1977; Yadav et al., 2021).

Research has demonstrated the effectiveness of RO and UF membranes for removing Cu(II), Ni(II), and Zn(II), as well as chromium and cyanide from metal-containing wastewater. Porous nanofiltration membranes have shown particular effectiveness for selective metal removal (Sato et al., 1977; Dutta and De, 2017; Vigneswaran et al., 2004; Huang et al., 2010; Landaburu-Aguirre et al., 2010; Yadav et al., 2021). Despite sometimes higher costs, membrane technology is valued for its high efficiency, environmental compatibility, and selective separation capabilities, making it a primary technique for treating heavy metal contaminated wastewater (Sato et al., 1977; Bhattacharyya et al., 1978; Dutta and De, 2017; Yadav et al., 2021).

3.2 Coagulation and Flocculation:

Coagulation and flocculation are established physicochemical processes for removing heavy metals from wastewater. Coagulation involves neutralizing the surface charge of colloidal particles, causing destabilization and aggregation. Common coagulants include aluminum sulfate (alum), polyaluminum chloride (PACl), magnesium chloride ($MgCl_2$), and polyethyleneimine (PEI) (Pang et al., 2011; Yadav et al., 2021). Flocculation follows coagulation, where destabilized particles are gently mixed to form larger flocs through bridging with polymeric additives (Tripathy and De, 2006; Yadav et al., 2021). Chitosan, a natural biopolymer, has also demonstrated effectiveness as an eco-friendly coagulant (Yang and Zall, 1984; Yadav et al., 2021).

This integrated process is widely used for drinking water purification and industrial wastewater treatment (Teh and Wu, 2014; Teh et al., 2016; Yadav et al., 2021). According to the U.S. Environmental Protection Agency (1978), lime treatment and coagulation with iron sulfate or alum can achieve up to 98% removal of lead, cadmium, and chromium at optimal pH conditions. Research has shown that iron sulfate achieves approximately 98% chromium removal at pH 6.5-9.3, while $FeCl_3$ enhances removal of Cu, Pb, Zn, and Ni (Johnson et al., 2008; Yadav et al., 2021). Coagulation-flocculation remains an economically viable and effective technique for heavy metal removal in various water treatment applications.

3.3 Ion Exchange:

Ion exchange is a highly effective method for removing heavy metals from wastewater through exchange of metal ions with less harmful ions such as sodium (Na^+) or potassium (K^+) on specialized resin materials. These resins contain functional groups that selectively bind specific metal ions including lead (Pb^{2+}), cadmium (Cd^{2+}), mercury (Hg^{2+}), and copper (Cu^{2+}). The process is reversible, with saturated resins regenerated using concentrated solutions (typically NaCl or HCl) that displace bound metal ions and restore resin capacity (Dabrowski et al., 2004).

Ion exchange offers advantages including high efficiency, selectivity, and effectiveness at low metal concentrations. The technology finds extensive application in electroplating, metal finishing, and battery manufacturing industries. However, treatment costs can increase significantly for high-volume applications or waters containing complex pollutant mixtures (Inglezakis and Poulopoulos, 2006).

3.4 Adsorption:

Adsorption represents one of the most commonly employed and cost-effective methods for heavy metal removal from contaminated water. This process involves accumulation of metal ions on the surface of solid adsorbents. Activated carbon remains the most widely used adsorbent due to its extensive surface area and high adsorption capacity. However, increasing attention has focused on low-cost natural alternatives including clay minerals, zeolites, and biochar derived from agricultural and industrial wastes (Babel and Kurniawan, 2003).

Adsorption effectiveness depends on multiple factors including adsorbent surface area and porosity, metal species and concentration, contact time, and solution pH. The method has demonstrated particular effectiveness for removing metals such as lead (Pb), copper (Cu), cadmium (Cd), and arsenic (As) from both drinking water and industrial effluents (Ali and Gupta, 2006). Following metal saturation, adsorbents can often be regenerated through chemical or thermal treatment. The simplicity, low energy requirements, and adaptability of adsorption make it suitable for applications in both developed and developing regions (Crini, 2006).

IV. CHEMICAL METHODS FOR HEAVY METAL REMOVAL

4.1 Neutralization:

Neutralization represents a fundamental technique for treating heavy metal contaminated waters, particularly acid mine drainage and industrial effluents. This process involves pH adjustment using alkaline agents to precipitate dissolved metals as insoluble hydroxides or carbonates. Common neutralizing agents include lime (CaO), limestone ($CaCO_3$), magnesium hydroxide ($Mg(OH)_2$), sodium hydroxide, and industrial byproducts such as fly ash and cement kiln dust. Calcium oxide is particularly effective due to its rapid hydrolysis and strong pH elevation capability, generating hydroxide ions that facilitate metal precipitation. Studies report up to 97% removal of lead (Pb) and 98% removal of antimony (Sb) and sulfate (SO_4) through neutralization processes (Balladares et al., 2018; Yadav et al., 2021).

Innovative approaches include using phosphate-rich minerals like apatite for neutralizing mine wastewater, resulting in metal precipitation and formation of potentially valuable phosphate-containing sediments (Ghirişan et al., 2007; Papassiopi et al., 1996; Conner and Hoeffner, 1998; Yadav et al., 2021). While valued for its simplicity and cost-effectiveness, neutralization requires careful management of resulting sludge and appropriate reagent selection based on water chemistry.

4.2 Chemical Precipitation:

Chemical precipitation represents the most widely used industrial method for heavy metal removal from wastewater. This technique involves converting soluble metal ions into insoluble compounds through pH adjustment or chemical additives, with subsequent removal by sedimentation, filtration, or flotation. Common precipitants include lime, caustic soda, soda ash, sodium bicarbonate, and sodium sulfide (Fu et al., 2007; Lim and Kim, 2013; Yadav et al., 2021).

Process efficiency depends on contaminant type, pH, precipitant dosage, and factors such as particle size and surface charge. Hydroxide and carbonate precipitation represent the most common approaches, with hydroxide precipitation particularly effective around pH 9. Sulfide precipitation demonstrates superior effectiveness for removing zinc, copper, and lead (Wang et al., 2018; Chen et al., 2018; Yadav et al., 2021). Despite high effectiveness, chemical precipitation generates substantial sludge volumes with associated handling and disposal costs. Novel precipitants such as dithiocarbamate derivatives (BDET) have shown promising results under acidic conditions due to their chemical stability (Matlock et al., 2002; Charerntanyarak, 1999; Yadav et al., 2021).

4.3 Electrochemical Treatment:

Electrochemical treatment employs electric current to remove heavy metals through oxidation, reduction, and deposition processes. As contaminated water passes between electrodes, metal ions undergo reduction and deposit on cathode surfaces or form insoluble compounds. Primary electrochemical approaches include electrocoagulation, where sacrificial electrodes (typically iron or aluminum) dissolve to form metal hydroxides that trap heavy metals, and electrowinning, which directly reduces metal ions at the cathode (Chen, 2004).

Electrochemical methods offer advantages including minimal chemical requirements, reduced sludge production compared to conventional precipitation, and potential for metal recovery. Removal efficiencies often exceed 90% for metals such as copper, nickel, and zinc. However, these techniques require significant energy input, electrode maintenance, and capital investment, potentially limiting large-scale applications (Mollah et al., 2004).

4.4 Solvent Extraction:

Solvent extraction represents a highly selective method for heavy metal recovery from wastewater, particularly valuable in industrial applications. This process involves transferring metal ions from aqueous to organic phases through selective chemical interactions. Organic extractants, typically with molecular weights between 210-500 and water-insoluble characteristics, are designed for specific metal recognition and complexation, enabling selective removal of copper, lead, zinc, nickel, and cadmium (Yadav et al., 2023).

Process effectiveness depends on pH, temperature, metal concentration, and extractant chemical structure. Following extraction, metal-loaded organic phases undergo stripping for metal recovery and solvent regeneration. Despite high selectivity and effectiveness, solvent extraction requires careful handling due to potential extractant toxicity and costs that may limit application for high-volume, low-concentration streams (Kislik, 2012).

4.5 Oxidation Processes:

Chemical oxidation employs strong oxidizing agents such as hydrogen peroxide (H_2O_2) and ozone (O_3) to convert heavy metals into less soluble or less toxic forms that can be removed by precipitation or filtration. Ozone has demonstrated particular effectiveness in oxidizing and precipitating metals including nickel, cadmium, and lead. While ultraviolet (UV) radiation is sometimes employed to enhance oxidation reactions, studies indicate limited direct contribution of UV to metal oxidation processes (Karwowska et al., 2022; Yadav et al., 2023).

Advanced Oxidation Processes (AOPs) enhance traditional oxidation through generation of highly reactive hydroxyl radicals (•OH), effective for rapid contaminant degradation. Common AOPs include Fenton oxidation ($H_2O_2 + Fe^{2+}$), electrochemical oxidation, photocatalytic oxidation (typically using TiO_2), and plasma discharge oxidation. These processes offer dual benefits of metal treatment and organic contaminant degradation. However, oxidation methods often require substantial energy inputs and careful control of pH and reagent doses (Du et al., 2020; Yadav et al., 2023).

V. BIOLOGICAL METHODS FOR HEAVY METAL REMOVAL

5.1 Bioremediation:

Bioremediation employs microorganisms including bacteria, fungi, and algae to detoxify or transform heavy metals in contaminated water and soil. These organisms utilize natural metabolic processes to adsorb, accumulate, or chemically modify metals, reducing their mobility and toxicity. Bioremediation approaches include in situ treatment at contamination sites and ex situ treatment where contaminated materials are removed for processing. Microbial communities may be naturally occurring, artificially introduced (bioaugmentation), or stimulated through nutrient addition (biostimulation). Recent research has demonstrated successful bioremediation of soils contaminated with lead, cadmium, and chromium, highlighting this approach as a cost-effective and environmentally compatible solution (Yadav et al., 2023).

Process effectiveness depends on environmental factors including pH, temperature, oxygen availability, and microbial community characteristics. While generally slower than physical or chemical methods, bioremediation offers advantages for long-term, sustainable remediation with minimal environmental disturbance (Gadd, 2010).

5.2 Phytoremediation:

Phytoremediation utilizes plants to remove, degrade, or immobilize heavy metals from contaminated water and soil. Derived from Greek "phyto" (plant) and Latin "remedium" (restoring balance), this approach leverages specific plant species' natural ability to absorb, accumulate, and detoxify pollutants using solar energy (Vasavi et al., 2010; Sharma et al., 2016; Yadav et al., 2021). The process involves metal ion uptake through roots with subsequent translocation to aerial parts or immobilization in the rhizosphere.

Plants selected for phytoremediation typically exhibit rapid growth, high biomass production, extensive root systems, and metal tolerance. These species are classified as excluders, accumulators, or hyperaccumulators based on their metal handling strategies (Ma et al., 2016; Yadav et al., 2021). Over 400 hyperaccumulator species have been identified, with particular attention to Thlaspi caerulescens and Indian mustard (Brassica juncea) (Ghosh and Singh, 2005; Lasat, 2002; Yadav et al., 2021).

Phytoremediation mechanisms include phytoextraction, phytostabilization, phytovolatilization, and rhizofiltration. Aquatic systems can employ plants like sunflowers and Brassicaceae species for direct metal uptake from water (Rezania et al., 2016; Yadav et al., 2021). Limitations include slow treatment rates and effectiveness primarily at lower metal concentrations. Enhancement strategies include plant growth regulators (Ullah et al., 2015; Yadav et al., 2021) and plant-microbe interactions (Rajkumar et al., 2012; Yadav et al., 2021), positioning phytoremediation as a sustainable alternative to conventional methods.

5.3 Bioaccumulation:

Bioaccumulation employs living organisms such as algae, fungi, and specific bacteria to absorb and concentrate heavy metals from contaminated environments over time. These organisms utilize natural metabolic or passive uptake processes to concentrate metals including lead, cadmium, mercury, and arsenic. Research has demonstrated bioaccumulation effectiveness for treating metal-containing wastewaters, representing a potentially low-cost and environmentally benign remediation approach (Yadav et al., 2023).

Microorganisms employed in bioaccumulation either intracellularly sequester metals or adsorb them to cell walls through mechanisms including biosorption, precipitation, and complexation. Fungi exhibit particularly high bioaccumulation potential due to their extensive surface area and metal binding capacity. This approach minimizes environmental disruption and can facilitate on-site treatment. However, bioaccumulation effectiveness can be limited by environmental variables including pH fluctuations, temperature variations, and co-contaminant presence. Despite these limitations, bioaccumulation represents a promising component of integrated biological treatment systems for heavy metal removal (Yadav et al., 2023).

VI. EMERGING AND HYBRID TECHNOLOGIES:

Recent advances in heavy metal removal focus on nanotechnology-enhanced materials and integrated hybrid systems. Nanomaterials including carbon nanotubes, metal oxide nanoparticles, and bionanocomposites demonstrate exceptional adsorption capacities and selectivity due to their high surface area-to-volume ratios and tunable surface chemistries (Qu et al., 2013). Hybrid systems combining physical, chemical, and biological approaches offer synergistic benefits, addressing limitations of individual methods. Examples include membrane bioreactors, electrocoagulation coupled with adsorption, and phytoremediation enhanced with soil amendments. These integrated approaches typically achieve higher removal efficiencies while reducing operational constraints, proving particularly effective for complex industrial wastewaters containing mixed contaminant streams.

VII. COMPARATIVE ANALYSIS AND DISCUSSION

The evaluation of physical, chemical, and biological heavy metal removal methods reveals distinct performance characteristics, operational requirements, and application domains. Physical methods generally offer high removal efficiencies and operational simplicity but may involve significant energy consumption or material costs. Chemical approaches provide rapid treatment and high effectiveness but often generate secondary waste streams. Biological methods offer environmental sustainability and lower operational costs but typically require longer treatment times and are sensitive to environmental conditions.

TABLE 1
COMPARATIVE SUMMARY OF HEAVY METAL REMOVAL METHODS

Method Category	Specific Technique	Removal Efficiency	Advantages	Limitations	Typical Applications
Physical	Membrane Filtration	90-99%	High efficiency, selective separation, minimal chemical use	Membrane fouling, high energy/cost, concentrate disposal	Industrial wastewater, drinking water
	Adsorption	70-95%	Cost-effective, wide material availability, simple operation	Adsorbent regeneration, selectivity issues, saturation limits	Municipal/industrial wastewater, groundwater
	Coagulation-Flocculation	80-98%	Effective for multiple metals, established technology, scalable	Sludge production, chemical consumption, pH sensitivity	Drinking water, industrial pretreatment
Chemical	Chemical Precipitation	85-99%	High efficiency, simple operation, cost-effective	Sludge volume, chemical consumption, pH control needed	Mining, electroplating, battery manufacturing
	Electrochemical Treatment	90-99%	Minimal chemicals, metal recovery potential, automation compatible	High energy, electrode maintenance, capital cost	Metal finishing, electronics, precious metal recovery
	Solvent Extraction	90-99%	High selectivity, metal recovery, concentrated product streams	Organic solvent use, multi-stage process, cost	High-value metal recovery, concentrated streams
Biological	Bioremediation	60-90%	Environmentally friendly, low cost, minimal secondary waste	Slow process, environmental sensitivity, monitoring needed	Soil/sediment, low-concentration wastewater
	Phytoremediation	50-85%	Solar-powered, soil improvement, carbon sequestration	Seasonal limitations, slow, depth limited	Constructed wetlands, mine tailings, agricultural runoff
	Bioaccumulation	70-95%	High selectivity, low energy, potential resource recovery	Biomass handling, process control, scalability challenges	Low-concentration streams, polishing treatment

Hybrid systems combining multiple approaches demonstrate particular promise for addressing complex contamination scenarios. For instance, combining chemical precipitation with membrane filtration can reduce sludge volumes while enhancing effluent quality. Integrating biological treatment with physical separation can improve overall system resilience and reduce chemical consumption. The selection of appropriate treatment technology depends on specific factors including wastewater characteristics, regulatory requirements, economic considerations, and sustainability goals.

VIII. CONCLUSION AND FUTURE PERSPECTIVES

The comparative analysis of physical, chemical, and biological heavy metal removal methods reveals that no single approach universally addresses all contamination scenarios. Physical methods offer efficiency and reliability but often at higher operational costs. Chemical methods provide rapid treatment but may generate secondary wastes. Biological approaches offer sustainability advantages but typically require longer treatment periods. The optimal technology selection depends on multiple factors including target metals, concentration levels, water chemistry, treatment scale, economic constraints, and regulatory requirements.

Hybrid systems integrating multiple treatment modalities represent the most promising direction for advanced heavy metal removal. These integrated approaches can leverage synergies between different mechanisms, overcoming individual limitations while enhancing overall performance. Future research should focus on developing cost-effective nanomaterials with enhanced selectivity, optimizing hybrid system configurations, improving biological process efficiency through genetic and metabolic engineering, and advancing real-time monitoring and control systems. Additionally, life cycle assessment and techno-economic analysis should guide technology selection and optimization for sustainable water treatment solutions.

As industrial activities continue to expand and water quality standards become increasingly stringent, the development and implementation of efficient, cost-effective, and environmentally sustainable heavy metal removal technologies remain critical for protecting water resources and public health worldwide.

AUTHOR CONTRIBUTIONS

Sahdeva contributed to the conceptualization of the study, data collection, analysis, and preparation of the initial manuscript draft. Dr. Shweta Choubey contributed to supervision, methodology design, critical revision of the manuscript, and overall guidance of the research work. Dr. Ajay Vikram Ahirwar contributed to data interpretation, validation of results, and review and editing of the manuscript. All authors read and approved the final manuscript.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Socio Economic Attributes of Wheat Growers in Mid Hills of Kangra Valley in Himachal Pradesh—An Appraisal

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Abstract—*The present study examines the socio-economic profile of wheat growers in Kangra Valley of Himachal Pradesh. Using a multistage random sampling design, 80 wheat growers were selected from ten villages across two randomly selected blocks. Results revealed that most farmers (53.75%) were smallholders with less than one hectare of land, indicating limited potential for large-scale mechanization and a focus on subsistence agriculture. Literacy rates among farm heads exceeded 90%, with large farmers showing slightly higher literacy (94.59%) than small farmers (93.02%), suggesting receptiveness to improved technologies. Agriculture remained the primary occupation (69.75% of household workers). Land use analysis showed cultivated land accounted for 81.43% of operational holdings, with 65.05% under irrigation. Wheat dominated the rabi season, occupying 39.04% of gross cropped area, while maize (25.27%) and paddy (12.83%) were major kharif crops. Cropping intensity averaged 190.32%, reflecting multiple cropping practices. The average family size was 5.78 members, with 58.75% nuclear families. Farm investment in machinery and implements showed a positive correlation with farm size, averaging ₹2,76,998 for small farms and ₹3,65,758 for large farms. Livestock inventory averaged 1.83 animals per farm, dominated by cows (39.36%) and buffaloes (33.29%). The study highlights the predominance of smallholders, high literacy, and diversified livelihood strategies in the region.*

Keywords— Wheat growers, family size, age, education, literacy rate, occupation, cropping pattern, farm investment, landholding, livestock.

I. INTRODUCTION

Wheat is predominantly a rabi crop in Kangra, sown from mid-September to November and harvested between mid-April and June. Agriculture is the main occupation in the district, with wheat playing a pivotal role in the local agrarian economy and food security. Kangra has approximately one lakh hectares of cultivable land, about 92,000 hectares of which are typically dedicated to wheat cultivation. A significant challenge is that only about 36% of the district's land has irrigation facilities, making most farmers reliant on rainfall. Wheat is typically grown in rotation with maize or rice and adapts to various soil types in the region, excluding waterlogged areas. Yield is susceptible to rainfall variability, particularly dry spells in January.

Examining the socio-economic attributes of wheat growers is essential as these factors influence farm management, technology adoption, productivity, and overall livelihoods, thereby guiding effective policy formulation and agricultural development strategies. Socio-economic status—including age, education, landholding size, and income—affects farmers' capacity and willingness to adopt new technologies and invest in modern inputs. Understanding these profiles helps identify specific challenges, such as limited access to credit, high input costs, or lack of machinery among smallholders. Tailored agricultural programs can then be designed to align with farmers' real-world conditions. Furthermore, socio-economic surveys reveal resource availability—family labour, irrigation access, farm assets—which are vital inputs for research and project planning. This study therefore examines the social and economic status of wheat growers in Kangra Valley to inform targeted interventions and support sustainable agricultural development.

II. METHODOLOGY

2.1 Study Area:

The study was purposively conducted in Kangra district of Himachal Pradesh. According to the Statistical Abstract of Himachal Pradesh (2022-23), Kangra holds the first position in area and production of wheat among the state's twelve districts. Wheat is cultivated on 86,493 hectares with a production of 192,804 MT, accounting for 27% of the state's total area and production, making it a suitable region for this study.

2.2 Sampling Design and Sample:

A multistage random sampling design was employed. First, a complete list of wheat-growing blocks was prepared with the district Agriculture Department's consultation. Two blocks, Nurpur and Indora, were randomly selected. Second, a list of wheat-growing villages was prepared for each block with the Block Development Office's assistance, and five villages per block were randomly selected. Third, a list of wheat growers in each selected village was prepared, and eight farmers were randomly chosen per village, resulting in a total sample of 80 farmers.

2.3 Categorization of Farmers:

Farmers were classified into small and large categories using the cumulative square-root frequency method, with 1 hectare as the demarcation line. Small farmers (<1 ha) numbered 43, and large farmers (1–3 ha) numbered 37.

2.4 Data Collection:

Both primary and secondary data were collected. A pre-tested schedule was used to collect socio-economic data on demographic features, family size, age, education, occupation, inventory, farm machinery investment, livestock composition, and land use for 2024–25. Secondary data were obtained from the Agriculture Department and Block Development Offices.

2.5 Analytical Framework:

Data were analyzed using simple tabular analysis, averages, percentages, and ratios to present the socio-economic profile.

III. RESULTS AND DISCUSSION

3.1 Landholding Distribution:

Table 1 shows that 53.75% of sampled farmers were smallholders (<1 ha), while 46.25% were large farmers (1–3 ha). This reflects the fragmented landholding pattern typical of hill regions, consistent with Kaur et al. (2023). Smallholders often focus on subsistence, while larger farmers engage in commercial surplus production.

TABLE 1
DISTRIBUTION OF SAMPLED HOUSEHOLDS BY LANDHOLDING SIZE

Farm Category	Size of Land Holding	Number of Farmers	Percentage
Small	<1 ha	43	53.75
Large	1–3 ha	37	46.25
Overall		80	100

3.2 Demographic Profile:

The average family size was 5.78 members, with large farms averaging 6.03 and small farms 5.56 (Table 2). Nuclear families predominated (58.75%), slightly more among small farms (60.47%). Joint families accounted for 41.25%. The gender ratio was balanced, with males comprising 33.44% and females 32.03% of the household population. These findings align with Menon (2023), who reported similar family patterns in Kangra.

TABLE 2
DEMOGRAPHIC PROFILE BY FARM CATEGORY

Particulars	Small	Large	Overall
Number of families	43	37	80
Joint family (%)	39.53	43.24	41.25
Nuclear family (%)	60.47	56.76	58.75
Average family size	5.56	6.03	5.78
Average number of males	1.88	1.99	1.93
Average number of females	1.75	1.97	1.85
Gender ratio for male	38.81	33.00	33.44
Gender ratio for female	31.47	32.67	32.03

3.3 Age Distribution of Household Heads:

Most household heads (45%) were aged 41–60 years, indicating an experienced farming population (Table 3). Those under 40 years constituted 37.5%, suggesting moderate youth involvement, while those above 60 years accounted for 17.5%. This age structure supports continuity in traditional practices while allowing gradual adoption of modern techniques (Kumar et al., 2025).

TABLE 3
AGE-WISE DISTRIBUTION OF HOUSEHOLD HEADS

Age Group (Years)	Small (%)	Large (%)	Overall (%)
Up to 40	32.56	35.14	37.5
41–60	48.84	48.65	45
Above 60	18.6	16.21	17.5

3.4 Educational Status:

Literacy among household heads was high (93.75%), with large farmers showing marginally higher literacy (94.59%) than small farmers (93.02%) (Table 4). Most heads had completed senior secondary (27.5%), matriculation (23.75%), or graduation (22.5%). Only 6.25% were illiterate. High literacy enhances capacity to adopt innovations, as noted by Mishra and Ghadei (2015).

TABLE 4
EDUCATIONAL STATUS OF HOUSEHOLD HEADS (NUMBER)

Education Level	Small	Large	Overall
Illiterate	3(6.98)	2(5.41)	5(6.25)
Primary	6(13.95)	4(10.81)	10(12.50)
Middle	3(6.98)	3(8.11)	6(7.50)
Matriculation	10(23.26)	9(24.92)	19(23.75)
Senior Secondary	12(27.91)	10(27.03)	22(27.50)
Graduation and above	9(20.93)	9(24.32)	18(22.50)
Total	**43(100.00)**	**37(100.00)**	**80(100.00)**
Literacy Rate (%)	**93.02**	**94.59**	**93.75**

Note: Figures in the brackets indicate percentages to the total in each category.

3.5 Occupational Pattern:

Agriculture was the primary occupation, engaging 69.75% of household workers (Table 5). Service (15.23%) and business (15.03%) provided supplementary income. Gender distribution in agriculture was nearly equal (males 51.79%, females 48.21%), highlighting women's active role. This aligns with Pratyush (2022), who reported similar occupational patterns in Himachal Pradesh.

TABLE 5
OCCUPATIONAL DISTRIBUTION

Occupation	Small (%)	Large (%)	Overall (%)
Service	16.67	13.88	15.23
Business	15.71	14.4	15.03
Agriculture	67.63	71.72	69.75
Av. of male in agriculture	51.18	52.33	51.79
Av. of female in agriculture	48.82	47.76	48.21

3.6 Farm Investment in Implements and Machinery:

Investment increased with farm size, averaging ₹2,76,998 for small farms and ₹3,65,758 for large farms (Table 6). Major implements (95.32% of investment) were dominated by tractors (56.62%) and threshers (28.16%). Minor implements (4.68%) included ploughs, levellers, and grass cutters. This reflects a trend toward mechanization to enhance productivity, consistent with Ruchika (2016).

TABLE 6
AVERAGE INVESTMENT ON FARM IMPLEMENTS AND MACHINERY (₹/FARM)

Particulars	Small	Large	Overall
Major Implements			
Tractor	1,45,400.00(55.12)	2,03,657.98(58.36)	1,72,344.32(56.62)
Threshers	75,946.87(28.79)	95,735.76(27.43)	85,099.23(28.16)
Power Tiller	27,786.67(10.53)	31,786.65(9.11)	29,636.66(9.87)
Others	3009.83(5.56)	3382.82(5.10)	3182.34(5.35)
Subtotal	**2,63,798.30(100.00)**	**3,48,986.72(100.00)**	**3,03,197.94(100.00)**
Minor Implements			
Plough	5,177.00(39.22)	7,569.47(45.13)	6,283.52(41.96)
Leveller	2,845.45(21.56)	3,184.45(18.99)	3,002.24(20.37)
Grass Cutter	2,167.23(16.42)	2,634.77(15.71)	2,383.47(16.09)
Others	14664.76(22.28)	17806.33(20.17)	16117.74(21.58)
Subtotal	**13,199.51(100.00)**	**16,771.51(100.00)**	**14,851.56(100.00)**
Total Average Investment	**2,76,997.81**	**3,65,758.23**	**3,18,049.50**

Note: Figures in the brackets indicate percentages to the total in each category.

3.7 Livestock Inventory:

Livestock averaged 1.83 animals per farm, dominated by cows (39.36%) and buffaloes (33.29%) (Table 7). Young stock comprised 13.23%, goats 7.63%, and poultry 6.49%. Dairy animals provide supplementary income and draft power, integral to mixed farming systems (Pratyush, 2022).

TABLE 7
LIVESTOCK INVENTORY BY FARM CATEGORY (NUMBER/FARM)

Particulars	Small	Large	Overall
Cow	0.64(38.79)	0.81(39.90)	0.72(39.36)
Buffalo	0.58(35.15)	0.64(31.53)	0.61(33.29)
Young Stock	0.2(12.12)	0.29(14.29)	0.24(13.23)
Goat	0.13(7.88)	0.15(7.39)	0.14(7.63)
Poultry	0.1(6.06)	0.14(6.90)	0.12(6.49)
Total	**1.65(100.00)**	**2.03(100.00)**	**1.83(100.00)**

Note: Figures in the brackets indicate percentages to the total in each category.

3.8 Land Use Pattern:

Cultivated land accounted for 81.43% of operational holdings, with 65.05% irrigated (Table 8). Large farms had a higher proportion of cultivated (86.57%) and irrigated land (69.54%). Orchards covered 5.78%, while pastures and non-agricultural uses constituted smaller shares. Efficient land use and irrigation management support crop productivity in the hills (Mohan et al., 2025).

TABLE 8
LAND USE PATTERN (HECTARES)

Particulars	Small	Large	Overall
Cultivated area	0.67(77.01)	1.74(86.57)	1.16(81.43)
- Irrigated	0.41(61.19)	1.21(69.54)	0.78(65.05)
- Unirrigated	0.26(38.81)	0.53(30.46)	0.38(34.95)
Orchard area	0.06(6.90)	0.09(4.48)	0.07(5.78)
Total operational land	0.73(83.91)	1.83(91.04)	1.24(87.21)
Pastures land	0.03(3.45)	0.04(1.99)	0.03(2.77)
Land put to non-agricultural use	0.11(12.64)	0.14(6.97)	0.12(10.02)
Total land holding	0.87(100.00)	2.01(100.00)	1.40(100.00)

Note: Figures in the brackets indicate percentages to the total in each category

3.9 Cropping Pattern:

Wheat occupied 39.04% of gross cropped area, dominating the rabi season (Table 9). Maize (25.27%) and paddy (12.83%) were major kharif crops. Vegetables and fodder crops occupied smaller shares. Cropping intensity was 190.32%, indicating intensive land use. Fruit crops like kinnow, guava, and sweet orange provided diversification. This pattern balances food security with income generation, typical of hill agriculture (Sood, 2024).

TABLE 9
CROPPING PATTERN (% OF GROSS CROPPED AREA)

Crops	Small (%)	Large (%)	Overall (%)
Wheat	38.69	39.2	39.04
Maize	23.36	26.14	25.27
Paddy	11.68	13.35	12.83
Vegetables	14.6	12.04	12.61
Fodder	2.92	2.56	2.68
Fruits	4.38	2.56	3.12
Gross cropped area (ha)	1.37	3.52	2.36
Net sown area (ha)	0.73	1.83	1.24
Cropping Intensity (%)	**187.67**	**192.34**	**190.32**

IV. CONCLUSION

This study reveals that wheat farming in Kangra Valley is characterized by small landholdings, high literacy, and a mixed livelihood strategy combining agriculture, livestock, and off-farm activities. The predominance of smallholders (53.75% with <1 ha) underscores the need for targeted policies supporting subsistence farmers, including improved access to credit, inputs, and small-scale mechanization. High literacy (93.75% among household heads) presents an opportunity for effective extension services and technology dissemination. Agriculture remains the primary occupation, with significant involvement of women (48.21% of agricultural labour). Investment in farm machinery correlates positively with farm size, highlighting disparities in capacity to mechanize. Livestock, particularly dairy animals, forms a crucial supplementary income source. Land use is efficient, with high cropping intensity is 190.32% and a significant irrigated portion (65.05% of cultivated area). The cropping pattern is dominated by wheat, maize, and paddy, with limited diversification into high-value fruits and vegetables.

Policy Implications:

1. Focus on smallholder support through tailored credit schemes and subsidized inputs.
2. Leverage high literacy for digital extension and training in improved agronomic practices.
3. Promote water-efficient irrigation technologies to optimize water use.
4. Encourage diversification into high-value horticulture and vegetable crops to enhance income.
5. Strengthen livestock development programs, particularly dairy, for additional revenue.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Comparative Evaluation of Domestic Sewage and Well Water Irrigation on the Mineral Profile, Nutritional, and Nutraceutical Attributes of *Cajanus cajan* (L.) Millsp.

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Abstract— *Water scarcity has severely impacted the global economy, livelihoods, and environmental quality, driving the use of municipal and industrial wastewater as an alternative irrigation source in urban and peri-urban agriculture. This practice addresses water deficits but raises concerns about risks to human and environmental health from contaminants. This study evaluated the effect of diluted domestic sewage wastewater (used in semi-urban Palakkad) versus well water (used in rural areas) on pigeon pea (Cajanus cajan). We conducted a comprehensive analysis of irrigation water, soil, and various plant parts (seeds, leaves, stems, pods) for physicochemical parameters, proximate composition, full mineral profile, heavy metals, and in vitro antioxidant activity. Results indicated that most physicochemical parameters of the irrigation water were within FAO permissible limits, though the semi-urban source showed elevated iron, phosphate, and alkalinity. Critically, concentrations of toxic heavy metals (Ni, Cr, Cd, Pb, Cu) in soils and, most importantly, in the edible seeds remained well below WHO/FAO safety thresholds. Proximate analysis confirmed good nutritional quality in seeds from both sources (e.g., protein: 15.5-17.6 g/100g). Plants irrigated with both water types exhibited significant in vitro antioxidant activity across five complementary assays (FRAP, DPPH, ABTS, Metal Chelating, NO Scavenging), which was strongly correlated with phenolic content. A notable finding was the elevated iron content in seeds, suggesting a natural bioaccumulation propensity in C. cajan. The study concludes that, under the observed conditions, the use of diluted domestic sewage wastewater did not induce harmful heavy metal accumulation in C. cajan, maintained its nutritional value, and preserved its bioactive potential. This supports its role as a viable and sustainable irrigation alternative, contributing to water security and nutrient recycling. Non-seed tissues (leaves, pods) showed high phenolic content, indicating value for nutraceutical use or animal feed.*

Keywords*— *Cajanus cajan, sewage wastewater irrigation, heavy metals, food safety, proximate composition, antioxidant activity, sustainable agriculture.

I. INTRODUCTION

The global population is expected to exceed nine billion people by 2050. Population increases are expected to further increase water usage and wastewater production. The world is facing a water quality crisis resulting from continuous population growth, urbanization, land use change, industrialization, food production practices, increased living standards, unsustainable water use practices and wastewater management strategies. Freshwater resources are continuously depleting over time due to a combination of climatic, political, and anthropogenic factors. This growing scarcity has compelled many farmers to use sewage water as an alternative irrigation source for cultivation. Wastewater has a direct impact on the biological diversity of aquatic ecosystems and its inappropriate management is capable of disrupting the fundamental integrity of life support systems, on which a wide range of sectors, from urban development to food production and industry (Buonocorea et al., 2016; Khan et al., 2025).

Use of domestic and industrial wastewater in agriculture for irrigating crops appears to be a lucrative option. Besides being a source of irrigation water, these waste waters contain appreciable amounts of plant nutrients. In India, total wastewater generated per annum from 200 cities is about 2600 Mm3 and also the use of sewage effluents for irrigating agricultural lands is on the rise, especially in the peri-urban area. The increasing demand for freshwater, driven by rapid urbanization and residential development, has intensified pressure on existing water resources. Consequently, the use of sewage water for irrigation in agricultural practices has become increasingly common. This trend substantially alters the physicochemical characteristics of natural water bodies, generates significant economic activity, and supports numerous livelihoods, particularly among socioeconomically disadvantaged farming communities. However, the reuse of wastewater in agriculture presents several environmental and health-related risks. Some impacts are short-term, such as contamination by microbial pathogens, while others are long-term, including the gradual accumulation of salts and heavy metals in the soil, which can adversely affect soil fertility and crop productivity. The controlled reuse of treated wastewater offers a potential strategy to mitigate pressure on conventional freshwater resources by redirecting part of this water for agricultural and industrial applications. The nutrient content present in treated wastewater can enhance plant growth, thereby transforming potential pollutants into valuable resources. Given that the agricultural sector accounts for approximately 92% of global freshwater consumption, wastewater reuse represents a pragmatic approach toward sustainable water management. Nonetheless, in many regions, untreated sewage and industrial effluents are directly discharged onto agricultural lands and used for cultivating crops, including vegetables, posing considerable ecological and public health concerns (FAO, 2010; Liu et al., 2015; Balkhair and Ashraf, 2016; Shakir et al., 2017).

The utilization of wastewater treatment plant effluents for irrigation in agricultural and green areas offers several significant advantages, including cost-effectiveness, year-round availability, and reduced treatment and disposal expenses (Ganji et al., 2024). These effluents are often rich sources of organic matter and essential plant nutrients, which can enhance soil fertility and crop productivity. However, their continuous application can also lead to the accumulation of heavy metals such as Fe, Mn, Cu, Zn, Pb, Cr, Ni, Cd, and Co in the receiving soils. The elevated concentrations of these metals pose serious environmental and health concerns, as they may enter the food chain through the cultivation of edible crops. Consequently, the consumption of food grown using sewage wastewater irrigation increases the potential risk of heavy metal exposure to the general population. (Surdyk et al., 2025; Siddhuraju et al., 2025)

Pigeon pea (*Cajanus cajan*) is an important grain legume cultivated and consumed extensively across tropical and semi-arid regions of the world, including Asia, Africa, Latin America, and the Caribbean (Fatokimi andTanimonure, 2021). The crop exhibits strong adaptability to rain-fed conditions owing to its deep root system, heat tolerance, and rapid growth rate, which make it particularly suitable for cultivation in semi-arid environments. Globally, pigeon pea ranks as the sixth most important legume, occupying approximately 5.4 million hectares, with an estimated annual production of 4.49 million tons. It is commonly fried with spices, consumed as germinated seeds either raw or cooked, or combined with cereals to enhance nutritional value. Pigeon pea offers multiple agronomic and nutritional benefits, serving as both a valuable source of human food and animal feed while also contributing to soil fertility enhancement through nitrogen fixation. Nutritionally, pigeon pea seeds are rich in protein (20–22%), fat (1–2%), carbohydrates (approximately 65%), and ash (6.8%), and they provide considerable amounts of dietary fiber and essential minerals. Moreover, pigeon pea is recognized for its high content of bioactive phenolic compounds, including total phenolics, total flavonoids, and strong antioxidant activity. The seed protein of pigeon pea exhibits favorable functional properties such as solubility, water- and oil-absorption capacity, emulsification, and foaming, which enhance its potential for use in various food formulations. (Anjulo et al., 2020; Haji et al., 2024).

C. cajan is widely distributed throughout the tropics as a pulse crop, mainly for grain and also as a cover crop or green manure crop. It is drought-tolerant and has better adaptation to poor soil condition than most tropical legumes. The foliage contains crude protein and fat contents of 20.2% and 1.7%, respectively. These legumes are classified as minor grain legumes because they are underutilized as human food in Nigeria due to the long hours of cooking them before consumption. However, utilization could be expanded because they are sources of dietary protein. They are indigenous and usually cultivated in association with arable crops like yam and cassava. Large biomass of these legume foliage is produced annually (Ajayi, 2011).

C. cajan, among legumes, has an important place in the diet of many people in the world. It is one of the oldest food crops. India alone contributes over 90% of the world's pigeon pea production. It is also a food crop in many other tropical countries and is commercially important in East Africa, the Caribbean, and Latin America. Different parts of this plant are used in traditional medicine in China and Brazil. The antioxidant, antidiabetic, antimicrobial, DNA damage protective and xanthine oxidase inhibitory properties of this plant are generally established. Extracts from this crop are reported to be effective for the treatment of diabetes, dysentery and hepatitis. Leaves have been useful for the treatment of wounds, bedsores, malaria and diet induced hypercholesterolemia, whereas the seeds are sedative and used to treat cough, hepatitis, plasmodial diseases and diabetes. In most of these cases, the effect or molecules need to be identified and characterized. Chemical investigations have been successful in bringing out the major molecules from each part of the plants, especially the leaves and seeds. Leaves are rich in polyphenolic com-pounds such as luteolin and apigenin, flavonoids such as genistein and genistin, anticancerous antiflavone cajanol, stilbenes such as cajaninstilbene acid (CSA) and pinostrobin, antibacterial coumarin cajanuslactone and cajaminose, phenylalanine, and hydroxybenzoic acid with anti-sickle cell disease effects (Mathew et al., 2017).

Considering the escalating global reliance on wastewater irrigation as an alternative water resource, it is imperative to evaluate its implications for soil and water quality, as well as for the safety of crops cultivated under such conditions. Domestic wastewater, derived mainly from household activities, generally contains lower industrial contaminants and provides a richer balance of essential nutrients and organic matter than mixed sewage wastewater, while offering greater soil fertility benefits than treated sewage effluents, which often lose nutrient content during treatment. These characteristics make domestic wastewater a potentially valuable resource for enhancing soil nutrient status, improving microbial activity, and supporting better crop growth and yield with reduced dependence on chemical fertilizers. Accordingly, the present study was undertaken to investigate the environmental and food safety aspects associated with pigeon pea cultivation using domestic sewage wastewater. This research aims to provide scientific insights into the sustainability of wastewater reuse, recycling, and recharge from domestic sewage systems for agricultural purposes, while also elucidating the broader implications for soil health, crop productivity, and public health. The study was conducted in selected urban agricultural fields of Palakkad, Kerala, with a comparative assessment of pigeon pea cultivated under well-water irrigation within the same agroecological zone.

While previous research has often focused on the impact of industrial or mixed wastewater, there is a distinct lack of comprehensive studies assessing the effects of *domestic* sewage wastewater—which has a different nutrient and contaminant profile—on the safety and quality of a multipurpose crop like *C. cajan*. This study aims to fill this knowledge gap by conducting a comparative evaluation of *C. cajan* cultivated using diluted domestic sewage wastewater (semi-urban site) and conventional well water (rural site). We comprehensively assess: (1) water and soil quality parameters, (2) the translocation of essential minerals and heavy metals into various plant tissues, (3) proximate nutritional composition, and (4) the profile of bioactive compounds and associated *in vitro* antioxidant activities. The findings will provide a scientific basis for the safe reuse of domestic wastewater in sustainable legume cultivation, with implications for food security and resource management.

II. MATERIALS AND METHODS

2.1 Plant Sampling Details and Processing:

Cajanus cajan samples were collected from agricultural fields in the Palakkad district of Kerala, representing two distinct irrigation sources:

- **Semi-Urban (SU):** Cultivated using diluted domestic sewage wastewater.
- **Rural (R):** Cultivated using local well water.

From each site, mature plants were collected. Seeds were separated and divided into raw and boiled (100 °C for 15 min) portions. Other plant parts (leaves, stems, pods) were also collected. All samples were washed, oven-dried at 45±5°C, ground, and stored in airtight containers until analysis.

2.2 Water and Soil Sampling and Analysis:

Irrigation water samples were collected in pre-cleaned bottles. Standard physicochemical parameters (pH, EC, TDS, hardness, anions and nutrients) were analyzed as per APHA (2012). Composite soil samples (0-30 cm depth) were collected, processed by quartering, and analyzed for pH, EC, total organic carbon (TOC), available nitrogen (N), phosphorus (P), potassium (K), and heavy metals using standard procedures. were analyzed following the standard procedures outlined in Standard Methods for the Examination of Water and Wastewater (APHA, 2012) Samples were labelled, transported to the laboratory, shade-dried, gently ground with a mortar and pestle, and sieved. A 2 mm sieve was used for general physico-chemical and trace element analysis, while a 0.5 mm sieve was employed for organic carbon estimation. Soil parameters analyzed included pH, EC, total organic carbon (TOC), available nitrogen (Subbiah and Asija, 1956), available phosphorus (Olsen et al., 1954), available potassium (Jackson, 1973), and selected trace and heavy metals, using standard procedures (APHA, 2012).

2.3 Mineral and Heavy Metal Analysis:

Plant, soil, and water samples were digested using tri-acid (HNO_3: H_2SO_4: $HClO_4$, 9:2:1). The concentrations of 17 elements (including Na, Mg, K, Ca, Fe, Zn, Mn, Cu, Ni, Cr, Cd, Pb, As) were determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS, Perkin Elmer NexION 300X).

2.4 Proximate Composition Analysis:

The moisture content of raw and processed samples was determined using the Moisture Analyzer MA35 (Sartorius AG, Germany) at 105°C. Crude lipid (Soxhlet extraction), crude fiber and ash contents (gravimetric) were also determined through the methods outlined in the Association of Official Analytical Chemists (AOAC, 1990). The Micro-Kjeldahl method was employed to determine the total nitrogen and a nitrogen protein conversion factor is used for crude protein (N x 6.25) determination. The crude carbohydrate (also called Nitrogen Free Extractives (NFE)) content was estimated by the difference. The proximate composition was expressed as g/100 g DM. The gross energy (KJ) was determined by multiplying the percentage of crude protein, crude lipid and NFE by 16.7, 37.7 and 16.7, respectively (Siddhuraju et al., 1996).

Solvent Extraction for Bioactive Compounds:

Powdered samples were defatted with petroleum ether and subsequently extracted with 70% aqueous acetone (1:7 w/v) at room temperature for 48 h. The crude extracts were filtered, concentrated, and the percentage recovery was calculated.

2.5 Analysis of Bioactive Compounds

- **Total Phenolics and Tannins:** Total phenolic content (TPC) was determined using the Folin–Ciocalteu method (FCM) as described by Siddhuraju and Becker (2003). The FCM measures the reducing capacity of samples and is considered an electron-transfer–based antioxidant assay. Briefly, 100 µl of extract was diluted to 1 ml with distilled water, followed by the addition of 0.5 ml Folin–Ciocalteu reagent (1:1, v/v) and 2.5 ml of 20% sodium carbonate solution. The reaction mixture was vortexed and incubated in the dark for 40 min, and absorbance was recorded at 725 nm against a reagent blank. Analyses were performed in triplicate, and results were expressed as tannic acid equivalents (TAE). Tannin content was estimated after polyvinyl polypyrrolidone (PVPP) treatment according to Siddhuraju and Manian (2007). One hundred milligrams of PVPP was mixed with 1.0 ml distilled water and 1.0 ml phenolic extract, vortexed, and incubated at 40°C for 4 h. After centrifugation at 3000 × g for 10 min, the supernatant containing non-tannin phenolics was analyzed for phenolic content as described above. Tannin content was calculated as: Tannin (%) = Total phenolics (%) − Non-tannin phenolics (%).
- **Total Flavonoids:** Total flavonoid content was determined by the spectrophotometric method of Zhishen et al. (1999) as outlined by Siddhuraju and Becker (2003). An aliquot of 0.1 ml of sample extract or rutin standard (0–100 mg/l) was mixed with 4 ml distilled water in a 10 ml volumetric flask. Subsequently, 0.3 ml of 5% $NaNO_2$ was added, followed after 5 min by 3 ml of 10% $AlCl_3$. At 6 min, 2 ml of 1 M NaOH was added, and the volume was made up to 10 ml with distilled water. Absorbance was measured at 510 nm against a blank. Results were expressed as mg rutin equivalents (RUT) per g extract

In Vitro Antioxidant Activity Assays:

The antioxidant capacity of the extracts was evaluated using five established assays:

1. **Ferric Reducing Antioxidant Power (FRAP):** FRAP activity was measured following the method of Benzie and Strain (1996), as modified by Pulido et al. (2000). The FRAP reagent, freshly prepared and incubated at 37°C, consisted of TPTZ, $FeCl_3 \cdot 6H_2O$, and acetate buffer (pH 3.6). The assay mixture contained 900 µl FRAP reagent, 90 µl distilled water, and 30 µl extract or methanol (blank). After incubation at 37°C for 30 min, absorbance was measured at 593 nm. $FeSO_4 \cdot 7H_2O$ (100–2000 µmol/l) was used for calibration. Antioxidant capacity was expressed as mmol Fe(II)/g extract, and EC_1 was defined as the concentration equivalent to 1 mmol/l $FeSO_4 \cdot 7H_2O$.
2. **Metal Chelating Activity:** Metal chelating activity was determined following the method of Dini et al. (1994). Briefly, 100 µl of extract was mixed with 0.05 ml of 2 mmol/l $FeCl_2$ solution. The reaction was initiated by adding 0.2 ml of 5 mmol/l ferrozine. The mixture was shaken vigorously and allowed to stand at room temperature for 10

min, after which absorbance was measured at 562 nm. Chelating activity was expressed as mg EDTA equivalents per g extract using an EDTA calibration curve (linearity range: 0.5–2.5 µg).

3. **DPPH Radical Scavenging Activity:** Assessed by the ability to scavenge the stable 2,2-diphenyl-1-picrylhydrazyl radical. The radical scavenging activity of sample extracts was measured using DPPH radical by the method of Brand-Williams et al. (1995) with some modifications. An extract of 0.1 mL prepared in methanol was mixed with 3.9 mL of $DPPH^{\cdot}$ (6×10-5mol/l methanol) and incubated in the dark for 30 min. Absorbance was read at 515 nm and the results were expressed as mmol trolox equivalents/g extract

4. **ABTS Radical Cation Scavenging Activity:** Measured by the decolorization of the 2,2'-azinobis (3-ethylbenzothiazoline-6-sulfonic acid) Triplicate determinations were made at each dilution of standard, and the percentage inhibition of the blank absorbance at 734 nm was plotted as a function of Trolox concentration (Re et al, 1999), described by (Siddhuraju and Becker, 2003). The unit of total antioxidant activity (TAA) is defined as the concentration of Trolox having equivalent antioxidant activity expressed as µmol/g sample extracts using the calibration curve of Trolox. The linearity range of the calibration curve was 0.25-1.25 mm/l. The total antioxidant activity of ASC and BHA was also measured by the ABTS•+ method for comparison.

5. **Nitric Oxide (NO) Scavenging Activity:** Nitric oxide scavenging activity was determined using the Griess reaction. Sodium nitroprusside (SNP, 5 mM) in phosphate-buffered saline (pH 7.4) was incubated with different concentrations of sample extracts at 25°C for 150 min. Nitric oxide generated from SNP reacted with oxygen to form nitrite ions, which were quantified by adding Griess reagent (1% sulfanilamide and 0.1% naphthylethylene diamine dihydrochloride in 5% phosphoric acid). Absorbance was measured at 540 nm. Ascorbic acid (ASC) and quercetin (QUE) were used as standards. Nitric oxide scavenging activity was calculated as:

$$\% \text{ Scavenging activity} = [(\text{Control OD} - \text{Sample OD}) / \text{Control OD}] \times 100 \quad (1)$$

Results for FRAP, DPPH, and ABTS were expressed as Trolox Equivalent Antioxidant Capacity (TEAC). Metal chelating activity was expressed as mg EDTA equivalent/g extract.

2.6 Statistical Analysis:

All analyses were performed in triplicate. Data are presented as mean ± standard deviation (SD). Significance of differences among means was evaluated by one-way analysis of variance (ANOVA) followed by Duncan's multiple range test ($p < 0.05$) using SPSS software (Version 21.0).

III. RESULTS AND DISCUSSION

3.1 Physicochemical Quality of Irrigation Water and Soil:

The analysis of irrigation water sources (Table 1) revealed that key parameters for both the semi-urban (diluted sewage) and rural (well water) sources, including pH, electrical conductivity (EC), total dissolved solids (TDS), chloride, and sulphate, were within the permissible ranges prescribed by FAO for irrigation. This indicates a basic suitability for agricultural use. However, water from the semi-urban source showed elevated levels of total alkalinity (254 mg/L) and phosphate (2.4 mg/L), slightly exceeding FAO (1992) thresholds, suggesting nutrient enrichment. Total hardness values (260–540 mg/L) indicated the presence of moderately hard to hard water. A more significant finding was the high concentration of iron (Fe) in both water sources (40.95–41.73 mg/L), far exceeding the FAO limit of 5 mg/L. Crucially, the concentrations of toxic heavy metals of primary concern—Nickel (Ni), Chromium (Cr), Cadmium (Cd), Copper (Cu), Lead (Pb), and Zinc (Zn)—were all below their respective FAO permissible limits, indicating that the diluted sewage was not contaminated with hazardous levels of these industrial pollutants. (FAO, 1992; Bandara et al., 2010). Nickel has been considered to be an essential trace element for human and animal health (Hassan et al., 2012). Higher concentrations of zinc can be toxic to the organism. It plays an important role in protein synthesis and is a metal that shows a fairly low concentration in surface water due to its restricted mobility from the place of rock weathering or from the natural sources. Collectively, these findings indicate that while most parameters conform to international irrigation water quality standards, urban water samples are characterized by elevated alkalinity, phosphate, and iron loads, necessitating stringent monitoring and management to mitigate long-term agro-environmental impacts.

TABLE 1
SELECTED PHYSICOCHEMICAL PARAMETERS OF IRRIGATION WATER

Parameter	Unit	Rural (Well Water)	Semi-Urban (Diluted Sewage)	FAO Permissible Limit
pH		7.16	7.02	6.5–8.5
EC	mS/cm	1.09	1.92	0.7–3.0
TDS	mg/L	530	1208	2000
Total Alkalinity	mg/L $CaCO_3$	134	254	250
Phosphate (PO_4^{3-})	mg/L	0.8	2.4	2
Iron (Fe)	**mg/L**	**41.73**	**40.95**	**5**
Nickel (Ni)	mg/L	0.005	0.003	0.2
Chromium (Cr)	mg/L	0.0045	0.005	0.1
Cadmium (Cd)	mg/L	0.0075	0.0075	0.01

Soil analysis (see Supplementary Table S3) indicated near-neutral pH (6.27–6.29), low salinity (EC: 0.08–0.12 dS/m), and moderate fertility. Most importantly, the levels of heavy metals (Ni, Cr, Cu, Pb, Zn, Cd) were found to be orders of magnitude lower than the WHO/FAO permissible limits for agricultural soils. ha and potassium between 490–650 kg/ha, with urban soils recording higher values.

Heavy metal analysis showed that Ni (0.44–0.48 mg/kg), Cr (2.1–5.2 mg/kg), Cu (2.3–4.5 mg/kg), Pb (0.11–0.22 mg/kg), Fe (84–86.5 mg/kg), and Zn (0.82–1.06 mg/kg) were all below the WHO (1996) permissible limits of 80, 100, 30, 100, 200, and 200 mg/kg respectively, except for Fe which was relatively high though still within acceptable agricultural ranges (Iyaka, 2011; Mandal et al., 2011; Wuana and Okieimen, 2011; Khajekar and Deshmukh, 2017; Colombo et al., 2014; Baran et al., 2018). Cd was not detected in any samples. The mineral profiling of C. cajan plant parts revealed Ni (0–0.081 mg/kg), Cr (0–0.02 mg/kg), Cu (0.001–0.13 mg/kg), Zn (0.065–0.74 mg/kg), Mn (0.03–0.30 mg/kg), and Pb (0–0.12 mg/kg) within safe dietary limits (FAO/WHO, 1976; Leshe and Tessema, 2014; Emamverdian et al., 2015). However, Fe content in seeds (96.60–173.19 mg/kg), leaves (143–221.23 mg/kg), stems, and pods consistently exceeded the FAO/WHO (1976) permissible limit of 48 mg/kg, suggesting potential iron accumulation in edible parts of the plant. Overall, while most soil and plant mineral levels remain within international safety limits, elevated iron concentrations pose a significant concern for crop and food safety. This confirms that, under the studied conditions, irrigation with this diluted sewage water had not led to a significant accumulation of toxic metals in the soil profile, mitigating a major long-term risk associated with wastewater reuse.

3.2 Heavy Metal and Essential Mineral Translocation to *C. cajan* Tissues:

The most critical aspect of this study pertains to food safety—the transfer of elements from soil and water into the edible parts of the plant. The analysis of edible seeds (Table 2) yielded reassuring results. Concentrations of potentially toxic heavy metals were all found to be within safe limits for human consumption as per FAO/WHO standards.

- **Toxic Elements:** Cadmium (Cd) was not detected (ND) in any seed sample. The concentrations of Nickel (Ni: 0.01–0.08 mg/kg), Chromium (Cr: 0.01–0.02 mg/kg), and Lead (Pb: 0–0.01 mg/kg) were substantially lower than their respective permissible limits (e.g., 2.3 mg/kg for Cr, 2 mg/kg for Pb).
- **Essential Minerals:** The seeds were confirmed as good sources of essential minerals. Potassium (K) content was high (73.7–954.4 mg/kg), and important micronutrients like Zinc (Zn: 0.07–0.74 mg/kg) and Copper (Cu: 0.01–0.04 mg/kg) were present at safe, nutritionally relevant levels.
- **Elevated Iron Content:** A notable finding was the elevated iron (Fe) content across all seed samples (96.6–173.2 mg/kg), which consistently exceeded the FAO/WHO reference limit of 48 mg/kg (Table 2). This suggests a high natural bioaccumulation propensity for iron in *C. cajan* under the studied conditions, rather than a sign of contamination, a point that warrants further agronomic and physiological investigation.

  The mineral profiling of *C. cajan* revealed distinct patterns of micronutrient and heavy metal accumulation across seeds, leaves, stems, and pods (Table 5). Nickel, although required only in trace quantities for urease activity and nitrogen metabolism (Brown et al., 1987), was present at low levels (0.01–0.081 mg/kg). The maximum concentration was detected in urban boiled seed samples (CCUBS), whereas leaves accumulated only 0.01 mg/kg. These values remain well below the dietary safety range of 3–7 mg/day (Leshe and Tessema, 2014), suggesting no risk of Ni-related toxicity. Chromium, which has not been recognized as an essential element for plants (Shanker et al., 2005), was observed only in seeds (0.01–0.02 mg/kg), with no detectable accumulation in vegetative tissues. All values were far below the FAO/WHO (1976) permissible limit of 2.3 mg/kg, consistent with findings that C. cajan generally exhibits low Cr uptake capacity (Akinyele and Shokunbi, 2015). Cadmium, a non-essential and highly toxic element, was undetectable in all samples, in agreement with previous studies showing limited Cd accumulation in leguminous crops grown under non-contaminated soils (Khan et al., 2017).

Copper concentrations ranged between 0.01–0.04 mg/kg in seeds and 0.001–0.13 mg/kg in vegetative tissues. Although Cu is indispensable for redox regulation and electron transport (Marschner, 2012), its tissue concentrations remained far below the FAO/WHO (1976) dietary limit of 30 mg/kg, minimizing the risk of Cu-induced toxicity. Zinc levels varied between 0.065–0.74 mg/kg in seeds and 0.08–0.30 mg/kg in vegetative tissues, with higher accumulation in CCUBS and rural pod samples. These findings are consistent with earlier reports indicating that pH and soil composition strongly influence Zn bioavailability (Emamverdian et al., 2015). In plants, Cu plays key roles in photosynthesis, respiration, cell wall metabolism and hormone perception. Multiple Cu transporters regulate the transport of Cu. (Majhi and Sikdar, 2023). Manganese concentrations were comparatively low (0.04–0.07 mg/kg in seeds; 0.03–0.30 mg/kg in vegetative tissues), yet the highest accumulation occurred in leaves, reflecting Mn's role in chloroplast function and photosystem II activity (Millaleo et al., 2010). Importantly, all Mn values remained within the tolerable daily intake of 11 mg/day (Leshe and Tessema, 2014). Iron exhibited markedly elevated concentrations (96.60–173.19 mg/kg in seeds; 143.0–221.23 mg/kg in vegetative tissues), significantly surpassing the FAO/WHO (1976) permissible limit of 48 mg/kg. This trend suggests a strong capacity of *C. cajan* for Fe bioaccumulation, particularly in rural leaves (CCRL, 221.23 mg/kg). While iron enrichment may be beneficial in addressing anemia in iron-deficient populations, excessive levels can disrupt the uptake of other essential micronutrients and pose risks of iron overload (Abbaspour et al., 2014).

Lead was detected only in trace amounts in urban raw seed (0.013 mg/kg), rural pod (0.01 mg/kg), and urban pod (0.12 mg/kg) samples. These concentrations were well below the FAO/WHO (1976) safety threshold of 2 mg/kg, suggesting minimal Pb contamination, despite its well-known persistence and cumulative toxicity (Jarup, 2003). Overall, *C. cajan* demonstrated nutritionally relevant concentrations of essential trace elements such as Zn, Mn, Cu, and Ni, with negligible contamination by Cd, Cr, and Pb. However, the consistently high Fe concentrations warrant further investigation into soil–plant interactions, potential sources of Fe enrichment, and implications for long-term dietary exposure. These results align with previous studies highlighting legumes as both a valuable nutritional source and a potential sink for soil-derived heavy metals (Alloway, 2013). Wastewater may have beneficial or harmful effects on crop production, depending upon its composition and the sensitivity of the plant species (Uzma et al., 2016).

TABLE 2
MINERAL AND HEAVY METAL PROFILE OF *C. CAJAN* SEEDS (mg/kg dry weight)

Element	Rural Raw Seed	Rural Boiled Seed	Semi-Urban Raw Seed	Semi-Urban Boiled Seed	FAO/WHO Reference Limit*
Potassium (K)	954.4	650.64	731.4	73.72	–
Iron (Fe)	158.41	173.19	96.6	150.17	**48**
Zinc (Zn)	0.103	0.065	0.56	0.74	60
Copper (Cu)	0.04	0.02	0.03	0.01	30
Manganese (Mn)	0.075	0.07	0.05	0.04	–
Nickel (Ni)	0.054	0.041	0.01	0.081	–
Chromium (Cr)	0	0	0.01	0.02	2.3
Lead (Pb)	0	0	0.013	0	2
Cadmium (Cd)	0	0	0	0	0.2

3.3 Proximate Nutritional Composition:

Proximate composition analysis of *C. cajan* was conducted using standard methods to evaluate its nutritional potential, including moisture, ash, crude lipid, crude fibre, crude protein, nitrogen-free extract (crude carbohydrate), and energy value per 100 g (Table 3). The results revealed marked variations among plant parts and between urban and rural samples. Moisture content, an important factor for storage stability (Nielsen, 2010), was generally higher in rural samples, indicating greater susceptibility to post-harvest deterioration. (Oke, 2014; Blazos and Belski, 2016; Chukwu et al., 2013). Seeds were characterized by high carbohydrate and protein levels, confirming their value as an energy-dense legume food (Sebastia et al., 2001).

Boiling reduced lipid, carbohydrate, and energy values but slightly improved protein content, consistent with earlier reports on processing effects in legumes (Pattee et al., 2009; Yellavila et al., 2015). Overall, the findings highlight C. cajan seeds as major sources of energy and protein, while vegetative parts, particularly leaves, contribute significantly to fibre, minerals, and lipids. Proximate analysis (Table 3) confirmed that *C. cajan* seeds from both irrigation sources are a nutritionally dense food. These values are comparable to earlier studies on legume crops (Kamboj and Nanda, 2017).Carbohydrates (as Nitrogen-Free Extract, NFE) were the predominant component (67.0–69.4 g/100g), typical for legumes. The crude protein content was substantial and comparable between sources, ranging from 15.5 to 17.6 g/100g. Crude fiber (3.2–4.8 g/100g) and crude lipid (6.1–7.2 g/100g) contents were also notable. Boiling, a common processing step, caused minor but significant reductions in some components like lipids and certain bioactive compounds due to leaching, but it did not drastically alter the core nutritional profile. Importantly, there was no consistent negative effect attributable to the sewage irrigation source; for instance, semi-urban boiled seeds exhibited slightly higher protein content than their rural counterpart.

TABLE 3
PROXIMATE COMPOSITION OF *C. CAJAN* SEEDS (g/100g dry matter)

Component	Rural Raw Seed	Rural Boiled Seed	Semi-Urban Raw Seed	Semi-Urban Boiled Seed
Moisture (%)	8.16	7.67	6.53	7.16
Crude Ash	4.62	4.19	4.52	4.14
Crude Protein	15.5	17.04	16.25	17.57
Crude Lipid	6.76	6.14	7.22	6.62
Crude Fiber	3.77	4.78	3.15	4.7
Carbohydrate (NFE)	69.35	67.85	68.86	66.98
Gross Energy (kJ/100g)	**1671.86**	**1649.11**	**1693.52**	**1661.4**

3.4 Bioactive Compounds and *In Vitro* Antioxidant Activity:

- **Extract Yield and Phenolic Content:** The yield of the 70% acetone extract varied among samples. Rural raw seeds yielded the highest extract (18.3%). Total phenolic content (TPC) was significant and generally higher in rural seeds (96.9 mg TAE/g extract) than in semi-urban seeds (62.8 mg TAE/g). Boiling reduced TPC due to thermal degradation and leaching. Analysis of non-seed tissues revealed them to be richer reservoirs of bioactive compounds than seeds. Leaves and pods, in particular, exhibited significantly higher levels of total phenolics (up to 326.2 mg TAE/g extract in rural pods) and antioxidant capacity (see Supplementary Table S4), underscoring their potential value as sources of nutraceuticals or for use in animal feed.

  Extraction of bioactive compounds is a crucial initial step for utilizing phytochemicals from *C. cajan* in nutraceutical, food, pharmaceutical, and cosmetic applications. Although nutritionally valuable, its use is constrained by anti-nutritional factors such as trypsin inhibitors, hemagglutinins, and saponins (Solomon et al., 2017). Solvent extraction efficiency depends on solvent polarity, extraction conditions, and sample characteristics (Dai and Mumper, 2010). Extract yields ranged from 10–18.3% in seeds, with higher yields in raw than processed samples, indicating losses due to processing, while vegetative parts—especially leaves—showed markedly higher yields (17.6–34.2%). Total phenolic content was highest in rural raw seeds and substantially reduced by boiling, whereas non-seed tissues, particularly pods, contained significantly higher phenolics, highlighting their antioxidant potential (Khattab et al., 2009; Xu and Chang, 2008; Balasundram et al., 2006). Tannin and flavonoid contents followed similar trends, with processing reducing concentrations due to thermal degradation and leaching (Khandelwal et al., 2010; Rani and Fernando, 2016). Overall, rural samples consistently exhibited higher levels of phenolics, tannins, and flavonoids, likely influenced by environmental factors that enhance secondary metabolite synthesis (Ali et al., 2013), emphasizing the importance of optimized processing and the valorization of non-seed plant parts.

- **Antioxidant Capacity:** All *C. cajan* extracts exhibited considerable *in vitro* antioxidant power across all five complementary assays (Table 4), confirming a robust and multifaceted antioxidant potential. A strong positive correlation was observed between the total phenolic content of the extracts and their activity across all five antioxidant assays (FRAP, DPPH, ABTS, Metal Chelating, NO Scavenging), confirming phenolics as the primary contributors to the observed antioxidant potential. Among seeds, rural raw samples consistently showed the highest activity (e.g., FRAP: 12,924.6 mmol Fe(II)/g; DPPH: 20,423.4 mmol TE/g). While the synthetic antioxidants BHA and ascorbic acid demonstrated higher absolute activity, the natural activity displayed by *C. cajan* extracts is promising for health and nutritional applications. The high antioxidant potential, maintained despite differing irrigation sources, underscores the nutraceutical value and resilience of pigeon pea.

The antioxidant activity of *C. cajan* extracts, evaluated using FRAP, metal chelating, DPPH, ABTS, and nitric oxide radical scavenging assays, demonstrated marked variation between raw and processed seeds as well as among different plant parts. The FRAP assay, widely applied for assessing reducing power in botanicals (Nithiyanantham et al., 2012), showed higher activity in raw samples than processed ones, indicating processing-induced losses of electron-donating antioxidants, consistent with earlier reports on legumes (Sathya and Siddhuraju, 2013).

Metal chelating activity, which reflects secondary antioxidant potential by stabilizing metal ions and preventing redox cycling (Joy et al., 2017; Siddhuraju et al., 2014), was also reduced after processing but not completely abolished. DPPH and ABTS radical scavenging assays revealed that boiling adversely affected antioxidant capacity due to leaching and thermal degradation of soluble antioxidants and polyphenols (Nithiyanantham et al., 2012; Siddhuraju et al., 2014). Nitric oxide scavenging activity further confirmed higher efficacy in raw samples, with reductions attributed to losses of polyphenols, vitamins, and minerals during thermal treatment (Boora et al., 2014; Dhanya et al., 2019). Although all plant extracts exhibited lower antioxidant activity compared to standards such as ascorbic acid and BHA, the observed trends strongly correlated with phenolic content, reinforcing that phenolic compounds are the principal contributors to antioxidant capacity in C. cajan (Irik and Bikmaz, 2024).

TABLE 4
ANTIOXIDANT ACTIVITY OF *C. CAJAN* SEED EXTRACTS

Sample	FRAP (mmol Fe(II)/g)	Metal Chelating (mg EDTA/g)	DPPH (TEAC mmol/g)	ABTS (TEAC mmol/g)	NO Scavenging (%)
Rural Raw Seed	12924.58 ± 35.9	2.78 ± 0.02	20423.36 ± 52.6	3903.74 ± 62.8	68.73
Rural Boiled Seed	8289.79 ± 75.5	2.67 ± 0.01	20350.36 ± 43.8	3665.42 ± 64.7	55.97
Semi-Urban Raw Seed	3869.14 ± 50.1	2.73 ± 0.01	15951.34 ± 22.3	18992.85 ± 186.5	59.35
Semi-Urban Boiled Seed	3764.45 ± 51.5	1.47 ± 0.01	15323.60 ± 36.7	18101.75 ± 189.5	NA
Standards					
Ascorbic Acid	730676.32 ± 91.2	–	493310.06 ± 1125.9	597116.67 ± 104.8	–
BHA	350278.70 ± 73.6	10.49 ± 0.06	386368.04 ± 9622.1	654356.06 ± 617.1	–

IV. CONCLUSION

This comprehensive study provides robust evidence that the use of diluted domestic sewage wastewater for irrigating *C. cajan*, under the specific conditions of this preliminary field assessment, did not result in the dangerous accumulation of toxic heavy metals (Cd, Pb, Cr, Ni, Cu) in the edible seeds. All measured values remained well within international food safety standards.

The irrigation water, while nutrient-rich and high in iron, was not contaminated with problematic levels of industrial pollutants. The proximate nutritional quality of the seeds—their protein, carbohydrate, and energy content—was maintained and was comparable to seeds grown with well water.

Furthermore, the plants retained significant levels of bioactive phenolic compounds and associated high *in vitro* antioxidant activity, which was strongly correlated. The elevated iron content in seeds warrants further study but appears to be a varietal or physiological trait rather than a contamination issue. The non-seed biomass (leaves, pods) showed particularly high phenolic content, indicating valuable by-products.

Therefore, with necessary precautions—primarily the ongoing monitoring of water quality (particularly for salts and Fe) and soil health—the controlled use of diluted domestic sewage wastewater can be considered a viable and sustainable irrigation alternative for pigeon pea cultivation. This practice supports critical goals of water conservation, nutrient recycling, and urban food security without compromising the safety or nutraceutical value of this important legume crop. Further long-term studies under varied field conditions are recommended to validate these promising findings.

AUTHOR CONTRIBUTIONS

- **Dhanya Viswanathan**: methodology, investigation, data curation, formal analysis, writing–original draft.
- **Velukutty Amrutha:** investigation, data curation, conceptualization, writing – review and editing.
- **Perumal Siddhuraju:** methodology, conceptualization, data curation, supervision, project administration, writing – review and editing.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author (P. Siddhuraju*, Email: psiddhuraju@buc.edu.in) upon reasonable request.

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Finger Millet Residue Management: Impacts on Soil Health and System Productivity in Succeeding Crops – A Review

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Abstract**—** *Rainfed and upland agriculture in India faces mounting challenges due to continuous cereal monoculture, leading to soil degradation and vulnerability to climate variability. Finger millet (Eleusine coracana L. Gaertn.), a climate-resilient and nutrient-rich small millet, offers a sustainable alternative for diversification. This review synthesizes evidence on the role of finger millet residue management in enhancing the productivity, nutrient uptake, soil properties, and economics of succeeding crops. With significant residue biomass (approximately 5 tonnes ha⁻¹) often underutilized, in-situ incorporation or mulching of these residues consistently improves dry matter accumulation, growth, and yield of subsequent legumes and cereals. These practices enhance nutrient cycling, increasing nitrogen, phosphorus, and potassium uptake by 10-30% in crops like greengram, groundnut, and maize. Long-term residue retention boosts soil organic carbon by 15-30%, reduces bulk density, and improves overall soil fertility compared to removal or burning. Economically, residue-based systems, particularly when integrated with legumes, yield higher gross and net returns with favorable benefit-cost ratios, despite marginally higher initial costs. Finger millet residue management is thus a viable strategy for ecological intensification. Adopting finger millet–legume systems with efficient residue recycling can significantly contribute to soil health, climate resilience, and livelihood security in India's rainfed regions.*

Keywords— Crop residue recycling; ecological intensification; Eleusine coracana; nutrient cycling; rainfed agriculture; soil organic carbon; sustainable cropping systems.

I. INTRODUCTION

Agriculture in India's rainfed and upland regions underpins rural livelihoods and national food security. However, reliance on intensive cereal-based systems, particularly continuous rice cultivation, has led to declining productivity, accelerated soil degradation, and heightened climate vulnerability (Woźniak, 2019). These issues are acute in fragile uplands, where water scarcity, poor soil health, and socio-economic constraints limit sustainable intensification. Consequently, identifying resilient, resource-efficient cropping alternatives is imperative.

Finger millet (*Eleusine coracana* L. Gaertn.) emerges as a promising solution. A hardy, climate-smart small millet traditionally grown in southern and central India, it is valued for its exceptional nutritional profile, being rich in calcium, iron, dietary fiber, and the essential amino acid methionine—often deficient in staple cereals (Devi et al., 2011). Agronomically, it thrives in marginal environments with minimal inputs, exhibits drought tolerance, and adapts to short growing seasons (Kumar et al., 2024). Beyond grain, its straw is a valuable resource, high in organic matter (89-92%) and containing significant crude protein (3-5%), calcium (344 mg $100g^{-1}$), and potassium (408 mg $100g^{-1}$) (Malleshi et al., 2021).

In India, finger millet is the leading small millet, cultivated on approximately 1.2 million hectares with a production of 1.56 million tonnes (Department of Agriculture & Farmers Welfare, 2023). With an estimated straw yield of 5 tonnes ha^{-1}, annual residue production approaches 6 million tonnes nationally. However, a considerable proportion is either discarded or burned, representing a significant loss of organic nutrients and contributing to environmental degradation. Efficient utilization of this residue through in-situ incorporation or mulching offers a direct pathway to enhance soil fertility, improve nutrient cycling, and bolster farm-system resilience.

Continuous cereal monoculture depletes soil organic carbon (SOC) and microbial diversity (Woźniak, 2019). Diversification with finger millet, particularly in rotation with legumes (e.g., greengram, groundnut, horsegram), facilitates ecological intensification by enabling biological nitrogen fixation, improving soil structure, and suppressing pests. Within such diversified systems, the management of finger millet residues becomes a critical lever for sustainability. This review synthesizes available evidence on the impact of finger millet residue management on the performance of succeeding crops, focusing on crop growth, nutrient uptake, soil properties, and system economics, to guide sustainable practices in rainfed agro-ecosystems.

II. METHODOLOGY FOR LITERATURE SYNTHESIS

This review was conducted by systematically searching peer-reviewed literature from 2000 to 2024. Primary databases included Scopus, Web of Science, Google Scholar, and the journals of the Indian Society of Agronomy. Key search terms were: "finger millet residue," "Eleusine coracana straw," "small millet residue management," "crop residue incorporation," "residue mulching," "rainfed cropping systems," and "soil organic carbon." Studies were selected based on relevance to finger millet systems or analogous residue management principles in comparable rainfed cereal-legume systems. Data on crop yield, nutrient uptake, soil parameters, and economics were extracted, compared, and synthesized thematically. Given the limited number of studies exclusively on finger millet residue, evidence from well-managed experiments with residues of similar quality (e.g., rice, wheat, other millets) is also discussed to elucidate underlying mechanisms, with clear distinctions made.

III. IMPACT ON GROWTH AND YIELD OF SUCCEEDING CROPS

Retaining crop residues on the soil surface as mulch or incorporating them into the soil significantly improves the growth environment for subsequent crops. Residue mulch conserves soil moisture, moderates temperature, and suppresses weeds, while incorporation adds organic matter and facilitates nutrient release upon decomposition.

Research consistently shows positive yield responses. Meena et al. (2008) reported that conventional tillage with residue retention produced significantly higher dry matter accumulation in greengram (467.0 g m^{-2} at 60 DAS) compared to residue removal (367.6 g m^{-2}). Similarly, in a rice-groundnut system, incorporation of field bean residues increased groundnut dry matter production by 23-25% over the control (Kumari et al., 2010). These benefits extend to cereals. For instance, wheat residue mulching at 5 t ha^{-1} increased maize plant height by 5% and dry matter per plant by 8% (Ajamirali and Halagalimath, 2017). Almaz et al. (2017) observed that incorporating soybean residue with balanced fertilization more than doubled maize plant height compared to a no-residue, no-fertilizer control.

The mechanism is multifaceted: residues improve soil physical properties (discussed later), which enhances root growth and water infiltration. Furthermore, as residues decompose, they release nutrients, particularly potassium, which is abundant in finger millet straw. The gradual nutrient release synchronizes better with crop demand compared to chemical fertilizers alone, leading to more sustained growth.

TABLE 1
SUMMARY OF RESIDUE MANAGEMENT EFFECTS ON CROP PERFORMANCE IN SELECTED STUDIES

Residue Type	Management Practice	Succeeding Crop	Key Impact	% Increase over Control	Reference
General Crop Residue	Incorporation + GM*	Wheat	Dry matter (120 DAS)	~155%	Dhar et al. (2014)
Wheat Straw	Mulching (5 t ha^{-1})	Maize	Plant height, Dry matter/plant	~5%, ~8%	Ajamirali & Halagalimath (2017)
Field Bean Residue	Incorporation	Groundnut	Dry matter at harvest	~25%	Kumari et al. (2010)
Soybean Residue	Incorporation + PK	Maize	Plant height	~116%	Almaz et al. (2017)

IV. ENHANCEMENT OF NUTRIENT UPTAKE

Effective residue management enhances the nutrient cycling efficiency within cropping systems. Crop residues act as a slow-release nutrient source and foster a more active microbial community responsible for mineralization.

Studies report substantial increases in macro-nutrient uptake. In a maize-wheat sequence, retaining maize residues increased nitrogen uptake in wheat grain and straw by 31% and 64%, respectively (Bakht et al., 2009). Integrating legumes in the rotation amplifies this benefit through biological nitrogen fixation. Bana and Shivay (2012) found that a preceding summer cowpea forage crop increased total N, P, and K uptake in basmati rice by up to 20% compared to fallow. Kouelo et al. (2013) reported that incorporating *Mucuna* residues increased grain N uptake in maize by over 350%.

The quality of residue is crucial. Finger millet straw, with a favorable carbon-to-nitrogen (C:N) ratio and high potassium content, is expected to decompose relatively quickly, minimizing nitrogen immobilization and rapidly supplying potassium—a key nutrient for legume seed development and stress tolerance. This makes it particularly suitable for legume-based systems prevalent in rainfed areas.

V. IMPROVEMENT OF SOIL PHYSICO-CHEMICAL PROPERTIES

The long-term benefits of residue recycling are most evident in soil health parameters. Continuous residue addition is a primary strategy for rebuilding SOC in degraded soils.

- **Soil Organic Carbon (SOC):** SOC is the cornerstone of soil health. Singh and Yadav (2006) reported that long-term residue incorporation increased SOC by 17.7% compared to residue removal. Similarly, Singh et al. (2009) found straw retention increased SOC by 29.6%, whereas burning only increased it by 11.6%. Higher SOC enhances cation exchange capacity, water retention, and provides energy for soil microbes.
- **Soil Physical Properties:** Residue management reduces soil compaction. Gangwar et al. (2006) recorded the lowest bulk density (1.58 Mg m^{-3}) with residue incorporation, compared to 1.61 Mg m^{-3} with removal. Lower bulk density improves porosity, aeration, and root penetration.
- **Soil Chemical Fertility:** Residue decomposition releases nutrients and can moderate soil pH. Kumar et al. (2008) observed that long-term residue application with fertilizers significantly increased available N, P, and K by 24%, 49%, and 39%, respectively, over fertilizer application alone. While some studies note a slight increase in pH with residue addition (Das et al., 2001; Kachroo & Dixit, 2005), this is often beneficial in acidic upland soils.

TABLE 2
IMPACT OF RESIDUE MANAGEMENT ON KEY SOIL PROPERTIES

Soil Property	Residue Management Practice	Reported Effect	Reference
Organic Carbon	Surface retention/Incorporation	Increase of 15-30% over removal/burning	Singh et al. (2009); Singh & Yadav (2006)
Bulk Density	Incorporation	Reduction of 1.8-2.0% compared to removal	Gangwar et al. (2006)
Available N, P, K	Long-term incorporation + fertilizers	Significant increase over fertilizers alone	Kumar et al. (2008)
pH	Residue incorporation	Slight increase/amelioration in acidic soils	Das et al. (2001)

VI. ECONOMIC VIABILITY

The adoption of any practice hinges on its economic feasibility. While residue incorporation may involve higher initial costs related to tillage or decomposition aids (e.g., microbial consortia), it typically results in superior returns.

Research indicates positive economic outcomes. In a legume-rice-groundnut sequence, incorporating field bean residues with FYM resulted in net returns of approximately Rs. 21,000 ha^{-1} and a favorable B:C ratio (Kumari et al., 2010). Pooniya and Shivay (2012) found that incorporating *Sesbania* green manure residues in rice provided net returns over Rs. 60,000 ha^{-1} with a B:C ratio above 2.0. Rajkumara et al. (2014) reported that applying crop residues under no-tillage enhanced net returns in a maize-chickpea system by about 9%.

The economic advantage stems from reduced need for purchased fertilizers (due to improved nutrient cycling), higher and more stable yields, and often, lower irrigation requirements due to better soil moisture conservation. Integrating a legume in the system provides an additional cash crop or fodder, further improving income diversity and risk resilience for smallholder farmers.

VII. SYNTHESIS, CHALLENGES, AND FUTURE PERSPECTIVES

Synthesis: The collective evidence strongly supports finger millet residue retention (via mulching or incorporation) as a keystone practice for sustainable rainfed farming. It creates a positive feedback loop: improved soil structure and moisture → better crop growth and yield → higher residue return → enhanced SOC and nutrient cycling → sustained system productivity and resilience.

Addressing Challenges:

Practical adoption faces hurdles:

1. **Resource Competition:** Residues are valuable fodder. Integrated farming systems that allocate a portion for soil health while meeting livestock needs are essential.
2. **Short-term Immobilization:** Incorporating high C:N residues can temporarily tie up soil N. This can be mitigated by co-applying a small dose of starter N fertilizer or using pre-decomposed residues.
3. **Operational Constraints:** Smallholders may lack access to appropriate machinery for incorporation or mulch management. Promoting community-based residue managers or low-cost choppers can help.
4. **Pest and Disease Risk:** Residue retention must be managed alongside integrated pest and disease management strategies to avoid harboring pathogens.

Future Research Needs:

- **Finger Millet-Specific Studies:** Quantified data on decomposition rates, nutrient release patterns (N, P, K, Ca), and soil carbon sequestration potential of finger millet residue under different agro-climates.
- **System Optimization:** Research on ideal rates, timing (immediate vs. decomposed), and methods (mulch vs. incorporation) of finger millet residue management within diversified cropping sequences (e.g., finger millet-legume-vegetable).
- **Trade-off Analysis:** Comprehensive studies evaluating the trade-offs between residue use for soil amendment, fodder, and alternative uses (e.g., bioenergy), considering both biophysical and socio-economic factors.
- **Climate Interaction:** Assessing how residue management affects system resilience under extreme weather events (drought, intense rainfall) and its impact on greenhouse gas fluxes (N_2O, CH_4).

VIII. CONCLUSION

Finger millet is more than a climate-resilient nutricereal; its substantial residue biomass represents a critical on-farm resource for ecological sustainability. This review affirms that in-situ management of finger millet residues through mulching or incorporation significantly enhances the productivity and nutrient uptake of succeeding crops, improves key soil health indicators like SOC and bulk density, and proves economically viable. Moving away from residue burning or removal towards systematic recycling is a low-cost, high-impact strategy. Promoting diversified finger millet–legume systems coupled with scientific residue management can be a cornerstone for achieving sustainable intensification, restoring degraded uplands, and securing livelihoods in India's rainfed regions. Policy support, extension services, and context-specific research are needed to translate this potential into widespread farm-level practice

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Evaluation of Single Cross Hybrids of Maize (*Zea mays* L.) in Winter Season at Rampur, Chitwan, Nepal

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Abstract— *A study was conducted to identify high-yielding single-cross maize hybrids. A total of 26 single-cross maize hybrids along with four checks were evaluated at the research field of the National Maize Research Program, Rampur, Chitwan, from November 2023 to May 2024. The experiment was laid out in an alpha-lattice design with two replications and six blocks per replication. Data for 14 agro-morphological and yield-related traits were recorded. Analysis of variance revealed significant differences in all traits, with heritability ranging from moderate (0.43-0.57) to high (0.64-0.87). ZH22668 (11.33 t ha^{-1}) was the highest-yielding hybrid, while ZH22741 (9.94 t ha^{-1}), ZH22712 (9.61 t ha^{-1}), ZH2182 (9.45 t ha^{-1}), ZH20379 (9.38 t ha^{-1}), and ZH22691 (9.37 t ha^{-1}) produced yields comparable to the commercial checks CP 808 (9.36 t ha^{-1}) and Sultan (9.33 t ha^{-1}). ZH22668, ZH22741, and ZH22712 showed a yield advantage of 2.62-21.04% over CP 808 and 26.38-49.11% over internal check CAH153. Therefore, ZH22668, ZH22741, and ZH22712 are promising hybrids for further evaluation in the inner-terai region of Nepal.*

Keywords— Maize hybrids, Grain yield, Agro-morphological traits, Yield advantage, Winter season.

I. INTRODUCTION

Maize (*Zea mays* L., 2n=2x=20) is a highly versatile and widely adaptable crop, recognized as one of the world's leading cereals with diverse types. It is also known as "queen of cereals" as it has the highest productivity compared to other cereals (Das et al., 2018). It has a wider range of uses as a 4F crop, i.e., food, feed, fuel, fodder, and industrial raw materials (Shikha et al., 2020). Globally, maize ranks second among cereals in terms of area under cultivation, occupying approximately 208 million hectares, and first in total production, with an annual output of about 1,241 million tons, with average productivity of 5.96 t ha^{-1} (FAOSTAT, 2023). In Nepal, maize occupies 0.94 million hectares of land with 2.97 million tons production and 3.16 t ha^{-1} productivity, contributing 7.61% to the total national AGDP (MoALD, 2023).

Single-cross hybrids are the first filial generation (F_1) obtained from the crossing of two inbred lines (Makavu, 2018) and generally produce higher grain yield compared to double and triple cross hybrids. The National Maize Research Program (NMRP) focuses on maize breeding and hybrid development, having released ten maize hybrids to date (MoALD, 2023). However, Nepal still imports substantial quantities of hybrid maize seed (3655.8 tons) and maize grain (435217.7 tons) annually (MoALD, 2023), indicating a need for developing competitive domestic hybrids.

Over the last 10 years, the demand for maize grain has increased by 5% annually (Adhikari et al., 2024), with the poultry feed industry alone requiring 391,538 tons of yellow maize annually (Koirala et al., 2020). Currently, domestic production fulfills only 25% of this demand. Hybrids are more responsive to irrigation and fertilizer, yielding 20-30% higher than open-pollinated varieties (Thapa et al., 2022). However, only 20% of Nepal's maize area is covered by hybrids, with 75% still under open-pollinated varieties (Yadav et al., 2023).

Winter maize production in the Terai region and river basins offers potential for increasing national maize production. Therefore, this study was conducted to evaluate single-cross maize hybrids to identify high-yielding genotypes suitable for winter cultivation in the inner-terai region of Nepal.

II. MATERIALS AND METHODS

2.1 Experimental site:

The field experiment was conducted during the winter season from November 24, 2023 to May 7, 2024 at the research field of NMRP, Rampur, Chitwan, Nepal (27°40' N, 84°19' E, 228 m altitude).

2.2 Climatic conditions:

Monthly mean climatic data recorded during the growing period showed a maximum temperature of 39.07°C and minimum of 8.11°C. Maximum relative humidity (97.33%) occurred in December and minimum (55.02%) in April. Rainfall was recorded only in March (24.40 mm).

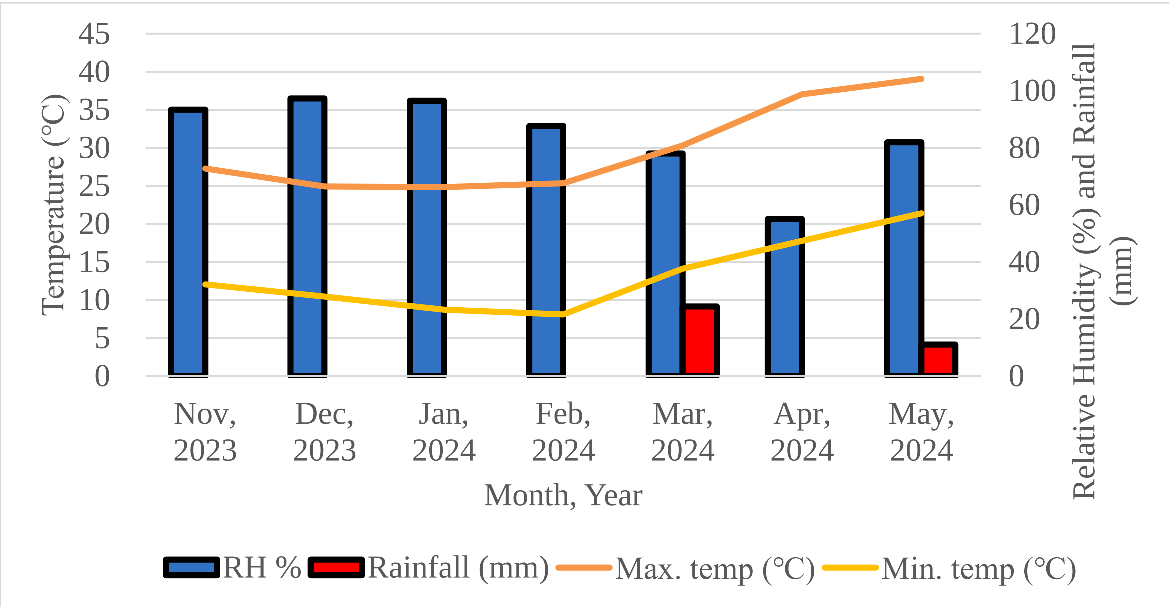

FIGURE 1: Climatic conditions during the research period at Rampur Chitwan, Nepal, 2023/24 (Source: NMRP, Rampur, Chitwan)

2.3 Plant Materials:

In this research, a total of thirty genotypes were used, comprising twenty-six experimental single-cross hybrids, two commercial checks (CP 808 and Sultan), one local check (Rampur Hybrid-10), and one internal check (CAH153). The single-cross hybrids and CAH153 were CIMMYT materials, CP 808 and Sultan were from multinational companies, and Rampur Hybrid-10 was from the National Maize Research Program (NMRP). All plant materials were obtained from NMRP. The complete list is presented in Table 1.

TABLE 1
LIST OF MAIZE HYBRIDS EVALUATED IN THE STUDY

Entry No.	Hybrid Name	Entry No.	Hybrid Name
1	ZH22707	16	ZH22742
2	ZH22700	17	ZH20379
3	ZH22713	18	ZH22724
4	ZH22697	19	ZH22740
5	ZH22702	20	ZH22741
6	ZH22668	21	ZH22780
7	ZH22691	22	ZH2157
8	ZH191006	23	ZH2182
9	ZH20272	24	ZH22727
10	ZH22712	25	ZH22731
11	ZH19770	26	ZH22744
12	ZH191003	27	CAH153 (Internal check)
13	ZH22698	28	CP 808 (Commercial check 1)
14	ZH22705	29	Sultan (Commercial check 2)
15	ZH22709	30	Rampur Hybrid-10 (Local check)

2.4 Experimental design and crop management:

The experiment was laid out in an alpha-lattice design with two replications. Each genotype was sown in two rows of 4 m length with spacing of 75 cm × 20 cm, giving a net plot area of 6 m^2. FYM at 10 t ha^{-1} was applied during land preparation. Fertilizer was applied at 180:60:40 kg ha^{-1} of $N:P_2O_5:K_2O$, with half N and full P and K as basal dose, and remaining N split-applied at knee height and pre-tasseling stages. Pre-emergence herbicide (Atrazine 50% WP + Pendimethalin 30% EC) was applied two days after sowing. Irrigation was applied at critical growth stages, and Spinosad 45 SC was sprayed at 30 DAS for fall armyworm control.

2.5 Data Recorded:

Data on agro-morphological and yield-attributing traits were recorded. Flowering traits (days to 50% anthesis and days to 50% silking), stand count (number of plants and number of ears per plot), and ear aspect were recorded on a plot basis. Plant height (cm), ear height (cm), number of leaves above the uppermost ear, cob length (cm), cob diameter (cm), number of kernel rows per ear, number of kernels per row, and thousand kernel weight (g) were recorded from five randomly selected competitive plants per plot.

The anthesis-silking interval (ASI, in days) was calculated as:

$$\text{ASI} = \text{Days to 50\% silking} - \text{Days to 50\% anthesis} \quad (1)$$

Ear position was calculated as:

$$\text{Ear Position} = \text{Ear Height (cm)} / \text{Plant Height (cm)} \quad (2)$$

Prolificacy was calculated as:

Prolificacy = (Number of ears per hectare) / (Number of plants per hectare) (3)

Ear aspect was recorded by visual rating on a scale of 1 to 5, where **1 = clean, uniform, large, and well-filled ear; 3 = average; and 5 = rotten, variable, small, and partially filled ear** (Rai et al., 2022).

A seed counting machine was used to count five hundred grains, and their weight was measured. The weight was adjusted to a 12.5% moisture content using the following formula (Yadav et al., 2024):

Adjusted 1000-kernel weight (g) = [(100 – Grain moisture content %) / (100 – 12.5)] × (2 × 500 kernel weight) (4)

Grain yield (t ha^{-1}) adjusted to 12.5% moisture content was calculated from the fresh ear weight using the formula described by Carangal et al. (1971):

Grain yield (t ha^{-1}) = [FW × (100 – HMC) × S × 10] / [(100 – DMC) × NAH] (5)

Where: FW = field weight (kg); HMC = moisture content in grains at harvest (%); DMC = desired moisture content (12.5%); S = shelling coefficient (0.8); and NAH = net area harvested per plot (6 m^2).

2.6 Statistical Analysis:

Data entry and processing were performed using MS Excel 365. Analysis of variance (ANOVA) for the alpha-lattice design and mean comparisons were conducted using R-Studio (Version 4.5.1). Analysis of covariance (ANCOVA) was performed using MINITAB to adjust grain yield for variations in plant population, using the number of plants per hectare as a covariate.

Broad-sense heritability (h^2bs) was estimated on an entry-mean basis using the formula of Justin and Fehr (1988):

h^2bs = Vg / Vp (6)

Where:

Genotypic variance (Vg) = (MSSgenotype – MSSerror) / r; Phenotypic variance (Vp) = Vg + Ve; and Ve = MSSerror

(where MSS is Mean Sum of Squares and r is the number of replications).

The broad-sense heritability was categorized as **low (0.00–0.30), moderate (0.30–0.60), and high (>0.60)** as suggested by Johnson et al. (1955).

The percentage yield advantage of the test hybrids over the trial mean and check varieties was calculated using the formula of Heisey et al. (1998):

% Yield Advantage over Check = [(Yield of Hybrid – Yield of Check) / Yield of Check] × 100 (7)

% Yield Advantage over Trial Mean = [(Yield of Hybrid – Trial Mean Yield) / Trial Mean Yield] × 100 (8)

III. RESULTS AND DISCUSSION

3.1 Mean Performance of Agro-Morphological, Yield, and Yield-Related Traits:

The analysis of variance revealed highly significant differences (p<0.01) among the thirty maize genotypes for all observed traits (Tables 2, 3, and 4), indicating the presence of substantial genetic variability. This variability is essential for effective selection and hybrid development (Belay, 2018).

TABLE 2
FLOWERING AND PLANT HEIGHT TRAITS OF THIRTY MAIZE HYBRIDS EVALUATED DURING THE WINTER SEASON AT RAMPUR, CHITWAN, NEPAL

Genotypes	AD	SD	ASI	PH (cm)	EH (cm)	EP
CAH153	108	110	2	185	74	0.4
CP 808	111	112	1	175	84	0.48
Sultan	106	108	2	206	90	0.43
Rampur Hybrid-10	109	110	1	175	71	0.41
ZH191003	107	110	3	177	76	0.43
ZH191006	111	112	1	176	97	0.55
ZH19770	106	110	3.5	192	83	0.43
ZH20272	109	111	2	204	115	0.57
ZH20379	108	108	0	193	94	0.49
ZH2157	108	110	2	207	86	0.42
ZH2182	106	108	2	163	84	0.52
ZH22668	108	109	1	193	91	0.47
ZH22691	108	110	1.5	177	97	0.55
ZH22697	106	108	2	185	86	0.46
ZH22698	106	107	1	187	78	0.42
ZH22700	109	112	3.5	198	90	0.45
ZH22702	109	111	2	164	76	0.46
ZH22705	107	107	0	183	83	0.45
ZH22707	107	109	2	173	84	0.48
ZH22709	106	108	2	166	70	0.42
ZH22712	112	113	1	189	98	0.52
ZH22713	109	112	3.5	182	86	0.47
ZH22724	107	110	3	172	73	0.43
ZH22727	107	110	2.5	193	80	0.42
ZH22731	107	109	1.5	200	99	0.49
ZH22740	110	111	1	208	99	0.48
ZH22741	107	109	2	198	100	0.5
ZH22742	107	109	2.5	188	91	0.48
ZH22744	108	110	2	181	79	0.44
ZH22780	103	105	2	137	61	0.44
Mean	108	109	1.8	184	86	0.46
SEm (±)	1.01	0.1	0.24	5.98	4.53	0.02
LSD (0.05)	2.99	3	0.72	17.7	13.4	0.06
CV (%)	1.33	1.29	18.66	4.6	7.48	6.35
F test	**	**	**	**	**	**
h^2bs	0.49	0.49	0.57	0.73	0.72	0.64

Note: **Significant at 1% level of probability; SEm, standard error of mean; LSD, least significant difference; CV, coefficient of variation; h^2bs, broad-sense heritability; AD, days to 50% anthesis; SD, days to 50% silking; ASI, anthesis-silking interval; PH, plant height; EH, ear height; EP, ear position.

TABLE 3
PLANT POPULATION, PROLIFICACY, EAR ASPECT, AND LEAVES ABOVE THE UPPERMOST EAR OF THIRTY MAIZE HYBRIDS EVALUATED DURING THE WINTER SEASON AT RAMPUR, CHITWAN, NEPAL

Genotypes	NOP (ha^{-1})	NOE (ha^{-1})	PROF	EA	NLAE
CAH153	55834	55834	1	2.3	6
CP 808	65000	65667	1.01	1.3	6.5
Sultan	58334	72500	1.25	2.8	6
Rampur Hybrid-10	7500	11667	1.36	3.3	6
ZH191003	60834	60834	1	3	6
ZH191006	51667	54167	1.05	3	5
ZH19770	55834	91667	1.65	3.5	6
ZH20272	61667	96667	1.59	3.3	4
ZH20379	55000	80833	1.47	3.3	6
ZH2157	64167	90000	1.4	3	6
ZH2182	51667	51667	1	1.3	5.5
ZH22668	48334	88333	1.89	3	6
ZH22691	50000	69167	1.4	2	6
ZH22697	65834	70834	1.08	3.3	5.5
ZH22698	56667	58333	1.03	2.5	6
ZH22700	50834	59167	1.17	2.3	5
ZH22702	46667	50000	1.07	1.8	5
ZH22705	57500	67500	1.17	3.5	6
ZH22707	50000	85834	1.71	3.5	5
ZH22709	55000	59167	1.08	2	6
ZH22712	66667	86667	1.3	2.3	5
ZH22713	63334	94167	1.48	3	5.5
ZH22724	56667	60000	1.06	2.5	6
ZH22727	63334	60833	0.96	2.5	6
ZH22731	41667	45000	1.09	3.3	6
ZH22740	60000	69167	1.15	3	5
ZH22741	64167	73334	1.14	1.5	5
ZH22742	57500	90833	1.58	2.5	5
ZH22744	60000	65000	1.08	2	6
ZH22780	46667	58333	1.25	3.5	5
Mean	54945	68106	1.25	2.7	5.6
SEm (±)	4708	7051	0.1	0.38	0.16
LSD (0.05)	13937	20872	0.29	1.11	0.48
CV (%)	12.12	14.64	11.25	20.06	4.15
F test	**	**	**	**	**
h^2bs	0.69	0.74	0.73	0.53	0.83

Note: **Significant at 1% level of probability; SEm, standard error of mean; LSD, least significant difference; CV, coefficient of variation; h^2bs, broad-sense heritability; NOP, number of plants per hectare; NOE, number of ears per hectare; PROF, prolificacy (ears per plant); EA, ear aspect (1=best, 5=worst); NLAE, number of leaves above the uppermost ear.

TABLE 4
YIELD AND YIELD-RELATED TRAITS OF THIRTY MAIZE HYBRIDS EVALUATED DURING THE WINTER SEASON AT RAMPUR, CHITWAN, NEPAL

Genotypes	CL (cm)	CD (cm)	NKRPE	NKPR	TKW (g)	GY (t ha⁻¹)
CAH153	15.2	4.71	14	25.1	419	7.6
CP 808	17	5.34	18	31.8	404	9.36
Sultan	14.9	4.75	14	28.6	400	9.33
Rampur Hybrid-10	18	4.65	14	31.5	429	4.75
ZH191003	15.8	4.66	14	27.2	471	7.92
ZH191006	16.2	4.67	12	30.7	443	7.38
ZH19770	13.7	4.58	14	29.3	336	7.35
ZH20272	15.2	4.4	12	28	404	8.53
ZH20379	17.9	4.21	10	28.5	454	9.38
ZH2157	13.3	4.9	14	28.1	378	9.24
ZH2182	17.1	5.19	16	34.7	295	9.45
ZH22668	15.3	4.89	14	29.4	372	11.33
ZH22691	15.7	5.14	14	31.1	364	9.37
ZH22697	14.4	4.77	14	30.1	386	7.65
ZH22698	16.4	4.57	14	28.6	435	8.65
ZH22700	16.6	4.67	14	32.5	435	9.33
ZH22702	17	4.83	14	33.2	417	8
ZH22705	15.6	4.11	10	26.7	449	7.11
ZH22707	14.4	4.35	12	30	342	8.22
ZH22709	16.9	4.64	16	28.4	437	8.87
ZH22712	15.4	5.17	14	33.9	368	9.61
ZH22713	15.4	5	16	30.9	314	8.22
ZH22724	16	4.57	14	28	422	8.26
ZH22727	16.7	4.68	14	29.5	446	8.53
ZH22731	17.5	4.57	14	30.3	404	6.44
ZH22740	17.1	4.53	14	29.9	462	8.1
ZH22741	18.2	4.8	14	31.7	439	9.94
ZH22742	16.4	4.45	14	33.4	308	8.8
ZH22744	17.9	4.62	14	29.6	430	8.05
ZH22780	13.1	4.64	14	24.6	372	6.64
Mean	16	4.7	14	29.8	401	8.38
SEm (±)	0.73	0.07	0.8	1.53	29.7	0.66
LSD (0.05)	2.15	0.22	2.38	4.54	87.9	1.97
CV (%)	6.43	2.22	8.5	7.26	10.47	11.21
F test	**	**	**	*	*	**
h^2bs	0.56	0.87	0.53	0.43	0.43	0.76

Note: **, *, Significant at 1% and 5% level of probability, respectively; SEm, standard error of mean; LSD, least significant difference; CV, coefficient of variation; h^2bs, broad-sense heritability; CL, cob length; CD, cob diameter; NKRPE, number of kernel rows per ear; NKPR, number of kernels per row; TKW, thousand kernel weight; GY, grain yield.

3.1.1 Flowering and Plant Architecture Traits:

There were highly significant differences for days to 50% anthesis and silking, which aligns with findings by Khan et al. (2019) and Rai et al. (2022). Days to 50% anthesis ranged from 103 (ZH22780) to 112 (ZH22712), and silking from 105 (ZH22780) to 113 days (ZH22712). These traits determine the maturity period, a crucial parameter for breeding (Ullah et al., 2017).

The anthesis-silking interval (ASI) also showed significant variation (0 to 3.5 days, with a mean of 1.8 days), in agreement with Adhikari et al. (2024) and Rai et al. (2022). A shorter ASI (0–3 days) indicates better synchronization between pollen shedding and silk emergence, which is vital for successful pollination under potential abiotic stresses (Ngugi et al., 2013). In this study, genotypes ZH20379 and ZH22705 exhibited a 0-day ASI, suggesting excellent synchrony.

Significant differences were observed for plant height, ear height, and ear position (Table 2), consistent with reports by Ogunniyan and Olakojo (2014) and Rai et al. (2022). Plant height ranged from 137 cm (ZH22780) to 208 cm (ZH22740), and ear height from 61 cm (ZH22780) to 115 cm (ZH20272). Ear position, calculated as the ratio of ear to plant height, ranged from 0.40 to 0.57. These architectural traits are critical for lodging resistance and yield optimization (Liu et al., 2021). An ear position around 0.50 ± 0.03 is generally considered optimal, balancing lodging risk with ease of harvest (Koirala et al., 2020; Zsubori et al., 2002).

3.1.2 Stand Count, Prolificacy, and Ear Quality:

The number of plants per hectare, number of ears per hectare, and prolificacy (ears per plant) showed highly significant differences (Table 3), supporting findings by Neupane et al. (2020). Plant population ranged from 7,500 to 66,667 plants ha^{-1}. Prolificacy ranged from 0.96 (ZH22727) to 1.89 (ZH22668). A value greater than 1.3 indicates a double-cobbed plant. Five hybrids (ZH22668, ZH22712, ZH20379, ZH22691, and ZH2157) showed prolificacy >1.3, a trait that can be crucial for higher productivity (Zsubori et al., 2002).

Ear aspect, a key visual quality trait, varied significantly among genotypes (1.3 to 3.5), with lower scores being desirable. This aligns with findings by Neupane et al. (2020). The number of leaves above the uppermost ear also varied significantly (4.0 to 6.5), which can influence canopy architecture and photosynthetic efficiency (Li et al., 2016).

3.1.3 Yield Components and Final Grain Yield:

Cob characteristics and yield components exhibited significant genetic variation (Table 4). Cob length ranged from 13.1 cm to 18.2 cm, and cob diameter from 4.11 cm to 5.34 cm. The number of kernel rows per ear varied from 10 to 18, and kernels per row from 24.6 to 34.7. These traits are direct yield determinants, and their significant variation is consistent with previous studies (Khan et al., 2019; Sesay et al., 2016).

Thousand kernel weight (TKW) ranged from 295 g to 471 g, showing significant but moderate differences. Grain yield, the primary trait of interest, showed highly significant differences, ranging from 4.75 t ha^{-1} (Rampur Hybrid-10) to 11.33 t ha^{-1} (ZH22668). The highest-yielding hybrid, ZH22668, significantly outperformed the best commercial check (CP 808, 9.36 t ha^{-1}). This significant variability for grain yield, a complex quantitative trait, is commonly reported (Belay, 2018; Rai et al., 2022).

3.2 Heritability Estimates:

Broad-sense heritability (h^2bs) estimates varied from moderate to high (Tables 2-4). High heritability (>0.60) was observed for plant height (0.73), ear height (0.72), ear position (0.64), prolificacy (0.73), cob diameter (0.87), number of leaves above the ear (0.83), and grain yield (0.76). This suggests that phenotypic selection for these traits would be effective, as they are less influenced by the environment (Adhikari et al., 2024; Magar et al., 2021).

Moderate heritability (0.30–0.60) was recorded for days to anthesis (0.49) and silking (0.49), ASI (0.57), ear aspect (0.53), cob length (0.56), number of kernel rows per ear (0.53), number of kernels per row (0.43), and TKW (0.43). For these traits, selection should be exercised with caution, preferably across multiple environments, due to greater environmental influence (Rai et al., 2022).

3.3 Yield Advantage of Test Hybrids:

The grain yield advantage of the 26 test hybrids over the trial mean and check varieties is presented in Table 5. The trial mean yield was 8.38 t ha^{-1}. The hybrid **ZH22668** demonstrated a superior yield advantage of **21.07% over CP 808**, **21.46% over**

Sultan, and a remarkable **49.11% over the internal check CAH153**. **ZH22741** and **ZH22712** also showed substantial advantages of 6.19–6.53% over commercial checks and 26.38–30.78% over CAH153.

TABLE 5
GRAIN YIELD AND PERCENTAGE YIELD ADVANTAGE OF 26 TEST HYBRIDS OVER THE TRIAL MEAN AND CHECK VARIETIES

S.N.	Hybrids	GY (t ha⁻¹)	% Yield Advantage Over				
			Trial Mean	CP 808	Sultan	CAH153	Rampur Hybrid-10
1	ZH22668	11.33	35.23	21.07	21.46	49.11	138.57
2	ZH22741	9.94	18.6	6.19	6.53	30.78	109.24
3	ZH22712	9.61	14.62	2.62	2.95	26.38	102.21
4	ZH2182	9.45	12.78	0.97	1.3	24.36	98.97
5	ZH20379	9.38	11.89	0.17	0.49	23.37	97.39
6	ZH22691	9.37	11.77	0.06	0.39	23.24	97.18
7	ZH22700	9.33	11.31	-0.34	-0.02	22.74	96.38
8	ZH2157	9.24	10.26	-1.28	-0.96	21.58	94.53
9	ZH22709	8.87	5.8	-5.28	-4.97	16.66	86.65
10	ZH22742	8.8	4.99	-6	-5.7	15.76	85.22
11	ZH22698	8.65	3.2	-7.61	-7.31	13.79	82.06
12	ZH22727	8.53	1.75	-8.9	-8.61	12.2	79.52
13	ZH20272	8.53	1.74	-8.91	-8.62	12.18	79.49
14	ZH22724	8.26	-1.38	-11.71	-11.43	8.74	73.98
15	ZH22713	8.22	-1.91	-12.18	-11.9	8.16	73.05
16	ZH22707	8.22	-1.92	-12.19	-11.91	8.14	73.03
17	ZH22740	8.1	-3.34	-13.46	-13.18	6.58	70.53
18	ZH22744	8.05	-3.99	-14.04	-13.76	5.87	69.39
19	ZH22702	8	-4.56	-14.55	-14.28	5.24	68.38
20	ZH191003	7.92	-5.47	-15.36	-15.09	4.24	66.78
21	ZH22697	7.65	-8.75	-18.3	-18.04	0.62	60.99
22	ZH191006	7.38	-11.98	-21.2	-20.94	-2.95	55.28
23	ZH19770	7.35	-12.3	-21.49	-21.23	-3.3	54.72
24	ZH22705	7.11	-15.14	-24.03	-23.78	-6.43	49.71
25	ZH22780	6.64	-20.74	-29.04	-28.81	-12.61	39.83
26	ZH22731	6.44	-23.15	-31.2	-30.98	-15.26	35.58

Note: Trial Mean = 8.38 t ha⁻¹; CP 808 = 9.36 t ha⁻¹; Sultan = 9.33 t ha⁻¹; CAH153 = 7.60 t ha⁻¹; Rampur Hybrid-10 = 4.75 t ha⁻¹. GY = Grain Yield.

Other hybrids like ZH2182, ZH20379, and ZH22691 yielded on par with the commercial checks but showed a 23–24% advantage over CAH153. The significant yield advantage of new hybrids over established checks, often ranging from 10–60%, highlights the continuous genetic gain achievable through breeding (Goshime et al., 2020). It is important to note that yield advantage is influenced by genotype, environment, and their interaction, underscoring the need for multi-environment testing to confirm the stability of these promising hybrids (Rezende et al., 2020)

IV. CONCLUSION

The evaluated maize hybrids showed significant genetic variability in days to 50% anthesis and silking, anthesis-silking interval, plant and ear height, ear position, number of plants, number of ears, prolificacy, ear aspect, cob length, cob diameter, number of kernels per row, number of kernel rows per ear, thousand-kernel weight, and grain yield. Among studied hybrids ZH22668 showed significantly higher grain yield followed by ZH22741 and ZH22712 as compared to commercial checks CP

808 and all these genotypes showed significantly higher grain yield compared to internal check CAH153. Genotype ZH22668 showed 21.07% yield advantage over CP-808. Genotypes ZH22668, ZH22741, and ZH22712 showed 49.11%, 30.78%, and 26.38% yield advantage over internal check CAH153 respectively. Overall, the results suggest that ZH22668, ZH22741, and ZH22712 are promising hybrids, showing positive yield advantages across all checks with desirable traits, making them suitable candidates for further testing in multi-season and multi-location trials.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Faunal Composition of Mookambika Wildlife Sanctuary, Karnataka: Insecta: Hemiptera (Terrestrial)

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Abstract— *The Mookambika Wildlife Sanctuary, a vital component of the Western Ghats biodiversity hotspot, remains under-explored regarding its insect diversity. This study presents the first comprehensive checklist of terrestrial Hemiptera from this sanctuary. Faunistic surveys conducted from 2019 to 2021 recorded* ***55 species*** *belonging to* ***47 genera*** *under* ***16 families****. The families Pentatomidae (9 species), Rhyparochromidae (6 species), and Coreidae (5 species) exhibited the highest species richness. Specimens were collected from two primary locations, Heddanmane Halkal Junction and Aanejcom Buttely Camp, using standard entomological methods. Detailed collection data and global distribution notes for all species are provided. This baseline inventory fills a significant knowledge gap and underscores the sanctuary's importance for hemipteran diversity and conservation in the region.*

Keywords— Hemiptera, Biodiversity, Checklist, Western Ghats, Mookambika Wildlife Sanctuary, Karnataka, Faunal Survey.

I. INTRODUCTION

The order Hemiptera, comprising true bugs, cicadas, hoppers, and allied forms, is one of the most diverse insect groups, representing approximately 8% of global insect fauna (Henry, 2017). Hemipterans occupy nearly every terrestrial and aquatic habitat, playing critical ecological roles as phytophages, predators, pollinators, and vectors of plant diseases, thus holding significant economic and ecological importance (Schuh & Weirauch, 2020). In India, the order is represented by over 6,500 species under about 92 families (Chandra, 2012, 2013), though many regions remain poorly documented.

The Western Ghats of India is a UNESCO World Heritage Site and a global biodiversity hotspot renowned for its exceptionally high levels of endemism and species richness (Myers et al., 2000). Within this chain, the Mookambika Wildlife Sanctuary (MWLS) in Karnataka spans 370.37 sq. km of evergreen, semi-evergreen, and moist deciduous forests. It serves as a crucial ecological corridor between the Someshwara and Sharavathi Wildlife Sanctuaries. Despite its ecological significance, detailed entomofaunal inventories from MWLS are scarce. Previous hemipteran records from the region are limited to isolated studies on specific groups, such as whiteflies (Sundraraj & Pushpa, 2011; Sandeep et al., 2022) and aquatic bugs (Thirumalai, 2004). A consolidated account of the terrestrial Hemiptera fauna is lacking.

This study aims to address this gap by providing the first systematic checklist of terrestrial Hemiptera from the Mookambika Wildlife Sanctuary. The objectives were to (1) document the species diversity and composition, (2) provide precise collection records with distributional data, and (3) establish a baseline for future ecological and conservational studies in this vital part of the Western Ghats.

II. MATERIALS AND METHODS

2.1 Study Area:

The Mookambika Wildlife Sanctuary (MWLS) is located in the Udupi district of Karnataka (Figure 1). It features a complex mosaic of tropical evergreen and moist deciduous forests, with patches of teak plantations, providing diverse microhabitats for insect life.

2.2 Collection and Preservation:

Field surveys were conducted by scientific teams from the Zoological Survey of India during 2019–2021. Specimens were collected from two main sites: Heddanmane Halkal Junction and Aanejcom Buttely Camp. Standard entomological techniques were employed: sweeping nets for vegetation-dwelling species, hand-picking from substrates, and light traps for nocturnal taxa. All collected specimens were preserved in 70% ethanol.

2.3 Identification and Documentation:

Specimens were identified using available taxonomic keys and descriptions (Distant, 1902-1918; Schuh & Slater, 1995; Ananthasubramanian, 1996; Rider et al., 2002) and by comparison with authenticated voucher specimens housed in the National Zoological Collection (NZC) of the Zoological Survey of India, Kolkata. Digital images of smaller specimens (<5 mm) were captured using a Leica M205-A stereo zoom microscope, and larger specimens (>5 mm) were photographed with a Sony DSC-W55 digital camera. All identified specimens have been deposited in the NZC for permanent reference.

2.4 Data Presentation:

The systematic list follows the current classification of Hemiptera (Henry, 2017). For each species, current valid name, collection details (location, coordinates, date, collector), and a summary of its known distribution within India and globally are provided in Table 1.

III. RESULTS

The study recorded a total of **55 species** of terrestrial Hemiptera, classified under **47 genera**, **16 families**, and **4 superfamilies** within the suborders Auchenorrhyncha and Heteroptera (Table 1). All species are reported for the first time from the Mookambika Wildlife Sanctuary.

3.1 Systematic Account:

Phylum: Arthropoda

Class: Insecta

Order: Hemiptera

The annotated systematic list is presented below. An asterisk (*) denotes species for which representative specimen data is provided in Table 1.

Suborder Auchenorrhyncha

Infraorder Cicadomorpha

Superfamily Membracoidea

Family Cicadellidae

1. *Cofana spectra* (Distant, 1908)*
2. *Exitianus indicus* (Distant, 1908)*
3. *Nephotettix virescens* (Distant, 1908)*
4. *Bothrogonia ferruginea* (Fabricius, 1787)*

Family Membracidae

5. *Leptocentrus leucaspis* (Walker, 1858)*
6. *Leptocentrus taurus* (Fabricius, 1775)*

7. *Otinotus oneratus* (Walker, 1858)*

Superfamily Cercopoidea

Family Aphrophoridae

8. *Poophilus costalis* (Walker, 1851)*
9. *Ptyelus affinis* Distant, 1908*
10. *Ptyelus nebulosus* (Fabricius, 1794)*
11. *Clovia conifer* (Walker, 1851)*

Family Lophopidae

12. *Pyrilla perpusilla* (Walker, 1851)*

Suborder Heteroptera

Infraorder Cimicomorpha

Superfamily Reduvioidea

Family Reduviidae

13. *Polididus armatissimus* Stål, 1859*
14. *Rhynocoris costalis* (Stål, 1866)*
15. *Rhynocoris fuscipes* (Fabricius, 1787)*
16. *Coranus fuscipennis* Reuter, 1881*

Superfamily Miroidea

Family Miridae

17. *Charagochilus longicornis* (Reuter, 1884)*
18. *Proboscidocoris capitatus* Distant, 1904*
19. *Cyrrtorhinus lividipennis* (Reuter, 1884)*

Infraorder Pentatomomorpha

Superfamily Pentatomoidea

Family Pentatomidae

20. *Plautia crossota* (Fabricius, 1787)*
21. *Agonoscelis nubilis* (Fabricius, 1775)*
22. *Eysarcoris montivagus* (Distant, 1902)*
23. *Eysarcoris ventralis* (Westwood, 1837)*
24. *Halys serrigera* Westwood, 1837*
25. *Erthesina fullo* (Thunberg, 1783)*
26. *Acrosternum graminea* Kirkaldy, 1787*
27. *Nezara viridula* (Linnaeus, 1758)*
28. *Bagrada hilaris* (Burmeister, 1835)*

Superfamily Coreoidea

Family Coreidae

29. *Cletus bipunctatus* (Westwood, 1842)*
30. *Cletus punctiger* (Dallas, 1852)*
31. *Cletus punctulatus* (Westwood, 1842)*
32. *Cletomorpha hastata* (Fabricius, 1787)*
33. *Notobitus meleagris* (Fabricius, 1787)*

Family Alydidae

34. *Leptocorisa acuta* (Thunberg, 1783)*

35. *Riptortus linearis* (Fabricius, 1775)*

Family Rhopalidae

36. *Liorhyssus rubicundus* (Signoret, 1859)*
37. *Liorhyssus hyalinus* (Fabricius, 1794)*
38. *Leptocoris augur* (Fabricius, 1781)*

Superfamily Lygaeoidea

Family Rhyparochromidae

39. *Elasmolomus sordidus* (Fabricius, 1787)*
40. *Metochus uniguttatus* (Thunberg, 1822)*
41. *Dieuches insignis* (Distant, 1904)*
42. *Pseudopachybrachius guttus* (Dallas, 1852)*
43. *Horridipamera nietneri* (Dohrn, 1860)*
44. *Gyndes pallicornis* (Dallas, 1852)*

Family Lygaeidae

45. *Spilostethus pandurus* (Scopoli, 1763)*
46. *Spilostethus hospes* (Fabricius, 1794)*
47. *Graptostethus servus* (Fabricius, 1787)*
48. *Nysius lacustrinus* (Distant, 1909)*

Family Geocoridae

49. *Geocoris ochropterus* Fieber, 1844*\

Family Oxycarenidae

50. *Oxycarenus laetus* (Kirby, 1891)*

Superfamily Pyrrhocoroidea

Family Largidae

51. *Physopelta schlansbuschi* (Fabricius, 1787)*
52. *Physopelta gutta* (Burmeister, 1834)*
53. *Macroceroea grandis* (Gray, 1832)*
54. *Iphita limbata* Stål, 1870*

Family Pyrrhocoridae

55. *Dysdercus koenigii* (Fabricius, 1775)*

TABLE 1
SYSTEMATIC ACCOUNT, COLLECTION DATA, AND DISTRIBUTION OF TERRESTRIAL HEMIPTERA RECORDED FROM MOOKAMBIKA WILDLIFE SANCTUARY, KARNATAKA.

Sl. No.	Species (with authority)	Material Examined (No. of ex., Location, Coordinates, Date, Collectors)	Distribution within MWLS	
			Heddanmane Halkal Junction	Aanejcom Buttely Camp
Suborder Auchenorrhyncha				
Infraorder Cicadomorpha				
Superfamily Membracoidea				
Family Cicadellidae				
Subfamily Cicadellinae				
Genus Cofana Melichar, 1926				

1	***Cofana spectra*** (Distant, 1908)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Subfamily Deltocephalinae				
Genus Exitianus Ball, 1929				
2	***Exitianus indicus*** (Distant, 1908)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Genus Nephotettix Matsumura, 1902				
3	***Nephotettix virescens*** (Distant, 1908)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Genus Bothrogonia Melichar, 1926				
4	***Bothrogonia ferruginea*** (Fabricius, 1787)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Superfamily Cercopoidea				
Family Aphrophoridae				
Genus Poophilus Stål, 1866				
5	***Poophilus costalis*** (Walker, 1851)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Genus Ptyelus Le Peletier & Serville, 1825				
6	***Ptyelus affinis*** Distant, 1908	2 exs., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓

7	***Ptyelus nebulosus*** (Fabricius, 1794)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Genus Clovia Stål, 1869				
8	***Clovia conifer*** (Walker, 1851)	2 exs., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓
Family Membracidae				
Genus Leptocentrus Stål, 1866				
9	***Leptocentrus leucaspis*** (Walker, 1858)	5 exs., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓
10	***Leptocentrus taurus*** (Fabricius, 1775)	2 exs., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓
Genus Otinotus Buckton, 1903				
11	***Otinotus oneratus*** (Walker, 1858)	2 exs., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓
Family Lophopidae				
Genus Pyrilla Stål, 1859				
12	***Pyrilla perpusilla*** (Walker, 1851)	2 exs., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓
Suborder Heteroptera				
Infraorder Cimicomorpha				
Superfamily Reduvioidea				
Family Reduviidae				
Subfamily Harpactorinae				
Genus Polididus Stål, 1858				

13	***Polididus armatissimus*** Stål, 1859	1 ex., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓
Genus Rhynocoris Hahn, 1834				
14	***Rhynocoris costalis*** (Stål, 1866)	1 ex., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓
15	***Rhynocoris fuscipes*** (Fabricius, 1787)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Genus Coranus Curtis, 1833				
16	***Coranus fuscipennis*** Reuter, 1881	1 ex., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓
Superfamily Miroidea				
Family Miridae				
Subfamily Mirinae				
Genus Charagochilus Fieber, 1858				
17	***Charagochilus longicornis*** (Reuter, 1884)	2 exs., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Genus Proboscidocoris Reuter, 1882				
18	***Proboscidocoris capitatus*** Distant, 1904	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Subfamily Orthotylinae				
Genus Cyrtorhinus Fieber, 1858				

19	***Cyrtorhinus lividipennis*** (Reuter, 1884)	2 exs., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Infraorder Pentatomomorpha				
Superfamily Pentatomoidea				
Family Pentatomidae				
Subfamily Pentatominae				
Tribe Antestiini				
Genus Plautia Stål, 1867				
20	***Plautia crossota*** (Fabricius, 1787)	2 exs., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓
Tribe Agonoscelidini				
Genus Agonoscelis Spinola, 1837				
21	***Agonoscelis nubilis*** (Fabricius, 1775)	2 exs., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓
Tribe Eysarcorini				
Genus Eysarcoris Hahn, 1834				
22	***Eysarcoris montivagus*** (Distant, 1902)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
23	***Eysarcoris ventralis*** (Westwood, 1837)	2 exs., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓
Tribe Halyini				
Genus Halys Fabricius, 1803				
24	***Halys serrigera*** Westwood, 1837	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Genus Erthesina Spinola, 1837				

25	***Erthesina fullo*** (Thunberg, 1783)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Tribe Nezarini				
Genus Nezara Amyot & Serville, 1843				
26	***Acrosternum graminea*** (Fabricius, 1787)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
27	***Nezara viridula*** (Linnaeus, 1758)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Tribe Strachiini				
Genus Bagrada Stål, 1862				
28	***Bagrada hilaris*** (Burmeister, 1835)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Superfamily Coreoidea				
Family Coreidae				
Subfamily Coreinae				
Genus Cletus Stål, 1860				
29	***Cletus bipunctatus*** (Westwood, 1842)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
30	***Cletus punctiger*** (Dallas, 1852)	1 ex., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓

31	***Cletus punctulatus*** (Westwood, 1842)	2 exs., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓
Genus Cletomorpha Mayr, 1866				
32	***Cletomorpha hastata*** (Fabricius, 1787)	2 exs., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓
Genus Notobitus Stål, 1873				
33	***Notobitus meleagris*** (Fabricius, 1787)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Family Alydidae				
Genus Leptocorisa Latreille, 1829				
34	***Leptocorisa acuta*** (Thunberg, 1783)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Genus Riptortus Stål, 1860				
35	***Riptortus linearis*** (Fabricius, 1775)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Family Rhopalidae				
Subfamily Rhopalinae				
Genus Liorhyssus Stål, 1870				
36	***Liorhyssus rubicundus*** (Signoret, 1859)	2 exs., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓
37	***Liorhyssus hyalinus*** (Fabricius, 1794)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–

Subfamily Serinethinae				
Genus Leptocoris Hahn, 1833				
38	***Leptocoris augur*** (Fabricius, 1781)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Superfamily Lygaeoidea				
Family Rhyparochromidae				
Subfamily Rhyparochrominae				
Genus Elasmolomus Stål, 1872				
39	***Elasmolomus sordidus*** (Fabricius, 1787)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Genus Metochus Scott, 1874				
40	***Metochus uniguttatus*** (Thunberg, 1822)	2 exs., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓
Genus Dieuches Dohrn, 1860				
41	***Dieuches insignis*** (Distant, 1904)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Tribe Myodochini				
Genus Pseudopachybrachius Malipatil, 1978				
42	***Pseudopachybrachius guttus*** (Dallas, 1852)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Genus Horridipamera Malipatil, 1978				
43	***Horridipamera nietneri*** (Dohrn, 1860)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–

Genus Gyndes Stål, 1862				
44	***Gyndes pallicornis*** (Dallas, 1852)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Family Lygaeidae				
Subfamily Lygaeinae				
Genus Spilostethus Stål, 1868				
45	***Spilostethus pandurus*** (Scopoli, 1763)	2 exs., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓
46	***Spilostethus hospes*** (Fabricius, 1794)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Genus Graptostethus Stål, 1868				
47	***Graptostethus servus*** (Fabricius, 1787)	1 ex., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓
Subfamily Orsillinae				
Genus Nysius Dallas, 1852				
48	***Nysius lacustrinus*** (Distant, 1909)	2 exs., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓
Family Geocoridae				
Genus Geocoris Fallén, 1814				
49	***Geocoris ochropterus*** (Fieber, 1844)	5 exs., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓
Family Oxycarenidae				
Genus Oxycarenus Fieber, 1837				

50	***Oxycarenus laetus*** (Kirby, 1891)	1 ex., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓
Superfamily Pyrrhocoroidea				
Family Largidae				
Subfamily Physopeltinae				
Genus Physopelta Amyot & Serville, 1843				
51	***Physopelta schlanbuschii*** (Fabricius, 1787)	2 exs., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓
52	***Physopelta gutta*** (Burmeister, 1834)	2 exs., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓
Genus Macroceroea (Spinola, 1837)				
53	***Macroceroea grandis*** (Gray, 1832)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
Genus Iphita Stål, 1870				
54	***Iphita limbata*** Stål, 1870	2 exs., Aanejcom Buttely Camp, MWLS, Udupi, Karnataka, 13.530020°N, 74.860130°E, 04.viii.2021, V.D. Hegde & Party Coll.	–	✓
Family Pyrrhocoridae				
Genus Dysdercus Amyot & Serville, 1843				
55	***Dysdercus koenigii*** (Fabricius, 1775)	1 ex., Heddanmane Halkal Junction, MWLS, Udupi, Karnataka, 13.350102°N, 74.836400°E, 31.viii.2021, V.D. Hegde & Party Coll.	✓	–
TOTAL SPECIES			**30**	**26**

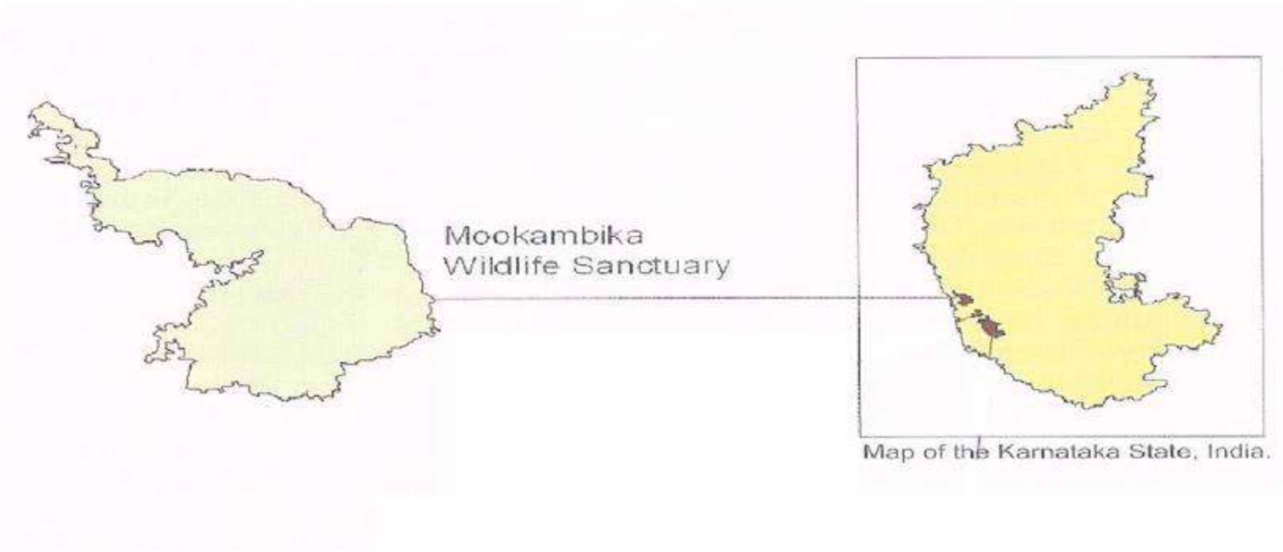

FIGURE 1: Map showing Mookambika Wildlife Sanctuary

3.2 Faunal Composition and Site-wise Distribution:

The recorded fauna comprised 16 families (Table 2). Pentatomidae was the most speciose family (9 species), followed by Rhyparochromidae (6 species), and Coreidae (5 species). Of the two surveyed sites, Heddanmane Halkal Junction yielded 30 species, and Aanejcom Buttely Camp yielded 26 species, with one species (*Dieuches insignis*) recorded from both locations.

TABLE 2
FAMILY-WISE DIVERSITY OF TERRESTRIAL HEMIPTERA IN MOOKAMBIKA WILDLIFE SANCTUARY

Sl. No.	Superfamily	Family	Number of Species
1	Membracoidea	Cicadellidae	4
2		Membracidae	3
3	Cercopoidea	Aphrophoridae	4
4		Lophopidae	1
5	Reduvioidea	Reduviidae	4
6	Miroidea	Miridae	3
7	Pentatomoidea	Pentatomidae	9
8	Coreoidea	Coreidae	5
9		Alydidae	2
10		Rhopalidae	3
11	Lygaeoidea	Rhyparochromidae	6
12		Lygaeidae	4
13		Geocoridae	1
14		Oxycarenidae	1
15	Pyrrhocoroidea	Largidae	4
16		Pyrrhocoridae	1

IV. DISCUSSION

This study provides the foundational checklist for terrestrial Hemiptera in the Mookambika Wildlife Sanctuary. The recorded diversity of 55 species from only two sampling sites underscores the rich hemipteran fauna harbored by the sanctuary's diverse forest ecosystems. The predominance of families like Pentatomidae (stink bugs) and Coreidae (leaf-footed bugs) is consistent with patterns observed in other tropical forest habitats, where these phytophagous groups often exhibit high diversity due to the variety of host plants (Schuh & Slater, 1995).

Notably, several species documented here are of wider agricultural importance. For instance, *Nezara viridula*, *Leptocorisa acuta*, and *Dysdercus koenigii* are known pests of various crops (Rider et al., 2002). Conversely, predators from families like

Reduviidae (assassin bugs) and Geocoridae (big-eyed bugs) play a beneficial role as natural biocontrol agents. Their presence highlights the sanctuary's ecosystem balance.

While this checklist is a significant step, it is preliminary. The Western Ghats are known for high endemism, but our current data lacks host plant associations and seasonal abundance patterns. Furthermore, many hemipteran groups, particularly small Sternorrhyncha (aphids, scale insects) and cryptic taxa, were likely undersampled. More intensive, seasonally-replicated surveys across varied microhabitats (forest floor, canopy, stream banks) and the use of additional methods (e.g., malaise traps, canopy fogging) are needed to develop a complete inventory.

V. CONCLUSION

This first account of the terrestrial Hemiptera from Mookambika Wildlife Sanctuary documents 55 species, establishing a crucial baseline record for this ecologically significant area in the Western Ghats. The data emphasizes the sanctuary's role as a reservoir of both widespread and potentially endemic hemipteran diversity. Future studies should focus on detailed ecological research, molecular taxonomy for cryptic species, and long-term monitoring to understand the impact of environmental changes on these insect communities. This work contributes to the broader goal of documenting and conserving invertebrate biodiversity in India's biodiversity hotspots.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Farmer's Mini Cold Storage: An Innovative CoolBot Technology for Enhancing Shelf Life of Green Chilli under Bangladesh Condition

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Abstract— *The study evaluated the effectiveness of a low-cost cold storage condition (CoolBot) in extending the shelf life of Green Chilli under different storage treatments. Six parameters viz., color retention, texture, bruising, rotting, weight loss and total remaining weight were studied across storage condition up to 27 days. Results revealed that the control treatment (T0) at room temperature exhibited rapid deterioration with complete loss of marketable quality within 9 DAS (days after storage). In contrast, all CoolBot treatments significantly delayed quality loss. Among them, Green Chilli stored under polythene covering (T4) showed superior color and texture retention up to 18 DAS (scores >4.0). It showed lowest bruising (1.33%) at 12 DAS and 20.67% at 21 DAS. Less rotting percentage (15%) at 18 DAS and (43.67%) at 21 DAS was also noticed in the same treatment. Weight loss was lowest under polythene coverings (T4) (6.37 kg loss at 27 DAS). The highest remaining Green Chilli weight at 21 DAS was observed in polythene covering (8.25 kg) and the second highest remaining weight was in newspaper coverings (7.73 kg). The findings demonstrate that CoolBot storage substantially prolongs Green Chilli shelf life compared to room temperature storage, with polythene covering (T4) providing the best short-term quality retention, maximum remaining weight and minimum loss during the study period. This suggests that CoolBot cold storage combined with appropriate packaging can serve as a cost-effective solution for reducing postharvest losses and improving Green Chilli marketability under Bangladesh condition.*

Keywords— CoolBot Technology, Green Chilli, Shelf life, Weight loss.

I. INTRODUCTION

Green Chilli (*Capsicum annuum* L.) is one of the most important spice and vegetable crops in Bangladesh, consumed both in green and dry forms. It holds significant economic value, contributing to farmers' income, national spice demand and export potential. However, despite its importance, Green Chilli production faces serious challenges in postharvest handling, resulting in substantial quantitative and qualitative losses. Green Chilli suffers considerable deterioration due to its perishable nature and lack of proper storage facilities (Mandal & Hoq, 2018). In Bangladesh, postharvest losses of fruits and vegetables range between 20–30%. Under ambient conditions in Bangladesh, where high temperature (27–35°C) and low relative humidity prevail, the shelf life of Green Chilli rarely exceeds 3–4 days, making it difficult for farmers to store and market their product efficiently. Texture softening and water loss are intensified at higher temperatures, while bruising accelerates microbial infection, leading to increased rotting percentage. As a result, growers are often forced into distress sales, limiting profitability and weakening the supply chain.

The absence of accessible cold storage facilities is one of the major constraints in preserving Green Chilli quality after harvest. Bangladesh lacks adequate cold chain facilities at the rural and farm-gate level. Consequently, the lack of affordable storage forces farmers to sell immediately after harvest, leading to oversupply in peak seasons, reduced farm-gate prices, and substantial postharvest losses. This situation results in economic losses due to distress sales and contributes to national food and nutritional insecurity. To address these constraints, there is a need for affordable and accessible cold storage technologies that can reduce postharvest losses, extend shelf life, and maintain the quality of Green Chilli.

CoolBot technology is a new innovative technique where temperature and humidity can be controlled at desirable conditions. The device allows a standard air conditioner to function as a refrigeration unit capable of cooling a well-insulated room down to 5–10°C at a fraction of the cost of conventional cold storage (Store It Cold, 2024). This technology is low-cost, energy-efficient, and simple to operate, making it suitable for farmer cooperatives, small traders, and rural entrepreneurs. Previous studies demonstrated that CoolBot-based mini cold rooms can significantly extend the shelf life of vegetables such as tomato, leafy greens, and collards by reducing weight loss, delaying colour change, maintaining texture, and minimizing microbial spoilage (Kathambi et al., 2022; UC Davis Horticulture Innovation Lab, 2022).

In addition to temperature regulation, relative humidity (RH) control is crucial in postharvest storage. High RH (85–95%) helps reduce transpiration, thereby minimizing weight loss and shriveling of Green Chilli (Kitinoja, 2018). For Green Chilli, maintaining cool and humid conditions slows respiration, reduces transpiration-related weight loss, minimizes bruising effects, and lowers rotten percentage, thereby preserving higher marketable yield over extended storage periods (Cheng et al., 2023; Mi et al., 2023). The adoption of CoolBot mini cold storage in Bangladesh can significantly reduce postharvest losses of Green Chilli, thereby improving marketable yield, enhancing farmer profitability, and strengthening the rural economy. By maintaining quality parameters such as colour, texture, and firmness, while reducing bruising, rotten percentage, and weight loss, CoolBot technology provides a viable solution for postharvest loss management in Green Chilli.

'Affordable Cold Storage Technology Extension for Mitigating Climate Change Risk and Increasing Farmers Income' is a Project funded by Environment, Forest and Climate Change Ministry, Government of the People's Republic of Bangladesh. The project was implemented by the Department of Agricultural Extension (DAE), Khamarbari, Dhaka, Bangladesh under the Project Director of Talha Zubair Masror. CoolBot Technology was first time initiated in Bangladesh under this project. This technology can also empower smallholders to delay sales, take advantage of better market prices, and expand into high-value markets such as exports and processing industries.

The overall objective of this study is to evaluate the effectiveness of low-cost mini cold storage using CoolBot technology in reducing postharvest losses of Green Chilli. The specific objectives are:

- To assess the effect of CoolBot storage on key postharvest quality parameters of Green Chilli.
- To compare the performance of CoolBot storage with ambient storage conditions in terms of postharvest loss reduction.
- To provide recommendations for optimizing CoolBot storage conditions (temperature and RH) for Green Chilli in the context of Bangladesh.

II. METHODOLOGY

The experiment was conducted at Horticulture Center, Rajalakh, Savar, Dhaka, Bangladesh. Ready to eat ripe Green Chilli was used as experimental material. Ten kg of Green Chilli was kept in a plastic crate box and considered as a unit of data recording. The experiment was conducted with three replications in a Randomized Complete Block Design (RCBD).

2.1 Treatments:

There were five treatments including control:

T0 = Control (Outside of CoolBot at room temperature)

T1 = Green Chilli in the open condition inside of the CoolBot

T2 = Green Chilli covered with newspaper inside of the CoolBot

T3 = Green Chilli covered with brown paper inside of the CoolBot

T4 = Green Chilli covered with polythene sheet inside of the CoolBot

2.2 CoolBot Setup:

CoolBot has three temperature sensors: the air conditioner's fins, the air conditioner's temperature sensor (heater) and the storage room. When coupled to an air conditioner, the device can trick and override the air conditioner in a well-insulated room and drop the air temperature to as low as 7°C depending on the pre-set temperature (Saran et al., 2013; Rivard et al., 2016; Majubwa et al., 2019). Installation of the CoolBot device (using an air conditioner and CoolBot controller) was done to create a temperature-controlled storage room. The CoolBot was set to maintain a temperature range of 7–8°C. Humidity range was maintained at 80-90% using a humidifier or dehumidifier as necessary. Different modifications were made in the cooling system to control the temperature and relative humidity considering local conditions. A small container with capacity of 6.00 to 7.00 tons was used as a store room. The inner side of the container was totally sealed by air tight sealing materials. The door of the container was made by three layer closing system, so that it is completely air tight and preserves the temperature and relative humidity. A solar panel electricity generation system was also included with general electricity supply system in the CoolBot.

2.3 Preparation of Samples:

Fresh and uniform samples were selected. The experimental materials (Green Chilli) were free from any damage or bruising. Initial data was recorded on weight, color, texture and other morphological characteristics.

2.4 Data Recording:

Data were recorded on the following parameters: (i) Colour of Green Chilli (ii) Texture of Green Chilli, (iii) Bruising percentage of Green Chilli, (iv) Rotten percentage of Green Chilli, (v) Remaining weight of Green Chilli & (vi) Weight Loss of Green Chilli in every 3 days after storage.

Data were recorded using a scoring scale of 1 = Very poor, 2 = Poor, 3 = Average, 4 = Good, 5 = Excellent. Data were recorded at three-day intervals from the initial day to the 27th day of the experiment for each treatment.

Weight measurement: Weight of Green Chilli fruit was measured by a digital scale. Fruit weight loss was measured by subtracting damaged Green Chilli weight from total Green Chilli weight.

2.5 Monitoring:

The temperature, humidity and air circulation inside the CoolBot storage was monitored regularly to ensure stable conditions. Ambient temperature and humidity was checked in the conventional storage room.

2.6 Statistical analysis:

Statistix-10 and other software were used for proper analysis.

III. RESULTS AND DISCUSSION

The postharvest quality of Green Chilli in the low-cost CoolBot cold room was evaluated over 27 days using multiple parameters, including colour, texture, bruising, rotten percentage, weight loss, and total remaining weight. The effects of different covering materials viz., open storage (T1), newspaper (T2), brown paper (T3), and polythene (T4) - were compared with ambient storage (T0). The major findings are given below:

3.1 Colour Retention:

Colour retention of Green Chilli is presented in Table 1. Green Chilli colour, an important visual quality parameter, deteriorated rapidly under ambient storage (T0), with the score dropping from 5.00 at initial time to 1.00 by 6 DAS, reflecting severe loss of freshness. In contrast, CoolBot storage significantly delayed colour change. Open storage (T1) maintained colour scores above 2.00 until 12 DAS, while newspaper (T2) and brown paper (T3) coverings preserved colour longer days and maintained scores above 3.00 until 18 DAS. Polythene wrapping (T4) was most effective, sustaining high colour scores above 4.00 up to 18 DAS and only declining to 1.00 at 27 DAS.

TABLE 1
COLOR OF GREEN CHILLI AT DIFFERENT DAYS AFTER STORAGE (DAS) IN THE LOW COST COLD ROOM (COOLBOT)

Treatment	Colour (1-5)									
	IT	3 DAS	6 DAS	9 DAS	12 DAS	15 DAS	18 DAS	21 DAS	24 DAS	27 DAS
T_0	5	2.67 b	1.00 b	1	1	-	-	-	-	-
T_1	5	5.00 a	5.00 a	2.33 c	2.33 c	1.00 c	1.00 c	1.00 c	-	-
T_2	5	5.00 a	5.00 a	4.67 b	4.00 b	3.67 b	3.33 b	2.33 b	1.00 b	1.00 a
T_3	5	5.00 a	5.00 a	4.67 b	4.33 b	4.00 a	3.33 b	2.33 b	2.00 a	1.33 a
T_4	5	5.00 a	5.00 a	5.00 a	5.00 a	4.67 a	4.33 a	3.67 a	1.67 a	1.00 a
$LSD_{0.05}$	-	1.04	1.22	0.44	0.4	0.4	0.5	0.47	0.5	0.45^{NS}
CV(%)	-	7.84	8.72	5.88	6.32	4.72	2.87	3.76	1.32	0.7

3.2 Texture Preservation:

Texture of Green Chilli is presented in Table 2. Texture or firmness of Green Chilli is critical for marketability. Ambient-stored fruits (T0) softened rapidly with scores declining to 1.00 by 6 DAS. CoolBot storage maintained firmness for longer periods. Open storage (T1) retained scores above 5.00 until 6 DAS but declined sharply after 9 DAS. Paper coverings (T2, T3) preserved firmness more effectively, with scores above 4.00 until 15 DAS. Polythene-wrapped fruits (T4) maintained the highest firmness, above 4.33 until 21 DAS.

TABLE 2
TEXTURE OF GREEN CHILLI AT DIFFERENT DAYS AFTER STORAGE (DAS) IN THE LOW COST COLD ROOM (COOLBOT)

Treatment	Texture of Green Chilli (1-5)									
	IT	3 DAS	6 DAS	9 DAS	12 DAS	15 DAS	18 DAS	21 DAS	24 DAS	27 DAS
T_0	5	2.67 b	1.00 b	1.00 d	1.00 d	-	-	-	-	-
T_1	5	5.00 a	5.00 a	2.67 c	2.33 c	1.33 c	1.00 c	1.00 c	-	-
T_2	5	5.00 a	5.00 a	4.67 b	4.00 b	3.67 b	3.67 b	2.33 b	1.33 a	1.00 a
T_3	5	5.00 a	5.00 a	4.67 b	4.33 b	4.00 b	3.33 b	2.33 b	1.67 a	1.33 a
T_4	5	5.00 a	5.00 a	5.00 a	5.00 a	4.67 a	4.33 a	3.33 a	1.33 a	1.00 a
$LSD_{0.05}$	-	0.5	0.63	0.22	0.4	0.44	0.49	0.4	0.59^{NS}	0.52^{NS}
CV(%)	-	6.71	7.34	5.63	7.92	9.27	11.24	8.53	1.36	0.72

3.3 Bruising Percentage:

The bruising percentage of chilli during storage in the low-cost CoolBot cold room across treatments is shown in Fig. 1. Bruising is a major factor affecting marketable quality. Ambient storage (T0) exhibited rapid bruising, reaching 72.67% by 9 DAS. CoolBot storage substantially reduced bruising. Open storage (T1) showed minor bruising until 6 DAS but increased to 90% by 21 DAS. Newspaper (T2) and brown paper (T3) coverings reduced bruising further, with T3 performing slightly better than T2. Polythene wrapping (T4) was most effective, with bruising remaining negligible up to 12 DAS and increasing only gradually to 45.67% by 24 DAS.

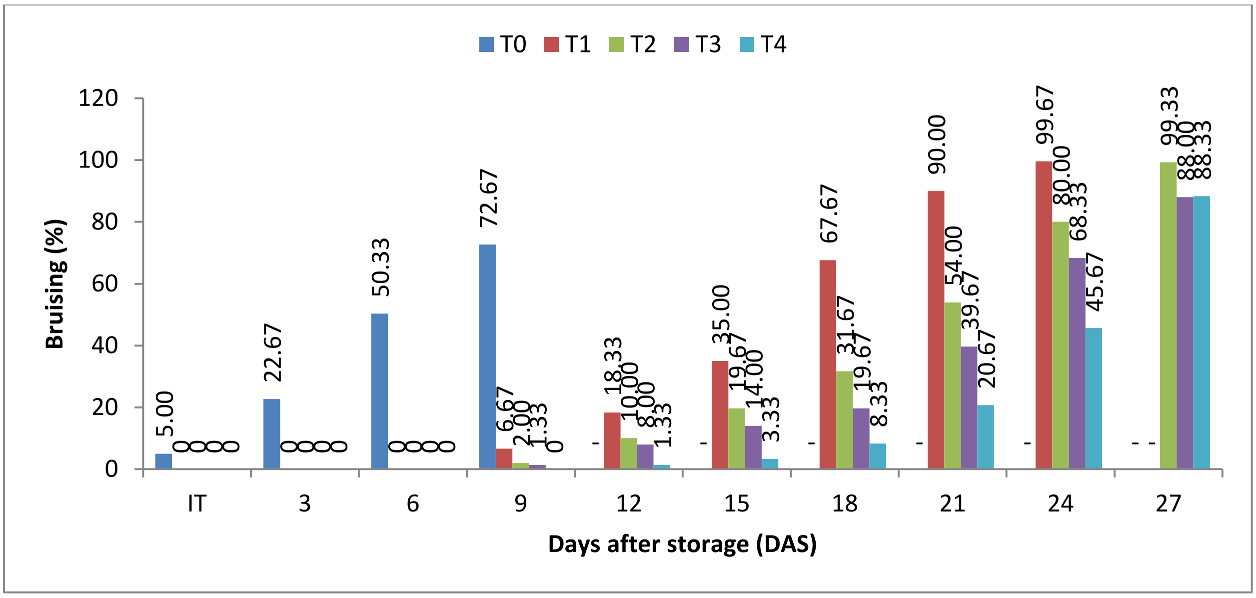

FIGURE 1: Bruising percentage of Green Chilli at different days after storage (DAS) in the low cost cold room (Coolbot)

3.4 Rotten Percentage:

Rotten percentage of Green Chilli is presented in Table 3. Green Chilli decay was significantly higher in ambient storage (T0), with 46.00% rotting by 6 DAS and near-complete spoilage (98.00%) at 9 DAS. CoolBot storage markedly delayed rotting. Open storage (T1) maintained almost zero rot until 6 DAS, but the rotten percentage rose to 63.67% by 27 DAS. Newspaper (T2) and brown paper (T3) further reduced spoilage, whereas polythene-wrapped fruits (T4) showed minimal rotting (1.33–45.67%) throughout the storage period.

TABLE 3
ROTTEN PERCENTAGE OF GREEN CHILLI AT DIFFERENT DAYS AFTER STORAGE (DAS) IN THE LOW COST COLD ROOM (COOLBOT)

Treatment	Rotten percentage of Green Chilli									
	IT	3 DAS	6 DAS	9 DAS	12 DAS	15 DAS	18 DAS	21 DAS	24 DAS	27 DAS
T_0	0	11.67 a	46.00 a	98.00 a	-	-	-	-	-	-
T_1	0	0.00 b	0.00 b	0.00 b	1.33 a	6.33 a	11.67 b	42.67 a	61.00 b	74.00 b
T_2	0	0.00 b	0.00 b	0.00 b	0.00 b	2.33 c	5.67 c	22.67 b	47.67 c	63.67 d
T_3	0	0.00 b	0.00 b	0.00 b	0.00 b	1.67 c	4.00 c	17.67 c	46.00 c	66.00 c
T_4	0	0.00 b	0.00 b	0.00 b	2.00 a	5.33 a	15.00 a	43.67 a	70.00 a	86.67 a
$LSD_{0.05}$	-	1.62	2.44	2.86	0.72	1.22	1.73	2.36	3.11	3.71
CV(%)	-	8.36	10.71	9.73	6.27	5.71	8.36	9.44	10.27	8.47

3.5 Weight Loss:

Weight loss is a key indicator of water loss and dehydration. Ambient storage (T0) showed rapid weight loss, reaching 9.80 kg by 9 DAS. CoolBot storage significantly reduced weight loss (Fig. 2). Polythene cover (T4) showed minimal loss up to 9 DAS, increasing to 6.37 kg by 27 DAS. Covering with Newspaper (T2) effectively maintained moisture with weight loss of 6.60 kg by 27 DAS. Polythene-wrapped fruits (T4) retained moisture all over the experimental period, hence it showed minimum loss.

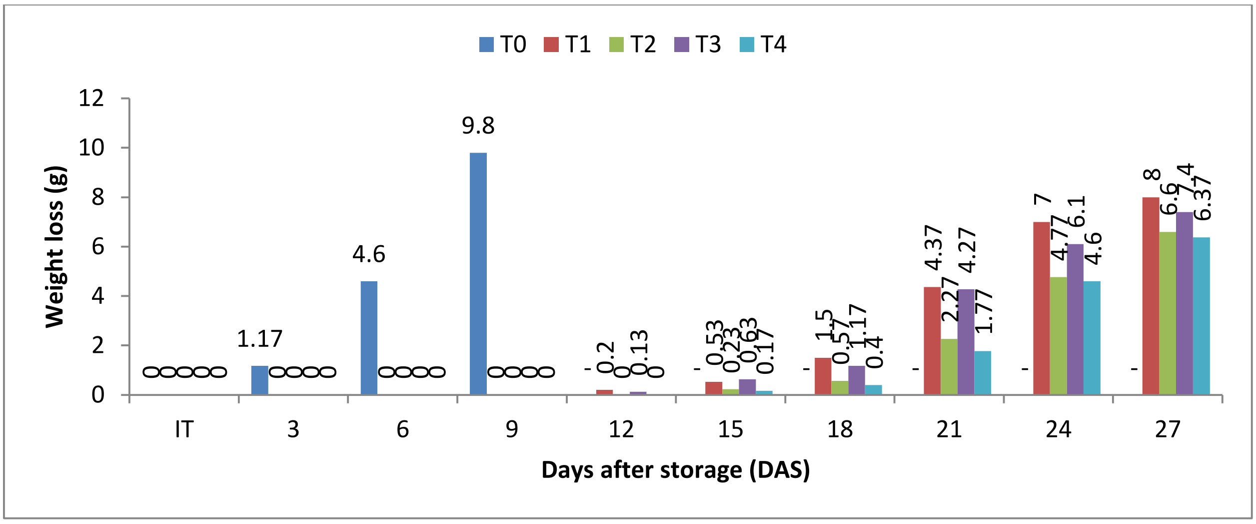

FIGURE 2: Weight loss of Green Chilli at different days after storage (DAS) in the low cost cold room (CoolBot)

3.6 Remaining Weight:

The remaining weight of chilli during storage in the low-cost CoolBot cold room varied significantly across treatments and storage duration, as shown in Table 4. The remaining weight of Green Chilli reflects cumulative effects of water loss, rot and bruising. Ambient-stored Green Chilli (T0) lost almost all weight by 9 DAS (0.20 kg). CoolBot storage maintained significantly higher weight retention. Open storage (T1) preserved 2.00 kg at 27 DAS, newspaper (T2) 3.40 kg, brown paper (T3) 3.1.33 kg and polythene wrapping (T4) 3.63 kg. The results suggest that Polythene coverings combined with low temperature are most effective in preserving cumulative Green Chilli weight and thus marketable yield.

TABLE 4
TOTAL WEIGHT OF GREEN CHILLI AT DIFFERENT DAYS AFTER STORAGE (DAS) IN THE LOW COST COLD ROOM (COOLBOT)

Treatment	Total weight/remaining weight of Green Chilli (kg)									
	IT	3 DAS	6 DAS	9 DAS	12 DAS	15 DAS	18 DAS	21 DAS	24 DAS	27 DAS
T_0	10	8.83 b	5.40 b	0.20 b	-	-	-	-	-	-
T_1	10	10.00 a	10.00 a	10.00 a	9.87 a	9.37 b	8.83 b	5.73 c	3.00 b	2.00 b
T_2	10	10.00 a	10.00 a	10.00 a	10.00 a	9.77 a	9.43 a	7.73 b	5.23 a	3.40 a
T_3	10	10.00 a	10.00 a	10.00 a	9.80 a	9.47 b	8.50 c	5.63 c	3.00 b	1.33 c
T_4	10	10.00 a	10.00 a	10.00 a	10.00 a	9.83 a	9.60 a	8.23 a	5.40 a	3.63 a
$LSD_{0.05}$	-	0.22	0.24	1.21	0.25	0.22	0.24	0.2	0.52	0.3
CV(%)	-	1.25	1.3	1.27	0.5	0.7	1.1	5.72	6.12	4.37

IV. DISCUSSION

Across all parameters, CoolBot storage significantly improved postharvest quality compared to ambient conditions. Protective coverings enhanced storage outcomes, with polythene maintaining colour, texture, and minimizing bruising in the early to mid-storage period, while paper coverings better preserved total weight and reduced rot in later stages. Maintaining low temperature (around 6–8°C) and high relative humidity (80–90%) is critical for extending shelf life, reducing postharvest losses, and improving marketable yield of Green Chilli in Bangladesh. These findings are consistent with international studies on low cost cold storage and protective packaging for capsicum and Green Chilli (Cheng et al., 2023; Costa et al., 2018; Mi et al., 2023; Sreeramulu et al., 2015).

In Green Chilli, losses occur primarily through physiological deterioration, weight reduction, microbial decay and physical damage during the storage and marketing chain. Such losses reduce both farmers' profitability and consumers' access to quality product (Kitinoja, 2018). Postharvest deterioration of Green Chilli is manifested in several quality parameters, including rapid colour change, softening of texture, mechanical bruising, microbial spoilage, weight loss, and reduced marketable yield (Cheng et al., 2023).

These results indicate that low temperature combined with controlled humidity slows pigment degradation, consistent with previous findings on capsicum and Green Chilli fruits (Costa et al., 2018; Martínez et al., 2019). The result is similar with the finding of Kader (2002), Mahajan & Goswami (2004) and Sreeramulu et al. (2015), who reported that the retention of turgor and reduced water loss in CoolBot, particularly with protective coverings, delays enzymatic softening of cell walls. It is mentioned by Cheng et al. (2023) and Mi et al. (2023) that protective coverings combined with low temperature preserve fruit integrity and reduce mechanical damage, aligning with prior studies. These observations confirm that low temperature and high relative humidity reduce microbial growth and enzymatic decay, prolonging shelf life (Kader, 2002; Sreeramulu et al., 2015; Mi et al., 2023).

V. CONCLUSION

The present study demonstrated that the use of a low-cost CoolBot cold room significantly reduces postharvest losses and preserves the quality of Green Chilli in Bangladesh. Storage under ambient conditions resulted in rapid deterioration of colour, texture, and firmness, with severe bruising, rotting, and weight loss within 9 days. In contrast, the CoolBot system effectively delayed these deteriorative changes by maintaining low temperature and high relative humidity, extending shelf life up to 27 days depending on the type of covering used.

Polythene wrapping (T4) showed superior performance in terms of weight loss and minimum rotting percentage of Green Chilli. Among the CoolBot treatments, protective coverings played a critical role in further enhancing storage quality. Polythene wrapping (T4) was most effective in maintaining colour, texture, and minimizing bruising during the early and mid-storage period. Overall, the combined use of low-cost CoolBot storage and appropriate protective coverings significantly reduced postharvest losses, maintained marketable quality, and improved potential yield and economic return for Green Chilli farmers in Bangladesh.

The findings highlight that CoolBot technology offers a practical, low-cost, and effective solution for smallholder farmers to extend the shelf life of perishable horticultural crops, ensuring better marketability and reduced economic loss

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Characterization and Mapping of Underground Water Quality in Dadri-II Block of Charkhi Dadri District in Haryana

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Abstract— *A study was conducted to characterize the groundwater quality in the Dadri-II block of Charkhi Dadri district, Haryana. A total of 122 groundwater samples were collected from Dadri-II and analyzed for key parameters. Based on Electrical Conductivity (EC), Sodium Adsorption Ratio (SAR), and Residual Sodium Carbonate (RSC), the water samples were classified: 18.85% as good, 28.68% as marginally saline, 50.81% as high SAR-saline, and 1.6% as highly alkali. Electrical conductivity ranged from 0.26 to 13.95 dS m^{-1}, SAR from 1.42 to 36.39 (mmol $L^{-1})^{1/2}$, and RSC from nil to 5.40 me L^{-1}. Sodium was the dominant cation (1.10 to 98.70 me L^{-1}), and chloride was the dominant anion (1.20 to 101.20 me L^{-1}), followed by sulfate, bicarbonate, and carbonate. The spatial variability of these parameters was mapped, confirming that high SAR-saline water is the most widespread quality issue in the block, which has significant implications for irrigation management.*

Keywords— Electrical conductivity, Residual Sodium Carbonate, SAR, Salinity, Sodicity, Groundwater, Spatial mapping.

I. INTRODUCTION

Groundwater is one of the most valuable replenishable natural resources on the planet and a major source of fresh water. A significant share of water resources is used in agriculture (89%). However, estimates indicate that growing demand from municipalities, industries, and other sectors will claim about 22% of the total resource by 2025, thereby reducing the supply of good-quality water for agriculture (Minhas, 1998). In the arid and semi-arid regions of India, including southeastern Haryana, farmers often rely on poor-quality groundwater for irrigation due to the limited availability of canal water and good-quality groundwater.

In Haryana, on average, 37% of tubewell waters are of good quality, 8% are normal, and 55% are of poor quality. Among the poor-quality waters, 11% are saline, 18% are sodic, and 26% are saline-sodic in nature (Manchanda, 1976). While past attempts have been made to establish water quality zones for Haryana (Manchanda, 1976), significant changes in water quality have occurred over the years due to over-exploitation (Phogat et al., 2008). Groundwater quality depends on distinct natural factors (precipitation, rock-water interaction, geology) and anthropogenic activities (agriculture, industry), which can make groundwater vulnerable to contamination (Vrba and Zoporozec, 1994; Adhikary et al., 2014). The suitability of water for agriculture is determined by its effects on crop yield and soil health (FAO, 1985; Zinabu et al., 2010). Therefore, a reappraisal of the nature, properties, and extent of groundwater quality in the Dadri-II block of Charkhi Dadri district is essential for sound irrigation planning in the area.

II. MATERIALS AND METHODS

2.1 Study Area:

The study was conducted in the Dadri-II block of Charkhi district, Haryana. The soils in the block range from sandy to sandy loam in texture. The dominant cropping systems are cotton-wheat and pearl millet-mustard under sprinkle irrigation. Other crops include jowar, bajra, cluster bean, and gram.

2.2 Sample Collection and Analysis:

A total of 122 groundwater samples were collected from running tubewells across the block using random sampling. The geographic coordinates of each sampling point were recorded using a handheld GPS. The location map of the sampling points is presented in Fig. 1.

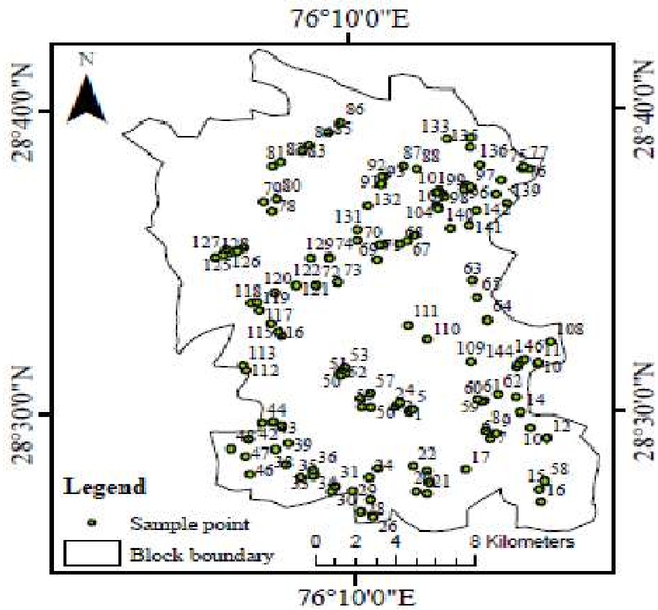

FIGURE 1: Location map of sampling points in Dadri-II block

The water samples were analyzed for pH, Electrical Conductivity (EC), carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^+) following standard methods (Richards, 1954). Potassium (K^+), chloride (Cl^-), and sulfate (SO_4^{2-}) were also determined. Residual Sodium Carbonate (RSC) and Sodium Adsorption Ratio (SAR) were calculated using the following formulas:

$$\textbf{SAR} = Na^+ / \sqrt{[(Ca^{2+} + Mg^{2+})/2]} \quad (1)$$

$$\textbf{RSC} = (CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+}) \quad (2)$$

2.3 Water Quality Classification and Spatial Mapping:

The water samples were classified based on the criteria adopted by the All India Coordinated Research Project (AICRP) on the management of salt-affected soils and use of saline water (Gupta et al., 1994), as detailed in Table 1.

TABLE 1
CRITERIA FOR WATER QUALITY CLASSIFICATION (AICRP, 1989)

Quality Class	EC (dS m^{-1})	SAR [$(mmol\ L^{-1})^{1/2}$]	RSC (me L^{-1})
Good	<2	<10	<2.5
Marginally saline	2-4	<10	<2.5
Saline	>4	<10	<2.5
High SAR - saline	>4	>10	<2.5
Marginally alkali	<2	<10	2.5-4.0
Alkali	<2	<10	>4.0
Highly alkali	Variable	>10	>4.0

Spatial distribution maps for EC, pH, SAR, RSC, and overall water quality were generated using the Inverse Distance Weighting (IDW) interpolation technique in ArcGIS software based on data from the 122 sampling points.

III. RESULTS AND DISCUSSION

3.1 Hydrochemical Characteristics:

The statistical summary of the analyzed water quality parameters is presented in Table 2. The pH of the water samples ranged from 7.70 to 8.40, indicating a slightly alkaline nature. Electrical Conductivity (EC), a measure of total dissolved salts, showed a wide range from 0.26 to 13.95 dS m^{-1}, with a mean of 4.20 dS m^{-1}, indicating high variability in salinity across the block.

TABLE 2
RANGE OF DIFFERENT WATER QUALITY PARAMETERS IN DADRI-II BLOCK OF CHARKHI DADRI DISTRICT

S.No.	Quality Parameter	Range	Mean
1	pH	7.70 - 8.40	7.95
2	EC (dS m^{-1})	0.26 - 13.95	4.2
3	RSC (me L^{-1})	0.00 - 5.40	0.6
4	SAR [(mmol $L^{-1})^{1/2}$]	1.42 - 36.39	12.5
5	Ca^{2+} (me L^{-1})	0.20 - 11.20	2.74
6	Mg^{2+} (me L^{-1})	0.60 - 23.80	6.49
7	Na^{+} (me L^{-1})	1.10 - 98.70	30.28
8	K^{+} (me L^{-1})	0.12 - 7.60	1.57
9	CO_3^{2-} (me L^{-1})	0.00 - 3.90	0.67
10	HCO_3^{-} (me L^{-1})	0.20 - 8.80	3.76
11	Cl^{-} (me L^{-1})	1.20 - 101.20	28.6
12	SO_4^{2-} (me L^{-1})	0.20 - 26.90	8.31

Sodium (Na^{+}) was the dominant cation, ranging from 1.10 to 98.70 me L^{-1}. Among anions, chloride (Cl^{-}) was dominant (1.20 to 101.20 me L^{-1}), followed by sulfate (SO_4^{2-}), bicarbonate (HCO_3^{-}), and carbonate (CO_3^{2-}). The high concentrations of Na^{+} and Cl^{-} are characteristic of saline groundwater influenced by weathering processes and possibly anthropogenic activities.

3.2 Irrigation Suitability Classification:

Based on EC, SAR, and RSC values (Table 1), the 122 water samples were classified. The majority of samples (50.81%) fell into the **High SAR-saline** category (EC >4 dS m^{-1} and SAR >10). This was followed by **marginally saline** (28.68%), **good** (18.85%), and **highly alkali** (1.60%) categories. The predominance of High SAR-saline water is a major concern as it poses a combined salinity and sodicity hazard. Irrigation with such water can lead to the accumulation of salts and exchangeable sodium in the soil, degrading soil structure and reducing crop yields (Isaac et al., 2009).

3.3 Spatial Variability of Key Parameters:

The spatial distribution maps provide a visual assessment of groundwater quality across the block.

- **Electrical Conductivity (EC):** The spatial variability map for EC (Fig. 2) shows zones of high salinity (EC >4 dS m^{-1}) concentrated in specific regions, potentially linked to local geology, evaporation, and irrigation return flows.

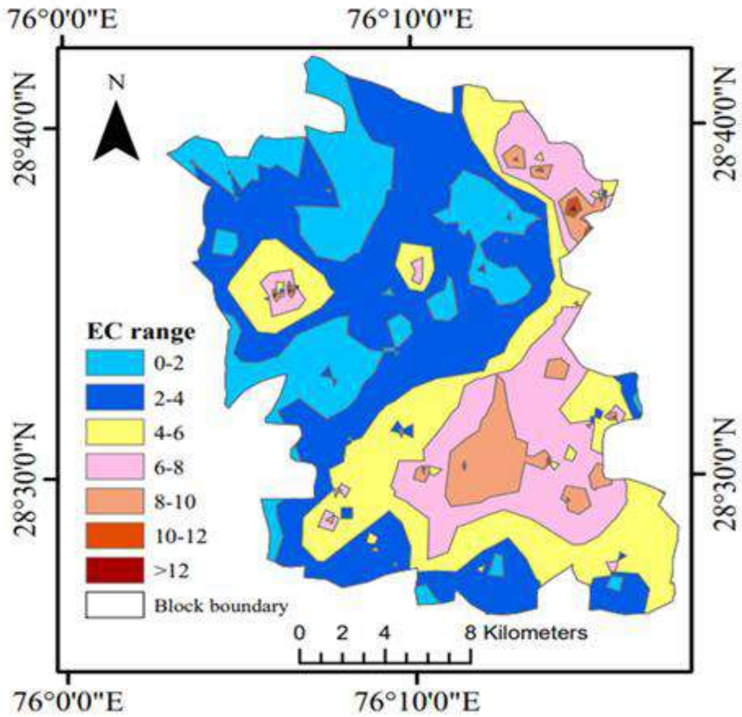

FIGURE 2: Spatial variability map for EC of groundwater in Dadri-II block]

- **pH:** The pH map (Fig. 3) shows slight alkalinity (7.70-8.40) across the block, which is typical for groundwater in arid regions.

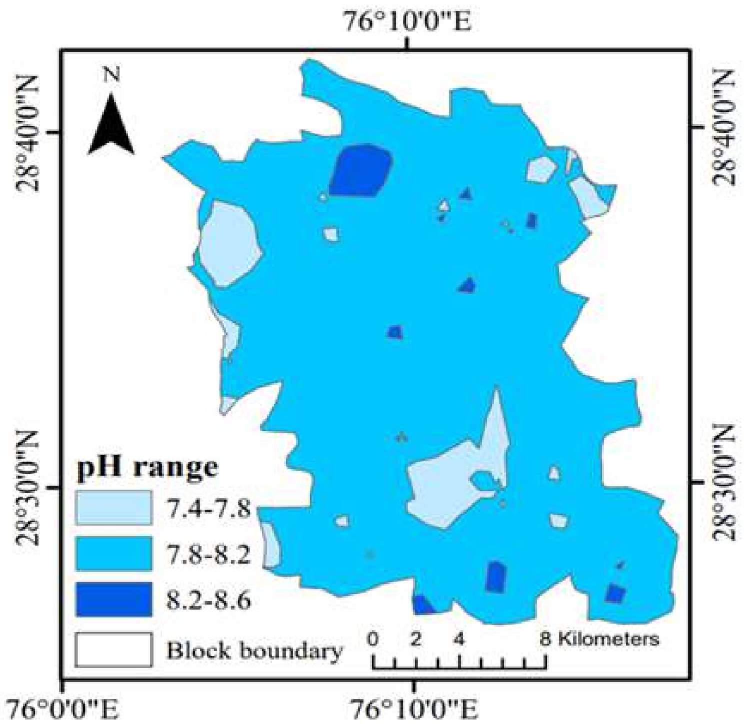

FIGURE 3: Spatial variability map for pH of groundwater in Dadri-II block]

- **Sodium Adsorption Ratio (SAR):** The SAR map (Fig. 4) reveals significant spatial variation (1.42 to 36.39). High SAR values (>10) correlate well with areas of high EC, confirming the prevalence of High SAR-saline water. Bhat et al. (2016) reported a similar SAR range (4.03-24.16) in the Gohana block of Haryana.

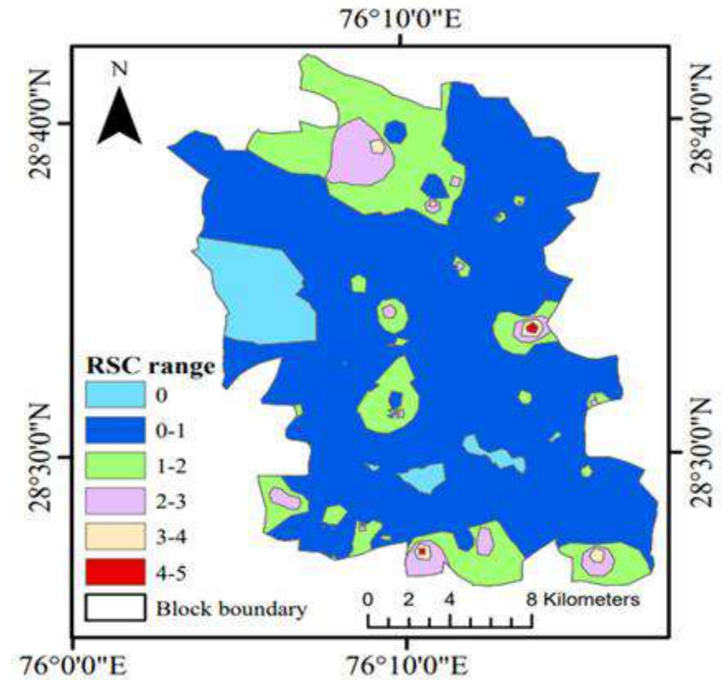

FIGURE 4: Spatial variability map for SAR of groundwater in Dadri-II block]

- **Residual Sodium Carbonate (RSC):** The RSC map (Fig. 5) shows most areas have low RSC (<2.5 me L^{-1}), consistent with the low percentage of alkali-classified waters. Sporadic patches of higher RSC exist. RSC significantly influences the pH, EC, and SAR of irrigation water (Naseem et al., 2010).

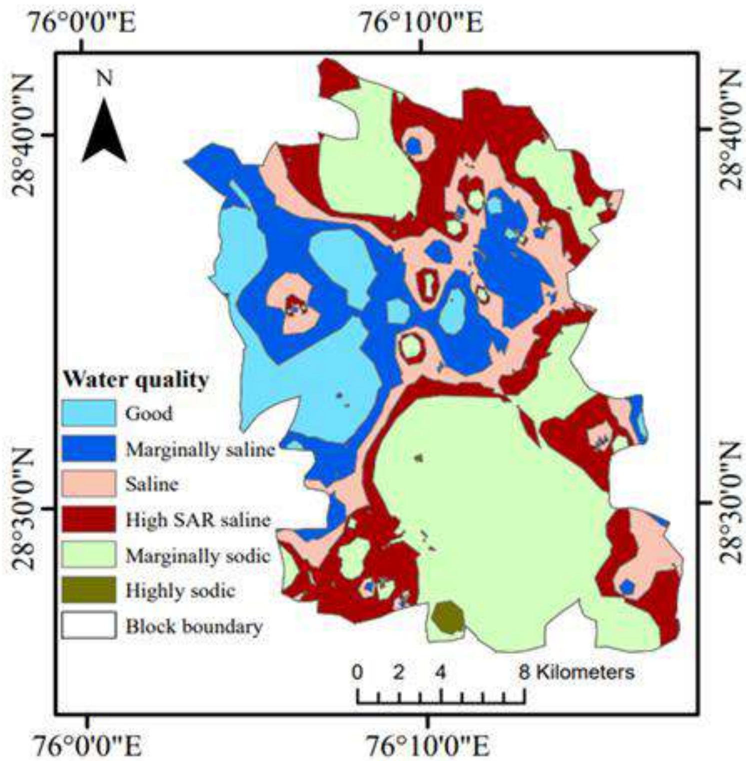

FIGURE 5: Spatial variability map for RSC of groundwater in Dadri-II block]

3.4 Integrated Groundwater Quality Zonation:

The final integrated water quality classification map (Fig. 6) synthesizes the criteria from Table 1. It visually confirms the findings from section 3.2: the **High SAR-saline** class (50.81% of samples) is the most extensive, covering large contiguous areas. Zones of **good** and **marginally saline** water are interspersed, while **highly alkali** water is very localized.

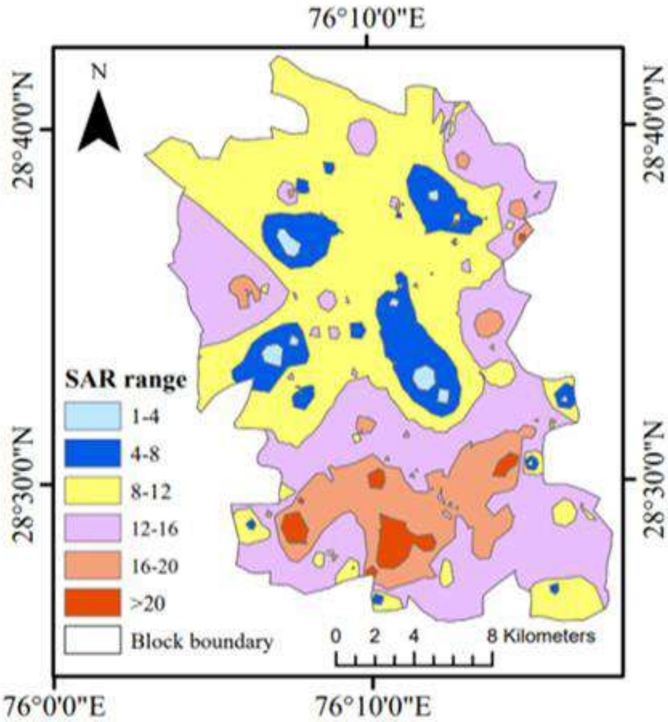

FIGURE 6: Spatial variability map of groundwater quality classification in Dadri-II block]

IV. CONCLUSION

The groundwater quality assessment of the Dadri-II block in Charkhi Dadri district reveals that the water is predominantly **High SAR-saline** (50.81% of samples), posing a significant combined salinity and sodicity hazard for irrigation. Good quality water is limited to only 18.85% of the samples. The spatial maps effectively delineate zones of different water quality hazards, which is crucial for site-specific agricultural planning.

Good and marginally saline waters can be used for irrigation with minimal management. However, the widespread High SAR-saline water requires careful management strategies, such as the application of gypsum or other calcium-based amendments to counteract sodicity, the use of salt-tolerant crop varieties, and blending with good quality water if available. The highly alkali waters, though limited in extent, require specific reclamation approaches. This study provides a foundational geospatial dataset for sustainable groundwater resource management and precision agriculture in the block.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Phenotyping of Thermotolerant Finger Millet (*Eleusine coracana* L.) Genotypes using Temperature Induction Response at the Seedling Stage

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Abstract— *The Temperature Induction Response (TIR) technique was standardized and employed to identify thermotolerant finger millet (Eleusine coracana L.) genotypes at the seedling stage. The technique involves exposing seedlings to a gradual sub-lethal temperature induction followed by a lethal temperature treatment, and subsequently assessing seedling recovery. Optimization of induction and lethal temperature regimes was based on percent seedling survival and percent reduction in root and shoot growth after a 72-h recovery period. An induction treatment ranging from 37°C to 52°C over five hours, followed by exposure to a lethal temperature of 58°C for two hours, was identified as optimal for screening. Fifteen finger millet genotypes were evaluated under induced and non-induced conditions. Genotypes were classified based on seedling survival percentage and growth reduction parameters. Cultivar Tirumala and genotype VR-1099 exhibited the least reduction in root and shoot growth along with higher survival rates, indicating superior thermotolerance. The study demonstrates that the TIR technique is an effective and rapid phenotyping tool for identifying thermotolerant finger millet genotypes at the seedling stage, facilitating the efficient selection of parental lines for breeding heat-resilient varieties.*

***Keywords*— *Finger millet, Temperature induction response, Thermotolerance, Heat stress, Seedling screening*.**

I. INTRODUCTION

High temperature stress is a major abiotic constraint affecting crop productivity, particularly in semi-arid and tropical regions. Plants exhibit both inherent (basal) thermotolerance and acquired thermotolerance, the latter being rapidly induced by prior exposure to moderately high temperatures. The Temperature Induction Response (TIR) technique was developed to exploit this adaptive mechanism by subjecting seedlings to sub-lethal temperature stress prior to lethal temperature exposure, thereby enabling the identification of genotypes with superior heat tolerance. Acquired thermotolerance is associated with cellular acclimation processes, including the synthesis and accumulation of heat shock proteins (HSPs), which function as molecular chaperones that maintain protein stability under stress conditions. Previous studies have demonstrated that seedlings exposed to induction temperatures prior to lethal stress show enhanced survival and recovery compared to directly stressed seedlings. Therefore, standardization of induction and lethal temperature regimes is crucial for accurately screening genotypes for intrinsic heat tolerance. Given the increasing frequency of heat stress episodes under climate change scenarios, identifying crops with enhanced thermotolerance is essential for sustainable crop improvement programs. Finger millet, a nutrient-dense, climate-resilient cereal crucial for food security in arid regions, is a prime candidate for such thermotolerance screening. The objectives of this study were to (1) standardize the TIR protocol for finger millet seedlings, and (2) employ this protocol to screen and classify fifteen genotypes for thermotolerance.

II. MATERIALS AND METHODS

2.1 Experimental location and plant material:

The experiment was conducted at the Phenotyping Laboratory, Institute of Frontier Technology, Regional Agricultural Research Station, Tirupati. Fifteen finger millet genotypes, representing local cultivars and advanced breeding lines with putative variability for stress response, were obtained from the Millet Breeding Programme, Agricultural Research Station, Perumallapalle, Chittoor district, Andhra Pradesh.

2.2 Temperature Induction Response (TIR) protocol:

Seeds were surface-sterilized using fungicide (Mancozeb 63% + Carbendazim 12% WP) at 2 g L^{-1} for 30 minutes and thoroughly rinsed 4–5 times with distilled water. Seeds were germinated in an incubator maintained at 30°C and 60% relative humidity. After 48 hours, uniform seedlings were selected and transplanted into aluminium trays containing soil. The TIR protocol was optimized through preliminary experiments. For the final screening, seedlings were subjected to an induction treatment where temperature was gradually increased from 37°C to 52°C over a period of five hours (a rate of 3°C per hour) in a programmable Plant Growth Chamber (WGC-450). Immediately thereafter, induced seedlings were exposed to a lethal temperature of 58°C for two hours. A parallel set of seedlings was directly exposed to the lethal temperature without induction (non-induced control). An absolute control was maintained at optimal 30°C conditions throughout. Following treatment, seedlings were allowed to recover for 72 hours under normal growth conditions.

2.3 Observations and data analysis:

Root length, shoot length, and percent seedling survival were recorded after the recovery period. Percent reduction in root and shoot growth under stress conditions was calculated relative to the absolute control seedlings. The experiment was laid out in a Completely Randomized Design (CRD) with five replications. Data were analyzed using analysis of variance (ANOVA), and treatment means were compared using Duncan's Multiple Range Test (DMRT) at a 5% probability level with appropriate statistical software.

III. RESULTS AND DISCUSSION

The Temperature Induction Response (TIR) technique effectively differentiated finger millet genotypes for thermotolerance under controlled laboratory conditions, revealing significant genetic variability in root growth, shoot growth, and seedling survival following exposure to high temperature stress (Table 1). Similar effectiveness of TIR-based phenotyping has been reported in small millets and cereals, confirming its reliability for early-stage screening of heat tolerance (Reddy et al., 2023; Kumar et al., 2022).

Under control conditions, root growth among the genotypes ranged from 3.60 cm in PPR 1216 to 6.60 cm in PPR 2885, reflecting inherent genotypic differences in seedling vigor. Exposure to induction and lethal temperature treatments caused a marked reduction in root growth across all genotypes; however, the magnitude of reduction varied significantly. Root growth under stress ranged from 1.08 cm in PPR 1216 to 5.18 cm in cultivar Tirumala. The percent reduction in root growth was lowest in Tirumala (19.06%), followed by VR 1099 (20.20%), PPR 1160 (22.57%), and PPR 1272 (23.39%), indicating superior thermotolerance. In contrast, PPR 1216 (70.00%), PPR 1094 (65.02%), and PPR 2885 (64.85%) exhibited severe reduction in root growth, suggesting higher sensitivity to temperature stress. Reduced root growth under heat stress has been associated with impaired cell elongation and membrane destabilization in susceptible genotypes (Sharma et al., 2024). The maintenance of root growth in tolerant genotypes like Tirumala and VR 1099 is critical, as a robust root system supports water and nutrient uptake under combined heat and drought stress scenarios common in semi-arid regions.

Shoot growth also exhibited significant genotypic variation under both control and stress conditions. Under control conditions, shoot length ranged from 1.82 cm in VR 1099 to 2.68 cm in PPR 1216. Following high temperature exposure, shoot growth declined substantially, ranging from 1.04 cm in genotype ID to 1.94 cm in Tirumala. The percent reduction in shoot growth varied from 17.80% in Tirumala to 60.82% in PPR 1216. Genotypes Tirumala, VR 1099 (18.68%), and PPR 1160 (18.56%) recorded significantly lower shoot growth reduction, indicating better maintenance of physiological and metabolic processes under stress. Similar observations were reported in finger millet and other millets, where tolerant genotypes maintained shoot growth through effective heat shock protein (HSP) synthesis and improved antioxidant defense mechanisms (Kumar et al., 2022; Trivedi et al., 2023).

Seedling survival percentage further reinforced the differential thermotolerance among genotypes. Survival under stress conditions ranged from 69% in PPR 1216 to 93% in cultivar Tirumala. Higher survival percentages were recorded in Tirumala (93%), VR 1099 (90%), PPR 1272 (88%), and PPR 1160 (87%), while lower survival was observed in PPR 1216, PPR 1094 (72%), and VR 1171 (74%). Higher survival in tolerant genotypes may be attributed to effective cellular acclimation during induction treatment, enabling rapid recovery following lethal temperature exposure, as also reported in recent heat-stress studies in small millets (Reddy et al., 2023; Sharma et al., 2024).

Overall, the present findings confirm that the TIR technique is a rapid and reliable phenotyping tool for identifying thermotolerant finger millet genotypes at the seedling stage. Based on minimal reduction in root and shoot growth and higher seedling survival, cultivar Tirumala and genotype VR 1099 were identified as highly thermotolerant, whereas PPR 1216 and PPR 1094 were highly susceptible. These results align with recent reports emphasizing the importance of early-stage physiological screening for developing heat-resilient millet cultivars under climate change scenarios (Kumar et al., 2022; Trivedi et al., 2023).

TABLE 1
SCREENING OF FINGER MILLET GENOTYPES THROUGH TEMPERATURE INDUCTION RESPONSE (TIR) TECHNIQUE UNDER LABORATORY CONDITIONS

SL. No	Genotypes	Root growth in control (cm)	Root growth in treatment (cm)	Percent reduction in root growth	Shoot growth in control (cm)	Shoot growth in treatment (cm)	Percent reduction in shoot growth	Percent survival in treatment
1	PPR 1096	4.6 i	2.34 g	49.13	2.16 d	1.12 ef	48.15	75
2	ID	4.82 h	2.9 e	39.83	1.95 f	1.04 g	46.67	77
3	PPR 1243	4.56 i	2.7 f	40.79	1.87 gh	1.08 fg	42.25	78
4	VR 1099	5.94 d	4.74 b	20.2	1.82 h	1.48 c	18.68	90
5	PPR 1160	5.76 e	4.46 c	22.57	1.94 fg	1.58 b	18.56	87
6	VR 1192	6.2 c	4.2 d	32.26	1.9 fg	1.22 d	35.79	82
7	VR 1171	4.9 g	2.1 i	57.14	2.08 e	1.22 d	41.35	74
8	PPR 2885	6.6 a	2.32 gh	64.85	2.08 e	1.18 de	43.27	76
9	PPR 1279	5.4 f	2.86 e	47.04	2.16 d	1.18 de	45.37	74
10	PPR 1272	5.9 d	4.52 c	23.39	2.1 de	1.6 b	23.81	88
11	PPR 1216	3.6 k	1.08 j	70	2.68 a	1.05 fg	60.82	69
12	VR 1188	3.68 j	2.29 gh	37.77	1.94 fg	1.1 fg	43.3	80
13	PPR 1094	6.46 b	2.26 h	65.02	2.54 b	1.1 fg	56.69	72
14	Tirumala	6.4 b	5.18 a	19.06	2.36 c	1.94 a	17.8	93
	SE m ±	0.007	0.005		0.005	0.005		0.316
	CD 5%	0.02	0.364		0.014	0.014		0.898

Means within a column followed by the same lowercase letter are not significantly different at $p < 0.05$ according to Duncan's Multiple Range Test (DMRT). Data represent the mean of five replications.

IV. CONCLUSION

The Temperature Induction Response (TIR) technique proved to be an effective and rapid method for screening finger millet (Eleusine coracana L.) genotypes for thermotolerance at the seedling stage. Significant genotypic variation was observed for root and shoot growth reduction and seedling survival under high temperature stress. Cultivar Tirumala and genotype VR 1099 exhibited minimal growth reduction and higher survival, indicating superior thermotolerance, whereas PPR 1216 and PPR 1094 were identified as susceptible. The study confirms the usefulness of TIR-based phenotyping for early-stage selection of heat-tolerant genotypes. The identified thermotolerant genotypes are recommended for use as donor parents in hybridization programs and for further validation under field-level heat stress conditions to develop climate-resilient finger millet varieties

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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A Profile of Personal and Socio-economic Characteristics of Sericulture Farmers in Malavalli Taluk, Mandya District, Karnataka

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Abstract— *Sericulture is an agrarian small-scale industry suited to marginal and small land holders, providing high returns and creating employment for family members. Studies indicate that the personal and socio-economic status of farmers significantly influences the adoption of improved sericulture practices. This study aimed to profile these characteristics among sericulture farmers in Malavalli taluk of Mandya district, Karnataka, India. Data were collected from 50 farmers across seven villages using a structured interview schedule. Results revealed that the majority of respondents were of middle age (60%), possessed primary or high school education (32%), had small family sizes (66%), and cultivated mulberry on less than one acre of land (60%). A significant proportion showed low involvement in social organizations, though limited participation was noted in milk cooperatives and mahila mandals. Conversely, a majority participated in at least one extension activity such as meetings, field visits, and training programs. The findings provide a baseline for understanding the farmer community and tailoring inclusive extension strategies to enhance technology adoption and socio-economic resilience in sericulture.*

Keywords— Socio-economic profile, sericulture farmers, land holding, extension participation, Karnataka.

I. INTRODUCTION

India holds a unique position as the only country producing all four commercial types of silk: mulberry, tasar, eri, and muga. It is the world's second-largest silk producer, with a total raw silk production of 41,121 MT. Mulberry silk alone accounts for 31,119 MT (75.67%) of this output (Anonymous, 2025). Sericulture is a vital sector for socio-economic development in rural areas. It is labour-intensive, profitable, requires low initial investment, and ensures frequent income, making it particularly suitable for rural women. With its agricultural base and industrial structure, sericulture serves as an excellent economic activity for farmers with marginal to medium land holdings in Karnataka, providing gainful employment, periodic income, and curbing rural-to-urban migration.

The socio-economic status of farmers is a well-established determinant of technology adoption. Studies have identified factors such as education, income, social participation, extension contact, and land holding as influential variables (Geetha et al., 2001). Sunildutt and Chole (2002) reported a positive relationship between adoption and factors like education and social participation, while age often shows a negative correlation. The impact of training is also notable; while trained and untrained farmers may differ in economic status and experience, other factors like age and family size may show no significant difference (Thangaraju, 1979). Furthermore, cluster-based approaches have been shown to enhance socio-economic outcomes significantly (Syed Shakir Ali et al., 2014).

Despite its importance, localized and current profiles of sericulture farmers are essential for formulating effective development strategies. Most existing studies in the region are dated or focus on broader districts. A detailed micro-level profile is necessary to understand the present-day demographic and socio-economic context, which directly influences the pace of innovation adoption. This study, therefore, aimed to: (1) document the personal and socio-economic characteristics of sericulture farmers in Malavalli taluk, and (2) analyze their level of participation in social and extension activities. The findings are intended to inform targeted policy and extension interventions for sustainable sericulture development.

II. METHODOLOGY

2.1 Study Area:

The study was conducted in Malavalli taluk of Mandya district, Karnataka. Mandya district comprises seven taluks with a total geographical area of 4,98,244 hectares. The district has 299 villages, of which 115 practice sericulture, utilizing 298.34 hectares for mulberry cultivation and producing approximately 239.231 MT of cocoons valued at ₹601.88 lakhs (2024-25). Malavalli taluk is a significant sericulture zone within the district.

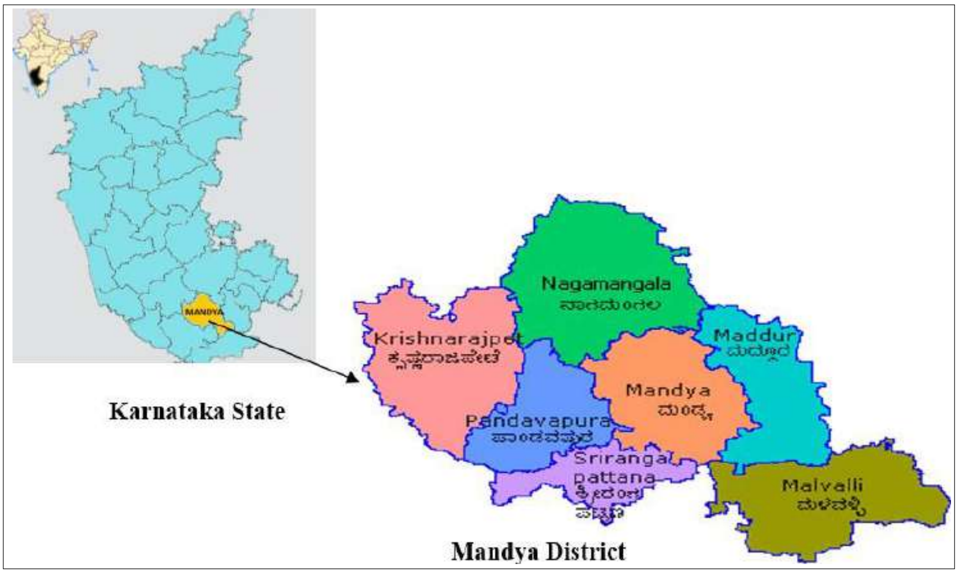

FIGURE 1: Details of study area

2.2 Sampling and Data Collection:

A purposive sampling method was employed to select seven villages known for active sericulture: Kundur, Halaguru, Belakavadi, D.C. Pura, T.K. Halli, and Gowdagere. From these villages, 50 sericulture farmers were selected based on their engagement in mulberry cultivation and silkworm rearing, in consultation with local officials from the State Department of Sericulture.

Primary data were collected through face-to-face interviews using a pre-tested, structured schedule. The schedule was designed to capture information on personal characteristics (age, education, family size) and socio-economic variables (mulberry land holding, social participation, extension participation).

2.3 Variables and Measurement:

- **Age:** Categorized as young (25-40 years), middle (41-55 years), and old (>55 years).
- **Education:** Classified as illiterate, primary (1st-7th standard), high school (8th-10th standard), and college (11th standard and above).
- **Family Size:** Grouped as small (≤4 members), medium (5-6 members), and large (>6 members).
- **Mulberry Land Holding:** Categorized as <1 acre, 1-2 acres, and >2 acres.

- **Social Participation:** Assessed through membership in formal organizations (e.g., Village Panchayat, Milk Cooperative, Mahila Mandal).
- **Extension Participation:** Measured by involvement in activities like meetings, training, field days, and demonstrations conducted by development departments over the previous year.

2.4 Data Analysis:

Collected data were analyzed using descriptive statistics—frequencies and percentages—with the assistance of SPSS software. Results are presented in tabular and graphical forms.

III. RESULTS AND DISCUSSION

3.1 Age Distribution of Farmers:

The age profile of respondents indicated that a majority (60%, n=30) belonged to the middle-age group (41-55 years), followed by the old-age group (28%, n=14), and young farmers (12%, n=6) as shown in figure 2. This suggests a predominantly mature farming community, which may influence the pace of adopting new technologies, as older farmers can be more risk-averse. This finding aligns with Sannappa et al. (2017b) but contrasts with Sunildutt and Chole (2002), who reported a younger demographic. An aging farmer population poses a challenge for the long-term sustainability of sericulture unless youth engagement is encouraged.

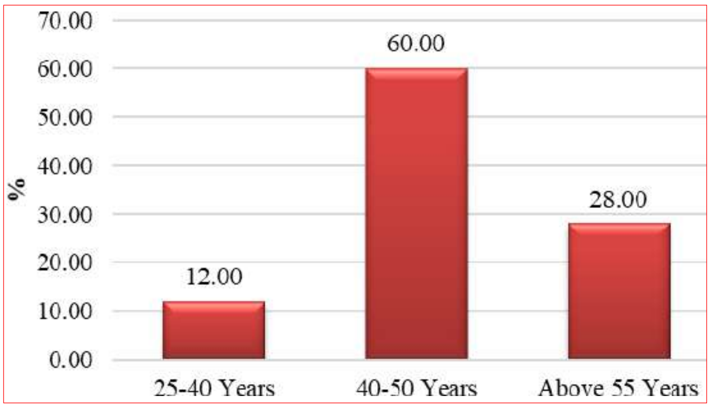

FIGURE 2: Age distribution of sericulture farmers in Malavalli taluk.

3.2 Education Level:

Education is a critical factor in technology adoption. In the study area, 26% (n=13) of farmers were illiterate, while the largest segment (32%, n=16) had attained primary to high school education. Only 10% (n=5) had college-level education as shown in figure 3. This educational profile is consistent with earlier studies in the region (Manju, 1997; Sannappa et al., 2017a) and highlights a need for extension materials and training that are visual, practical, and tailored to low-literacy audiences.

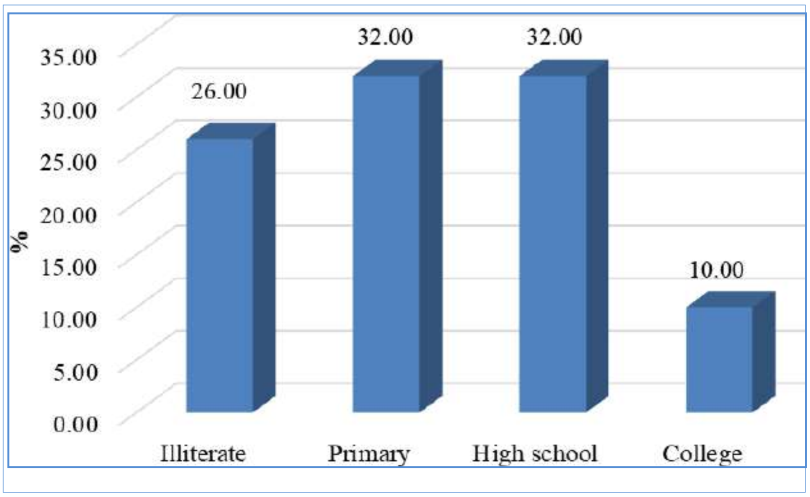

FIGURE 3: Education level of sericulture farmers in Malavalli taluk.

3.3 Family Size:

Most respondents (66%, n=33) had a small family size (≤4 members), with 18% (n=9) and 16% (n=8) having medium and large families, respectively as shown in figure 4. Smaller family sizes may imply limited family labour availability, which is a crucial input in labour-intensive sericulture. This trend contrasts with some earlier studies (Sannappa et al., 2017a) that reported a higher proportion of medium-sized families, possibly indicating a demographic shift toward nuclear families.

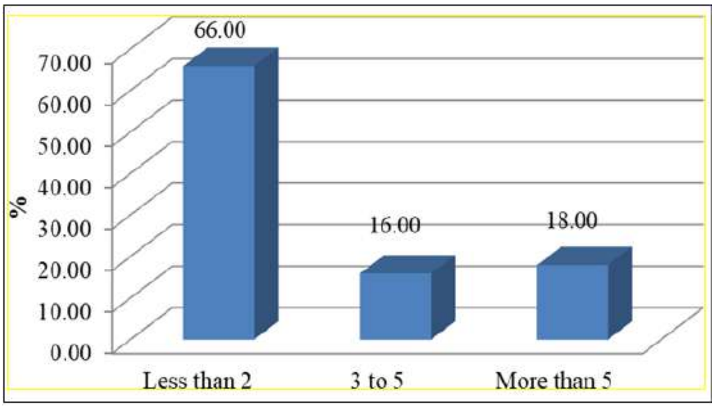

FIGURE 4: Family size distribution of sericulture farmers in Malavalli taluk.

3.4 Mulberry Land Holding:

Landholding is a key economic indicator. A significant 60% (n=30) of farmers cultivated mulberry on less than one acre, confirming the small-scale nature of sericulture in the region. Another 24% (n=12) held 1-2 acres, and only 16% (n=8) had more than two acres as shown in figure 5. This fragmentation underscores the importance of technologies and practices that maximize productivity per unit area to ensure economic viability for smallholders.

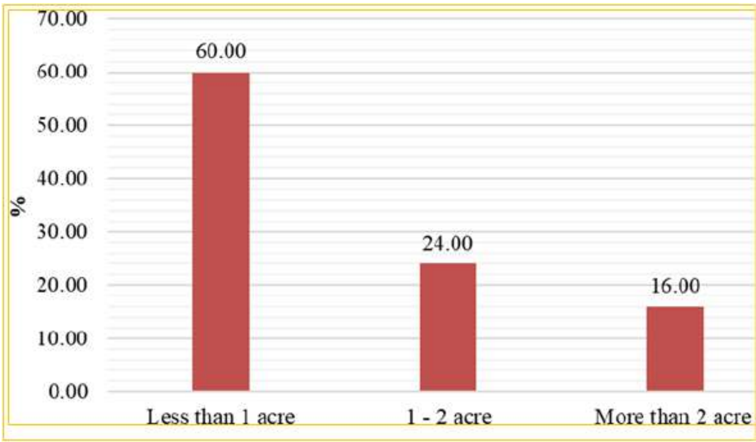

FIGURE 5: Mulberry land holding pattern among sericulture farmers in Malavalli taluk.

3.5 Social Participation:

Social participation was assessed by examining membership in formal organizations, including Village Panchayat, Taluk Panchayat, Zilla Panchayat, Youth Clubs, Mahila Mandals, Cooperative Agriculture Banks, Milk Cooperative Societies, and Sericulture Clubs.

The findings revealed a widespread lack of engagement. A large majority of farmers did not evince interest in any social activities. Active involvement was minimal and confined to only a few organizations: a small number of farmers were members of Milk Cooperative Societies (n=3, 6.00%) and Mahila Mandals (n=1, 2.00%). No participation was recorded in other listed institutions (Fig. 5). This low level of social capital limits opportunities for collective learning, resource sharing, and accessing institutional support. The trend aligns with observations from irrigated areas in Mandya district, where farmers showed similarly low interest, and notably, no small farmers participated in social activities (Raju, 2018). Consequently, concerted efforts by extension personnel, NGOs, and local bodies are needed to raise awareness about the benefits of social organizations for enhancing knowledge and socio-economic status.

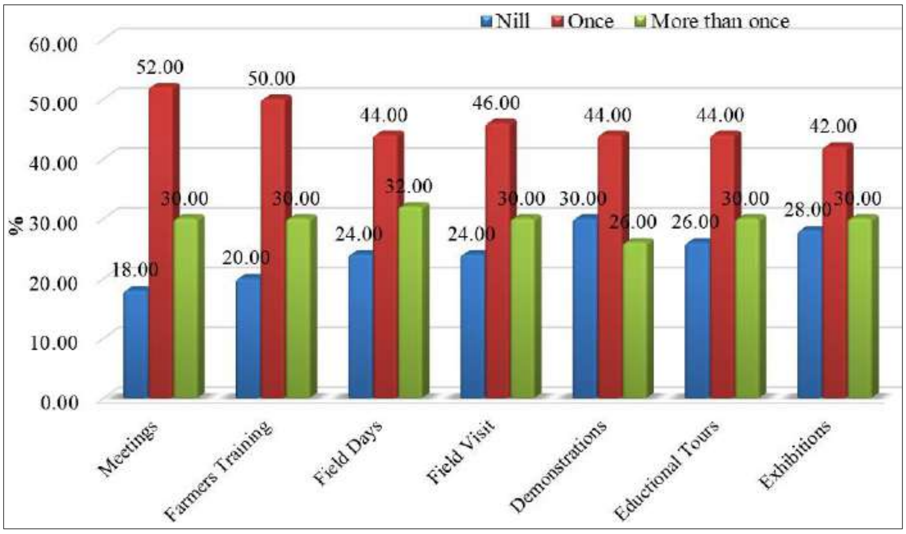

FIGURE 6: Social participation patterns of sericulture farmers in Malavalli taluk.

3.6 Extension Participation:

Farmers' involvement in extension activities was measured across seven categories: Meetings, Farmers Trainings, Field Days, Field Visits, Demonstrations, Educational Tours, and Exhibitions. Participation was categorized as 'Nil,' 'Once,' or 'More than once' during the study period.

The data indicate that while a majority of farmers participated in at least one extension activity, the frequency was typically low. For participation **'Once'**, the rates were: Meetings (52.00%, n=26), Farmers Training (50.00%, n=25), Field Visits (46.00%, n=23), Field Days (44.00%, n=22), Demonstrations (44.00%, n=22), Educational Tours (44.00%, n=22), and Exhibitions (42.00%, n=21).

Participation **'More than once'** was less common: Field Days (32.00%, n=16); Meetings, Farmers Training, Field Visits, Educational Tours, and Exhibitions (30.00% each, n=15); and Demonstrations (26.00%, n=13).

Conversely, a significant proportion abstained from certain activities altogether: Demonstrations (30.00%, n=15 did not participate), Exhibitions (28.00%, n=14), Educational Tours (26.00%, n=13), Field Days and Field Visits (24.00% each, n=12), Farmers Training (20.00%, n=10), and Meetings (18.00%, n=9) (Fig. 6).

This pattern of moderate, often single-attendance engagement contrasts with a more disengaged pattern reported by Raju (2018) in irrigated conditions, where non-participation rates were higher: Demonstrations (82.50%), Meetings (72.50%), Field Days (65.00%), Educational Tours (64.17%), Farmers Trainings (50.83%), Exhibitions (43.33%), and Field Visits (42.50%). In that study, a higher proportion participated only 'Once' in Field Visits and Exhibitions (50.83%) and Farmers Trainings (45.00%), while only 15.83% participated 'More than once' in Field Days

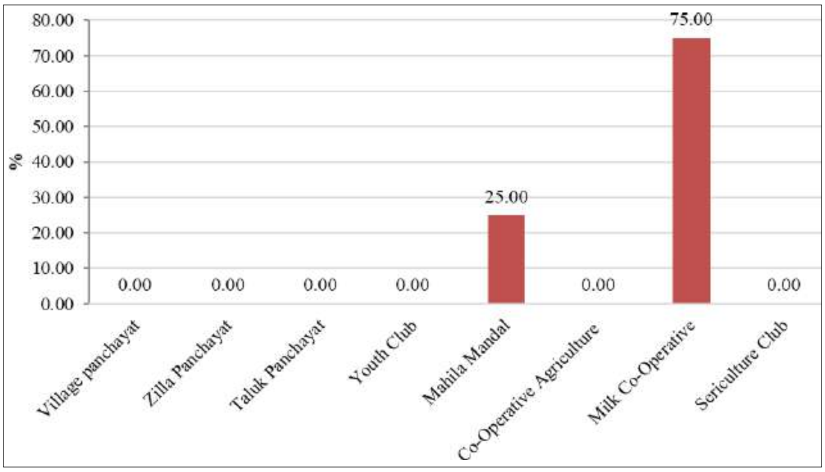

FIGURE 7: Extension participation patterns of sericulture farmers in Malavalli taluk.

IV. CONCLUSION AND IMPLICATIONS

This study profiles the sericulture farmers of Malavalli taluk as predominantly middle-aged, with basic education, small landholdings, and small family sizes. Their limited social capital, juxtaposed with moderate engagement in extension activities, presents a clear avenue for intervention.

The findings have direct implications for extension policy and practice:

1. **Tailored Extension:** Extension programs should be designed considering the average education level and age of farmers, emphasizing hands-on, visual, and practical demonstrations over text-heavy materials.
2. **Focus on Smallholders:** Research and development should prioritize space- and labour-efficient technologies that enhance productivity on small plots of land.
3. **Promoting Collectives:** There is a critical need to promote and revitalize farmer organizations, including sericulture clubs and cooperatives. These can serve as platforms for knowledge sharing, input procurement, and marketing, thereby enhancing social participation and economic bargaining power.
4. **Engaging Youth:** To ensure sustainability, schemes and training programs specifically targeting the younger rural population should be developed to attract them to sericulture.

In conclusion, while sericulture remains a vital livelihood in Malavalli, its future growth depends on strategically addressing the socio-economic constraints identified in this profile. A focused, farmer-centric approach integrating technology dissemination with institutional building is recommended.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Climate-Induced Livelihood Vulnerabilities and Adaptation in Contrasting Watersheds of Tamil Nadu, India

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Abstract— *Climate change and land-use alterations are intensifying vulnerabilities in critical river basins, particularly within semi-arid agro-ecologies. This study assesses agro-ecology-specific climate risks, environmental degradation, and adaptation practices in the farming households of two contrasting watershed systems in Tamil Nadu: the Upper Vaigai (rainfed, drought-prone) and the Lower Palar (coastal, flood-prone). Primary data were collected from 200 farm households using a structured survey. The study found that the Upper Vaigai watershed is severely impacted by drought, leading to groundwater depletion, soil moisture deficits, and ecosystem degradation. In contrast, the Lower Palar watershed experiences intensive rainfall, cyclones, and floods, resulting in socioeconomic stresses such as migration and drinking water scarcity. While institutional mechanisms like MGNREGA, crop insurance, and extension services provided some adaptive support, implementation gaps persist. The findings underscore the need for location-specific strategies: enhancing soil and water conservation in Upper Vaigai and strengthening flood resilience and traditional water system management in Lower Palar. Integrating participatory GIS and ICT tools is recommended for building adaptive capacity across these climate-sensitive agro-ecologies.*

Keywords— Climate vulnerability; watershed management; agro-ecology; adaptation strategies; Tamil Nadu.

I. INTRODUCTION

Tamil Nadu, situated in the rain shadow region of the South-West Monsoon, depends heavily on the North-East Monsoon for its rainfall [1]. The region's topography fosters west-to-east flowing watersheds, which are increasingly stressed by changes in land-use patterns and climate variability [2, 3]. These changes manifest differently across agro-ecological zones, affecting the 'carrying capacity' of ecosystems and demanding 'environmental justice' in resource management [4].

This study focuses on two critical and contrasting watersheds: the Upper Vaigai and the Lower Palar. The Upper Vaigai watershed, a tropical wet to semi-arid transition zone, is crucial for originating the Vaigai River. Despite pockets of high rainfall (1500-2500 mm/year), most of this watershed receives only 500-1000 mm annually [5]. Environmental degradation in this upper catchment therefore threatens the entire river basin. Conversely, the Lower Palar watershed lies in a semi-arid to coastal zone. While its upper reaches are dry, its lower part receives higher rainfall (1000-1500 mm/year) and historically relied on tank-based water systems [6].

Climate vulnerabilities have intensified in both watersheds, but their manifestations differ, affecting agricultural livelihoods in distinct ways. Previous studies have often examined watersheds in isolation. A comparative analysis of contrasting agro-ecologies is essential to develop nuanced, location-specific adaptation policies. Therefore, this study aims to: (1) assess and compare agro-ecology-specific climate risks and environmental vulnerabilities at the farm household level, and (2) identify and evaluate prevalent and potential climate-resilient adaptation practices in the Upper Vaigai and Lower Palar watersheds.

II. METHODOLOGY

2.1 Study Area:

The study was conducted in two districts of Tamil Nadu: Theni District (representing the Upper Vaigai watershed) and Kancheepuram District (representing the Lower Palar watershed). These sites were purposively selected for their contrasting agro-climatic profiles and documented climate vulnerabilities.

2.2 Research Design and Sampling:

An ex-post facto research design was employed. A multi-stage sampling technique was used. First, the two districts were purposively selected. Second, one Community Development Block (CDB) with severe climate vulnerabilities was chosen from each district. Third, two villages were randomly selected from each CDB. Finally, from each village, 50 farmer households were randomly selected, yielding a total sample size of 200 (100 from each watershed).

2.3 Data Collection and Analysis:

Primary data were collected through face-to-face interviews using a pre-tested, structured schedule. The questionnaire captured data on:

- Socio-economic characteristics.
- Perceived climate risks and impacts (using a Likert-scale for severity).
- Observed agro-ecological changes.
- Adaptation practices and institutional support accessed.

Data were analyzed using descriptive statistics (frequencies, percentages) to profile vulnerabilities and practices. Inferential statistics (Chi-square tests) were used to compare significant differences between the two watershed groups for key categorical variables.

III. RESULTS AND DISCUSSION

3.1 Characterizing Differential Climate Risks:

The climate risks perceived by farmers differed markedly between the two watersheds, underscoring their distinct agro-ecological contexts.

- **Drought-Related Vulnerabilities:** As presented in Figure 1, the Upper Vaigai watershed was more severely affected by drought parameters. Severe early-season drought (78% of respondents) and continuous soil moisture deficit (72%) were critical concerns. Consequently, groundwater level reduction was a high-impact issue for 65% of farmers. In contrast, while drought was present in Lower Palar, its socioeconomic impacts were more pronounced, with temporary human migration reported by 70% of farmers due to urban employment opportunities.
- **Rainfall and Extreme Event Vulnerabilities:** The pattern reversed for rainfall-related extremes (Figure 2). The Lower Palar watershed was highly vulnerable to frequent floods (88%), cyclones (85%), and intensive rainfall (84%). The Upper Vaigai watershed was predominantly affected by rainfall deficits, with less rainfall (89%) and delayed monsoon onset (68%) cited as major stresses.

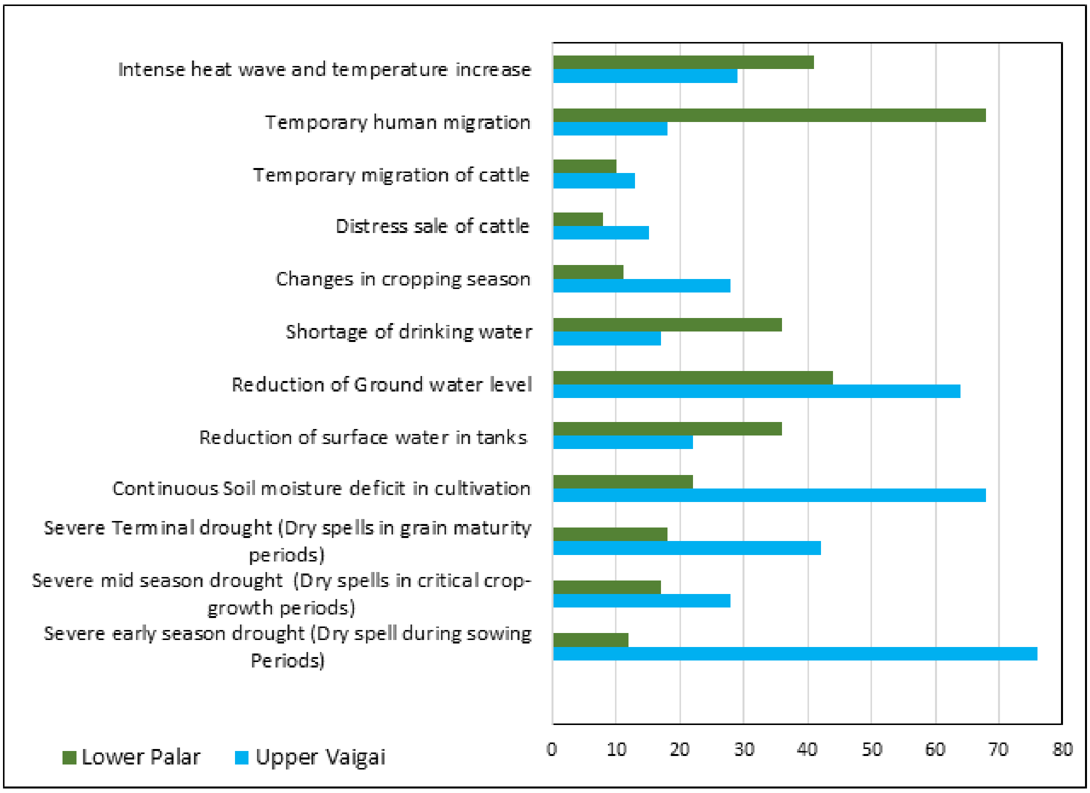

FIGURE 1: Severity of drought-related climate impacts in the study watersheds.

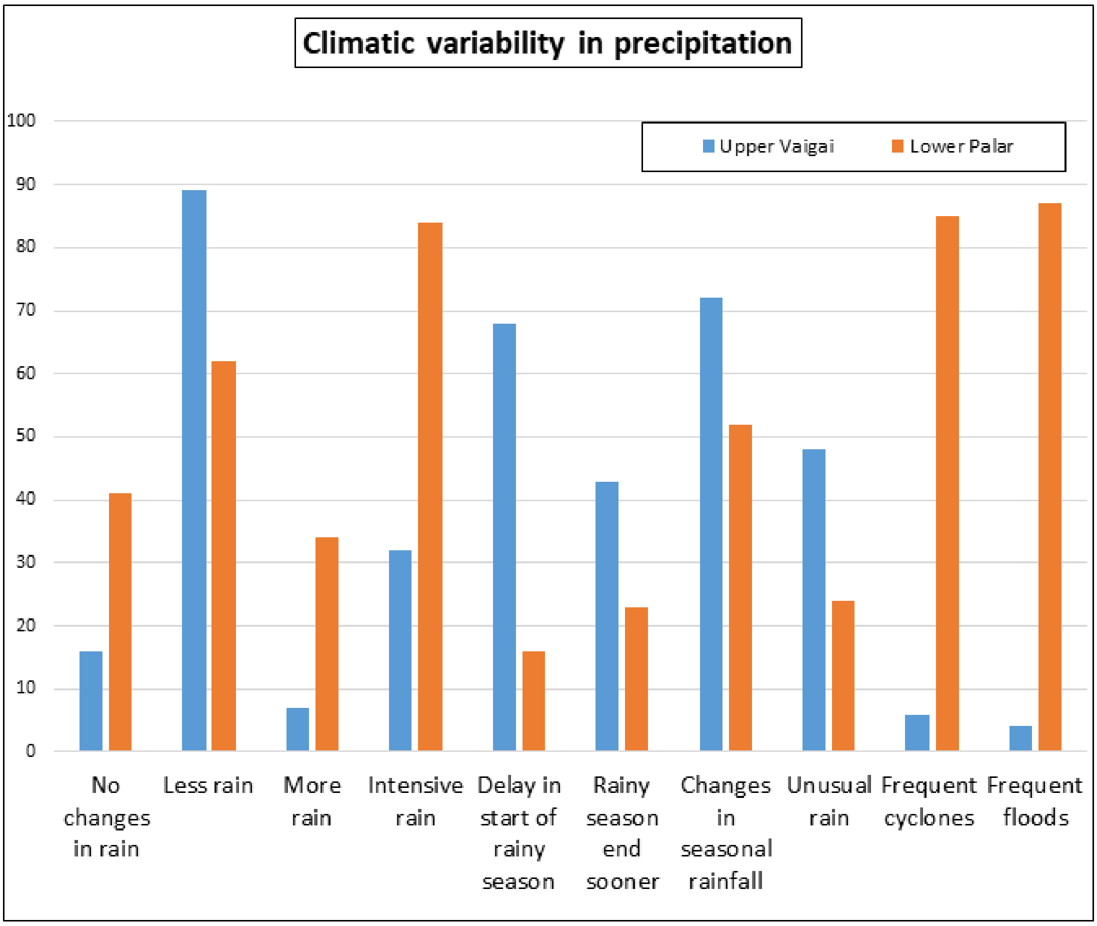

FIGURE 2: Severity of rainfall-related climate variability and extremes in the study watersheds.

These results confirm that vulnerability is not monolithic but shaped by local geography. The Upper Vaigai, a rainfed upland system, is a drought-vulnerable hotspot, aligning with concerns about land-use change reducing infiltration [7]. The Lower Palar, a coastal lowland, is an extreme-weather hotspot, where urbanization compromises natural drainage [8].

3.2 Agro-Ecological Changes and Adaptive Practices:

Survey results on agro-ecological indicators revealed both common challenges and divergent trends (Table 1)

TABLE 1
COMPARATIVE PROFILE OF AGRO-ECOLOGICAL INDICATORS IN THE STUDY WATERSHEDS (N=200).

S. No.	Agro-ecological Indicator	Upper Vaigai (% of HHs)	Lower Palar (% of HHs)
1	Increased climate-related problems	85	80
2	Changes in cropping pattern	70	75
3	Pests and diseases issues	30	40
4	Reduction in productivity	55	35
5	Degradation of grasslands	25	70
6	Reduced millets cultivation	75	65
7	Adoption of integrated farming	10	20
8	Area under agroforestry	8	10
9	Promotion of animal husbandry	12	15
10	Crop rotation practices	15	18

A high proportion of households in both watersheds reported increased climate problems and had altered cropping patterns. However, key differences emerged: **reduction in productivity** was a more acute concern in Upper Vaigai (55% vs. 35%), likely linked to severe moisture stress. Conversely, **degradation of grasslands** was far more widespread in Lower Palar (70% vs. 25%), possibly linked to flooding and salinity. The adoption of sustainable practices like integrated farming, agroforestry, and crop rotation remained low (<20%) in both regions, indicating a significant adaptation gap.

3.3 Institutional Support and Proposed Adaptation Framework:

Institutional mechanisms played a positive but incomplete role in adaptation. Programs like MGNREGA (for water conservation works), the National Rainfed Area Programme, crop insurance, and agricultural extension services were identified as crucial for livelihood security. However, their reach and farm-level implementation were reported as inconsistent.

Based on the findings, a two-pronged, location-specific adaptation approach is proposed (Figure 3):

- **For the Upper Vaigai Watershed:** The priority is enhancing **soil and water conservation (SWC)** and groundwater recharge. This requires strengthening MGNREGA-linked SWC works, promoting in-situ moisture conservation (e.g., mulching, contour bunding), and revitalizing community-based water management.
- **For the Lower Palar Watershed:** The focus must shift to **flood resilience and saline intrusion management**. This involves rehabilitating the traditional tank and lake system for drainage and storage, promoting saline-tolerant crop varieties, and developing climate-resilient coastal agroforestry models.

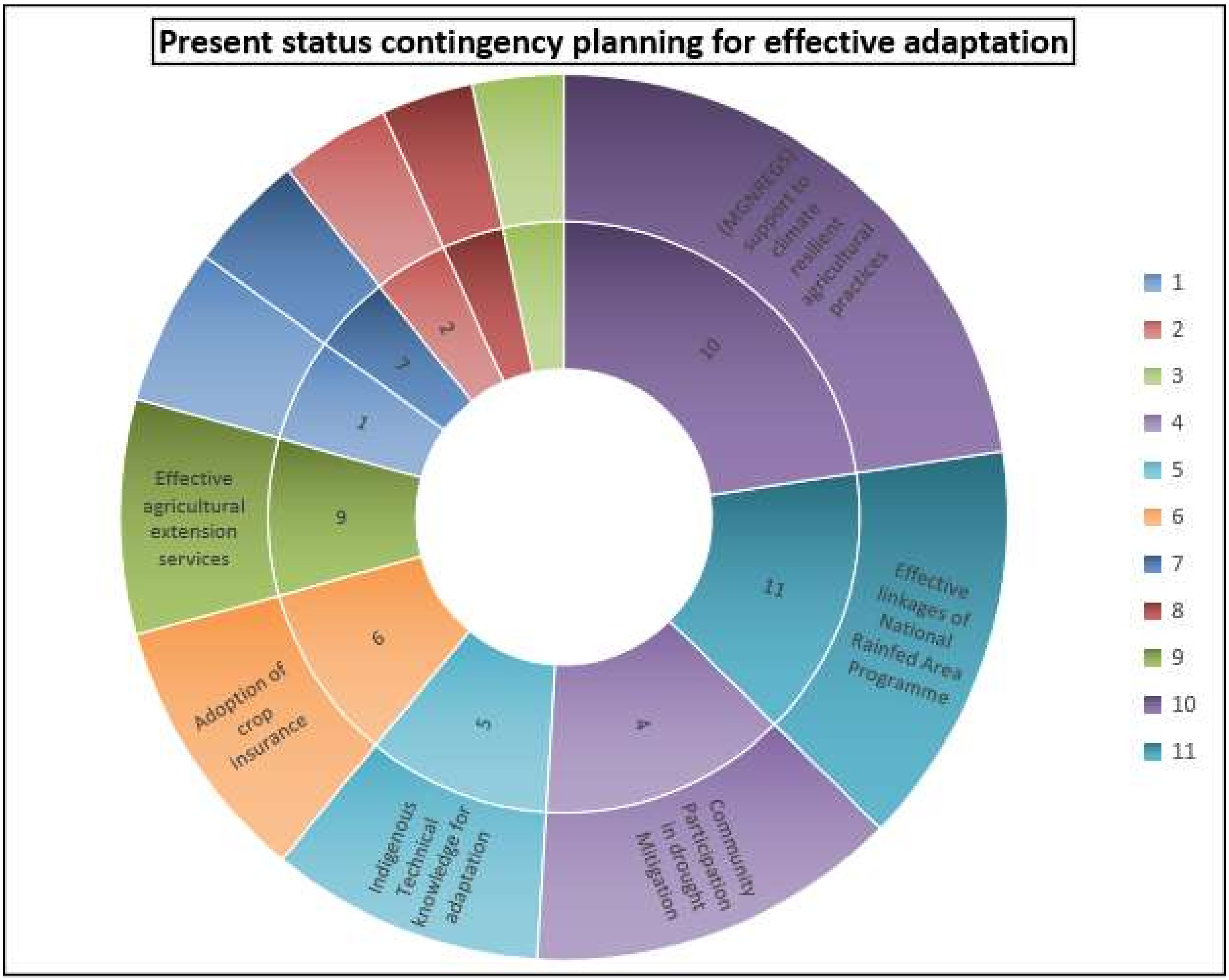

FIGURE 3: Conceptual framework for location-specific climate adaptation in contrasting watersheds.

Cross-cutting both regions is the need to **build social capital** through farmer collectives and to leverage **digital tools** (Participatory GIS, ICT-based advisories) for better natural resource management and dissemination of climate-smart practices.

IV. CONCLUSION

This comparative study reveals that climate vulnerabilities in Tamil Nadu's critical watersheds are profoundly shaped by local agro-ecology. The **Upper Vaigai watershed is a drought-vulnerable system** where agricultural stress and groundwater depletion are paramount. The **Lower Palar watershed is an extreme-weather vulnerable system** facing floods, ecological degradation, and associated socioeconomic disruptions.

A uniform climate adaptation policy is therefore inadequate. Resilience building must be location-specific:

- **Policy in Upper Vaigai** must prioritize investments in watershed-scale soil and water conservation and community-managed groundwater recharge.
- **Policy in Lower Palar** should focus on modernizing traditional water infrastructure for flood control, rehabilitating degraded lands, and promoting diversified, saline-resilient farming systems.
- **Across both regions**, there is a critical need to bridge the gap between institutional schemes and farm-level adoption by strengthening agricultural extension, fostering farmer institutions, and integrating geospatial and ICT technologies for targeted advisory services.

By adopting such a differentiated approach, stakeholders can enhance the adaptive capacity of farming communities, ensuring the ecological and socio-economic sustainability of these vital watersheds

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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