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Agro-Tourism in India: Bridging Farms, Culture, and Tourism

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In the modern era, rapid urbanization, industrial growth, and the rush of city life have created a noticeable distance between people and the natural environment. Many individuals, especially those living in urban areas, are now longing for experiences that provide relaxation and a closer bond with nature. Rural areas, with their fresh air, scenic landscapes, agricultural fields and cultural diversity have emerged as ideal destinations to meet this emerging demand. Travellers are not just looking for leisure they are seeking meaningful experiences that combine enjoyment with gaining knowledge. This changing trend in tourism has given rise to an innovative and sustainable approach known as agro-tourism, which allows visitors to step into the world of farming and rural life while also supporting the local economy.

What is Agro-Tourism?

Agro-tourism refers to a form of tourism where agricultural activities, farm life and rural traditions are unified into travel experiences for visitors. It goes beyond simple sightseeing by engaging tourists in hands-on farming based activities such as planting seeds, harvesting crops, milking cows or exploring organic farming methods. Visitors also enjoy local cuisine, folk art, and cultural practices, thereby gaining a holistic understanding of rural life. For farmers, agro-tourism serves as an additional source of income, while for society, it acts as a medium to spread awareness about sustainable farming practices and rural development. Thus, agro-tourism is not merely a leisure activity but a bridge that connects urban populations with agricultural communities, promoting both economic growth and cultural exchange.

Benefits of Agro-Tourism to Rural Areas and Farmer Community

1. Supplementary Income for Farmers

Agriculture is highly vulnerable to risks such as fluctuation in market prices, unpredictable weather, pest outbreaks and rising input costs. Agro-tourism offers farmers an additional and stable stream of income by attracting visitors to their farms. Income can be generated through homestays, guided farm tours, selling fresh farm produce, handicrafts or offering traditional food experiences. This reduces their dependence solely on crop sales and provides financial security.

2. Employment Opportunities in Rural Areas

Agro-tourism creates both direct and indirect job opportunities for rural communities. Apart from farmers, it employs local youth as guides, drivers, cooks and hospitality workers. Women and elderly members of families also find opportunities in preparing local cuisine, weaving, handicrafts and cultural performances.

3. Boost to Local Economy

Tourist spending in rural areas benefits not just farmers but also local shopkeepers, artisans, transport providers and small-scale entrepreneurs. Money circulates within the rural economy, that uplifts the

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entire community. Rural areas gain better access to markets for their products, such as honey, spices, organic vegetables, traditional art etc.

4. Preservation of Rural Culture and Traditions

Agro-tourism highlights the rich cultural heritage of rural areas through folk art, festivals, traditional farming practices and indigenous food. Tourists experience these customs first hand. This also helps preserve local traditions that may otherwise be forgotten under the influence of modernization.

5. Infrastructure Development

As villages become tourist destinations, governments and private stakeholders are encouraged to invest in infrastructure such as better roads, electricity, sanitation and internet connectivity. These improvements benefit not only tourists but also the local residents.

6. Educational and Awareness Opportunities

Agro-tourism serves as an interactive learning space where urban students, researchers and families can understand agriculture, biodiversity and rural lifestyles. It bridges the knowledge gap between rural and urban populations and also promotes awareness about sustainable farming, water conservation and climate-friendly practices.

7. Women Empowerment

In many rural households, women actively participate in agro-tourism activities like cooking traditional dishes, handicraft making and managing homestays. This provides them with direct income, enhances their confidence and improves their social and economic status.

8. Environmental Sustainability

Agro-tourism promotes organic farming, eco-friendly practices and conservation of natural resources. It motivates farmers to adopt sustainable techniques since most of the tourists prefer chemical-free and authentic farm experiences.

9. Stress-Free Rural Living for Visitors, Motivation for Farmers

While visitors gain relaxation, peace and an escape from the city, farmers receive recognition and respect for their work. This motivates the farming community to continue agriculture with pride and enthusiasm.

Success Stories of Agro-Tourism in India

1. Baramati Agro-Tourism Model – Maharashtra

Baramati in Pune district, Maharashtra, is regarded as the birthplace of agro-tourism in India. The initiative was pioneered by the Agri Tourism Development Corporation (ATDC), founded by Pandurang Taware in 2005. Farmers here had transformed their fields into tourist-friendly destinations where visitors could participate in activities such as sugarcane cutting, bullock-cart rides, folk dances and rural games. Tourists are also served traditional farm-fresh meals, creating an authentic village experience. This model provided farmers with a stable supplementary income, generated employment for rural youth and became a replicable success across the state. Today, Maharashtra is considered the leader in agro-tourism.

2. Pochampally Village – Telangana

Pochampally, located near Hyderabad, is famous for its handloom weaving and is often called the "Silk City of India." The village has successfully integrated agro-tourism with cultural heritage, offering visitors an opportunity to explore farming practices while also experiencing traditional weaving. Tourists can stay in rural homestays, watch artisans at work and participate in farming activities, creating a unique blend of agricultural and cultural tourism. This initiative has improved the livelihoods of both farmers and weavers by connecting them directly to the tourism market. In recognition of its achievements, Pochampally was

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declared one of the **Best Tourism Villages in the World (2021)** by the UNWTO.

3. Kodagu Coffee Plantations – Karnataka

In Kodagu (Coorg), Karnataka, coffee growers have successfully diversified into agro-tourism. Plantation owners opened their estates to tourists, offering guided walks through coffee fields, demonstrations of coffee processing, bird-watching tours and homestay experiences amidst the scenic Western Ghats. This model reduced farmers' dependence solely on coffee sales, provided additional income and created rural employment. Moreover, plantation tourism has contributed to biodiversity conservation by promoting eco-friendly tourism in one of India's most important ecological hotspots. Coorg is now widely recognized as a premier destination for plantation-based tourism in India.

4. Valley of Flowers Homestays – Uttarakhand

Villages located near the Valley of Flowers National Park in Uttarakhand have developed a community-based agro-tourism model. Farmers here offer homestay facilities combined with farming experiences, where visitors can learn about terrace cultivation and traditional Himalayan farming techniques. The model has strengthened the fragile mountain economy, reduced migration of people to urban areas and promoted eco-friendly tourism in a biodiversity-rich region. At the same time, it helps preserve indigenous farming practices that are well-adapted to the Himalayan ecosystem.

5. Kumarakom Responsible Tourism Project – Kerala

Kumarakom backwater in Kerala's Kottayam district, is one of the most successful examples of agro-tourism in India. Introduced in 2007, the **Kumarakom Responsible Tourism Project** integrated agriculture with tourism in a way that benefited the entire community. Tourists visiting Kumarakom are engaged in activities such as paddy cultivation, coconut harvesting, fishing, toddy tapping and traditional cooking, while also enjoying cultural performances like Kathakali. More than 500 local families, including women's self-help groups, participate by supplying farm produce, handicrafts, coir products and home-made food to the tourism sector. This initiative not only created sustainable livelihoods for farmers but also preserved the fragile Vembanad wetlands ecosystem. Its success earned international recognition when it received the **UNWTO Ulysses Award in 2013**.

6. Wayanad and Idukki Agro-Tourism – Kerala

Wayanad and Idukki districts in Kerala have emerged as important agro-tourism destinations. In Wayanad, spice and coffee plantations welcome tourists for farm visits, interactive experiences in pepper and cardamom cultivation and stays in eco-friendly homestays. Similarly, in Idukki and Munnar, tea plantations and spice gardens have been opened for tourists, who can combine trekking and farm experiences with learning about plantation crops. These initiatives have not only provided farmers with supplementary income but also helped promote organic farming, biodiversity conservation and sustainable rural development.

Conclusion

Agro-tourism has emerged as a transformative approach that bridges the gap between urban and rural life, offering tourists authentic experiences while simultaneously empowering farmers and rural communities. The success stories from Baramati in Maharashtra, Pochampally in Telangana, the coffee plantations of Kodagu in Karnataka, the Himalayan homestays in Uttarakhand and Kumarakom, Wayanad and Idukki in Kerala demonstrate that agro-tourism is more than a leisure activity—it is a tool for sustainable development, cultural preservation and economic empowerment. By providing farmers with supplementary income, creating rural employment, promoting eco-friendly practices and preserving local traditions, agro-tourism contributes to the holistic growth of rural areas. In the present scenario, where sustainable livelihoods and environmental awareness are crucial, agro-tourism not only strengthens the rural economy but also fosters a meaningful connection between people and the land, making it a vital component of India's tourism and agricultural strategy.

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Impacts of Socio-Political Instability on Agricultural Business Prospects in Manipur

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The socio-political instability in Manipur, a phenomenon with deep historical roots, has metastasized into a severe and multifaceted agrarian crisis. This report reveals that agriculture, which functions as the economic backbone of the state by employing over half the population and contributing approximately 22% to the Gross State Domestic Product (GSDP), is now in a state of near-total collapse. The crisis is not merely a temporary setback but a systemic degradation of the state's productive capacity, threatening its long-term economic viability and food security. Quantitative analysis underscores the scale of the devastation. Since the outbreak of violence in May 2023, official data indicates that nearly 5,127 hectares of agricultural land have been left uncultivated or barren, leading to an estimated loss of more than 15,000 metric tonnes of rice alone. The impact on the high-value horticulture sector, a key component of the state's economic diversification strategy, has been particularly severe, with documented export losses exceeding 102 crore rupees within a single quarter. While governmental relief efforts, such as the Farmer Compensation Programme, have provided a crucial financial lifeline, they appear to be short-term solutions that fail to address the fundamental, on-the-ground challenges of security and land access. A significant gap exists in the form of a coordinated, multi stakeholder effort to restore land, rebuild fractured supply chains, and re-establish the market confidence necessary for long-term recovery. The long-term prospects of agri-preneurship and high-value exports are in jeopardy, requiring a strategic shift from a reactive aid-based approach to a proactive, systemic rebuilding strategy that addresses the core drivers of instability

Introduction

An attempt has been made in this article to provide an exhaustive examination of the multifaceted impacts of the ongoing socio-political instability in Manipur, with a particular focus on the 2023-2025 ethnic violence and its consequences for the agricultural sector and its long-term business prospects. The analysis is predicated on the understanding that for a state where agriculture is the primary economic driver and a way of life for the majority of its population, political instability is not a peripheral concern but a direct, existential threat to the rural economy. The crisis unfolding in Manipur is a poignant case study of how deeply intertwined political and economic systems are, particularly in developing regions. The report's central thesis is that the disruption to farming and the broader agricultural value chain is not an unintended side effect of the conflict but a direct outcome of the core disputes over land, resources, and administrative control. This analysis, synthesized from expert commentary, official data, anecdotal accounts, and comparative studies, seeks to move beyond a simple description of events to provide a nuanced understanding of the causal relationships and long-term implications for the state's developmental trajectory.

Manipur's Agricultural Backbone: An Economic Profile

Agriculture is not just an industry in Manipur; it is the cornerstone of the state's economy and the primary source of livelihood for a majority of its population. An understanding of the agricultural sector's significance and its long-term potential is

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crucial to appreciating the full scale of the current crisis.

The Pre-Conflict Economy Prior to the 2023 ethnic violence, agriculture was the primary occupation for over 52% of Manipur's population, a figure that rises to over 60% in certain regions. This sector contributes a substantial 22% to the state's Gross State Domestic Product (GSDP), solidifying its role as a critical economic pillar. However, this dependence also highlights the state's vulnerability. Manipur's macroeconomic context is fragile, with a real GSDP growth rate of 4.9% between 2012-13 and 2021-22, which is lower than the national average of 5.6%. Furthermore, the state's debt-to-GSDP ratio stands at a markedly high 47%. This fragile economic foundation means that any significant shock to the agricultural sector would have a disproportionate and potentially catastrophic effect on the state as a whole. The table below presents the sector-wise contribution to Manipur's Gross State Value Added (GSVA) for the year 2021-22. The data highlights the predominance of the tertiary sector, followed by the primary sector, with the secondary sector contributing the least.

Sector	**Sub-Sectors Included**	**Share in GSVA (2021-22, %)**	**Remarks / Notes**
Primary Sector	Agriculture, Forestry & Logging, Fishing, Mining & Quarrying	27%	Significant contributor, but vulnerable to climate variability and infrastructure gaps.
Secondary Sector	Manufacturing, Construction, Electricity, Gas, Water Supply	7%	Smallest share; industrial growth remains slow due to lack of investment and connectivity issues.
Tertiary Sector	Trade, Hotels, Transport, Banking, Real Estate, Public Administration & Other Services	66%	Dominant sector, driven by public services, trade, and tourism-related activities.

Table 1: **Economic Contribution of Key Sectors in Manipur (2021-22)** [Source: PRS Legislative Research – Manipur Budget Analysis 2023-24 (https://prsindia.org/budgets/states/manipur-budget-analysis-2023-24)]

Diversity of Crops and Potential

Manipur's diverse agro-climatic conditions allow for the cultivation of a wide array of crops. Rice is the dominant staple, accounting for over 90% of the total land area under cultivation. The fertile soil of the Thoubal district, for example, allows for double and even triple cropping of paddy. Beyond staples, the state has significant potential in high-value horticulture. Key crops include fruits like pineapple, banana, and citrus; vegetables such as cabbages, cauliflower, and pumpkins; and spices like ginger, turmeric, and large cardamom. In recent years, the state has strategically moved toward a model of agri-preneurship, which integrates agriculture with entrepreneurial ventures to drive sustainable rural development. This strategy focuses on "low volume high value crops" that have low perishability, such as black rice, pineapple, ginger, and turmeric. Government programs and institutional support have fostered a conducive environment for this shift, which aims to diversify the economy beyond subsistence farming and leverage the state’s unique biodiversity. This strategic vision positions agriculture not just as a source of sustenance but as a potential engine for future economic upliftment. The present conflict, however, has specifically and severely impacted this very sector of the economy. The disruption to the cultivation, processing, and export of high-value crops represents a direct blow to the state's long-term economic strategy. This suggests that the crisis is not merely a temporary setback but a systemic reversal of the state's planned development trajectory, pushing it back towards a more fragile, low-value, subsistence-based economy.

The Direct Impacts: From Fallow Fields to Fractured Livelihoods

The most immediate and tangible effect of the socio-political instability has been the crippling of agricultural production. The violence has not only halted farming activities but has also led to a significant degradation of the state's productive land and the destruction of rural livelihoods.

Quantifying the Agrarian Crisis

Official data provides a stark picture of the agrarian crisis. Since the outbreak of violence in May 2023, nearly 5,127 hectares of agricultural land have remained uncultivated or barren for over two years. This abandonment has resulted in an estimated loss of more than 15,000 metric tonnes of rice, a critical figure given that rice is the staple food for the state . In districts like Churachandpur, entire villages have been cut off from their fields due to their location in "buffer zones" that are deemed too dangerous to cross. These once-productive fields now serve as tense, disputed areas, lined with barricades instead of crop rows.

Item	Value / Estimate	Notes / Source	Comment on Uncertainty
Affected land (fallow / uncultivated)	~5,127 hectares	NDTV, Sep 2024	Captures only directly reported land; excludes hill areas or partial damages.
Paddy lost (volume)	~15,437 MT	Economic Times, Mar 2024	Likely only covers first season; excludes vegetables and other crops.
Value of paddy loss	~Rs. 38.6 crore	Economic Times, Mar 2024	Based on average local farm-gate price; actual value may differ.
Farmers affected	~5,901 farmers	Imphal Free Press, Mar 2024	Some farmers have multiple plots; not all losses reported.
Compensation sanctioned	Rs. 38.06 crore	Economic Times, Oct 2023	Relief may be less than actual losses; not all farmers compensated yet.
Estimated sector income loss	Rs. 226.50 crore	Economic Times, Oct 2023	Broader survey estimates; may exclude remote/tribal areas.
Horticulture/organic produce loss	Rs 100 crore	Hindustan Times, Aug 2023	Covers pineapples, ginger, chillies, turmeric etc.; not exhaustive.

Table 3.2: Estimated Agricultural Losses in Manipur (2023-2025)

The abandonment of agricultural land is not a passive outcome; it is leading to the active deterioration of the state's productive assets. Anecdotal accounts describe fields that were once lush and productive now lying fallow and "overgrown with weeds" . This means that even if security is restored, the cost and labor required to reclaim and restore this land for future cultivation will be significantly higher, increasing the barrier to recovery.

A Fractured Value Chain: Implications for Agri-Business Prospects

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The impact of the conflict on Manipur's agricultural sector goes beyond production to inflict a systemic breakdown of its entire value chain. The disruption of markets, trade, and investment has far-reaching implications that threaten to dismantle the state's progress toward a modern, business-oriented agricultural economy.

Systemic Disruption of Markets and Trade

The ongoing conflict has severely impacted farm productivity, leading to a sharp decline in food production. This disruption extends across the entire value chain, from the procurement of agricultural inputs to the distribution and marketing of finished products. The inability of farmers to access their fields and the security threats on major transportation routes have created a significant breakdown in supply chains. The imposition of mobility restrictions and the need for farmers to take lengthy, dangerous detours have also increased the cost of transportation, adding another layer of economic burden. The effect on the state's high-value, export-oriented horticulture sector has been particularly devastating. A farmer has reported that black rice exports to European nations have been hit by at least 60%. Official data from the Manipur Organic Mission Agency corroborates this, estimating a loss of Rs 40 crore for black rice, organic turmeric, and king chilli in 2023 alone. The total loss for horticulture products between May and July 2023 was a staggering Rs 102 crore. This demonstrates a strategic reversal: the state's efforts to build a reputation and secure international markets for its high-value products have been severely undermined. The loss is not just about a single season's crops, but about the state's ability to secure future contracts and investment, which are far more difficult to rebuild than physical infrastructure.

Erosion of Confidence and Investment

The pervasive uncertainty and the high operating costs associated with the conflict create an unfavorable environment for agricultural investment. For a state that has struggled to operationalize planned Special Economic Zones and industrial clusters, this further erodes both local and external investor confidence. The conflict is effectively pushing the state back toward a low-productivity, subsistence-based economy. This stagnation is in stark contrast to the development trajectories of neighboring states. While Manipur's manufacturing and industrial base remains stagnant, states like Mizoram have successfully diversified into pharmaceuticals and processed food, and Sikkim has capitalized on hydropower and organic farming. This comparison highlights that while the conflict is the proximate cause of the current crisis, it has compounded pre-existing structural weaknesses in Manipur's economy, exposing its high vulnerability to external shocks and internal turmoil.

Conclusion: A Call for Coordinated Action

The socio-political instability in Manipur has evolved from a historical legacy into a devastating agrarian crisis, threatening the state's long-term economic viability and its rural way of life. The report's findings confirm that the conflict is not merely an external disruption but a systemic attack on the state's most critical economic sector. The abandonment of thousands of hectares of farmland, the severe decline in food production, and the significant financial losses in the high-value export market represent a profound reversal of the state's development goals. The path to recovery is not simply about providing financial aid. It requires a coordinated, multi-stakeholder approach to restore security, rebuild productive capacity, and address the deep-seated grievances that have placed land and livelihood at the center of this devastating crisis. Until the fundamental issues of security and land access are resolved, and a robust plan to rebuild the agricultural ecosystem is implemented, Manipur's rural economy will remain on a path of prolonged degradation, with lasting repercussions for its people and its future. Rebuilding the Agri-business ecosystem beyond the fields, efforts must be focused on rebuilding the agri-business ecosystem. Strategies

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are needed to re-establish the broken supply chains for high-value products like black rice, pineapple, and turmeric, and to reconnect farmers with their markets, both domestic and international. To mitigate future risks, the state should actively encourage and de-risk investment in agri-processing and value-added products, focusing on crops with low perishability.

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Rancidity: The Hidden Reason Pearl Millet isn't in Every Kitchen

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Pearl millet (Bajra), is a powerhouse of nutrition—rich in protein, fiber, essential minerals, and antioxidants. Its low glycemic index and high energy value make it especially beneficial for managing diabetes, boosting stamina, and improving overall health. As a hardy, climate-resilient crop, it also holds great promise for sustainable agriculture. Yet, despite all these advantages, pearl millet flour remains absent from mainstream markets. The major barrier is rancidity—a natural process where enzymes break down fats in the flour, leading to an unpleasant smell and taste shortly after milling. This rapid spoilage limits its shelf life, making storage, transport, and commercial use difficult. In this article, we explore the nutritional strengths of pearl millet, the science behind its spoilage, and how rancidity affects its market potential. With increased awareness and modern processing solutions, pearl millet can reclaim its place as a staple in our kitchens and contribute to a healthier, more diverse food system.

Introduction

Pearl millet, commonly known as Bajra, is nutritionally superior to many cereals in terms of energy value and mineral content, yet it is consumed by only a small fraction of the global population. It is a climate-resilient crop, capable of thriving in extreme environmental conditions such as drought, low moisture, high temperatures, and low-fertility soils. It also performs well in saline soils. As a summer annual crop, it fits well into various cropping systems and remains a staple food in many arid and semi-arid regions of the world. Pearl millet flour is used to prepare a variety of traditional dishes such as roti, porridge, khichdi, upma, and ladoos. Despite its high nutritional value, the commercialization of pearl millet flour is limited due to its reduced shelf life. In this article, we will explore what makes pearl millet a nutritional powerhouse, the biochemical reasons behind its limited shelf life, the challenges in commercializing its flour, and the ongoing efforts to overcome this bottleneck.

Pearl Millet: "The Forgotten Super Cereal"

Pearl millet possesses higher levels of protein, dietary fiber, and energy compared to common cereals such as rice, wheat, and maize. Therefore, it is considered a nutritional powerhouse. It is especially rich in essential minerals such as iron, zinc, magnesium, and phosphorus, making it an ideal food to combat malnutrition in both rural and urban populations. Pearl millet is known for its low glycemic index, which helps regulate blood sugar levels, especially in diabetic patients. In addition, it contains natural antioxidants and phytochemicals that help reduce oxidative stress and lower the risk of chronic diseases such as cardiovascular disorders and certain types of cancer. Its high fiber content improves digestion and promotes gut health, while its high energy value makes it an excellent choice for children, athletes, and labor-intensive workers.

Why Pearl Millet Flour Struggles in the Market:

Despite its impressive nutritional profile, the large-scale commercialization of pearl millet flour remains a challenge. One of the main reasons is its short shelf life, primarily caused by a phenomenon called rancidity. Once the grains are milled, the natural fats present in the flour are exposed to oxygen, moisture, and enzymes like lipase and lipoxygenase (LOX). These enzymes break down fats through hydrolytic and oxidative reactions, leading to the development of off-flavors and foul odors—collectively known as rancidity. This rapid spoilage not only reduces consumer acceptability but also makes packaging, storage, and transportation difficult for industries. As a result, most pearl millet flour is limited to small-scale or local use, while commercial markets prefer cereals with longer shelf life, such as wheat and rice.

Impact of Rancidity on Marketability and Consumer Acceptance:

Rancidity is one of the primary reasons pearl millet flour has failed to secure a stable place in mainstream grain markets. Once milled, the flour undergoes rapid spoilage due to the activity of endogenous enzymes like lipase and lipoxygenase, which break down fats and release volatile compounds responsible for foul odor and bitter taste. This deterioration starts within a few days at room temperature, especially under humid conditions, making long-term storage nearly impossible without specialized preservation techniques. From a consumer perspective, rancid smell and taste immediately affect food quality and trust. Most urban consumers are unfamiliar with traditional handling or quick usage of pearl millet flour, and they expect the same shelf life and neutral flavor they get from wheat or rice flour. Once a batch turns rancid, it is often thrown away, leading to food waste and negative perception. This has discouraged repeat purchases and limited pearl millet's market growth. From the retail and supply chain side, short shelf life means higher risk of product returns, wastage, and customer complaints. Distributors are unwilling to take on a product that spoils fast, needs refrigeration, or requires airtight packaging that increases logistics cost. As a result, even health-conscious or nutrition-driven brands avoid using pearl millet as a primary grain in their flour mixes or ready-to-eat products. For farmers and processors, the lack of consistent market demand reduces their incentive to grow or invest in pearl millet processing. Since flour has to be used or sold quickly, large-scale storage, transport, and retail become financially risky. This hampers the entire value chain—from production and processing to branding and consumer delivery. In short, rancidity not only spoils the flour but breaks trust in the product, limits its economic value, and prevents its integration into modern food systems.

Conclusion:

Pearl millet is a true gift of nature—packed with nutrients, energy, and health benefits. Known for its climate resilience and rich composition, it has the potential to improve both our diets and our health. Yet, this super grain is missing from our modern meals mainly because its flour spoils quickly due to rancidity. As consumers, understanding this challenge helps us appreciate why pearl millet isn't on every supermarket shelf yet. With continued research and smart processing methods, we can overcome this hurdle and bring pearl millet into everyday kitchens. By choosing and supporting traditional grains like pearl millet, we take a step toward better health, sustainability, and food diversity.

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Vegetable farming as a livelihood security for an Unemployed Rural youth

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Shri Thongam Rabichand S/O Shri Th. Basanta Singh is a 26-year-old enthusiastic rural youth. He is a resident of Leimaram Heinoubok, Bishnupur district of Manipur. He completed his graduation in the Science stream in the year 2017 and married Smt. N. Ronibala Devi in the year 2018. They have a baby girl of about 5 years old. He resides with his parents in a joint family. His father was a labourer and his mother was a housewife. After marriage, he worked as an electrician on a wage basis to earn his livelihood, which was not a regular source of income and was inadequate for his family expenditure. So, he started thinking of another source of income generation, especially farming on his 0.5 ha farm.

Problem

Since after completion of his 12 standard Board examination, he was helping his parents by practicing as a part time job in electrification under wages system. He could earn an amount of about Rs 90,000 per annum which is insufficient for the maintenance of his family expenditures and to mingle in the present/current society. So, he started thinking of suitable farming at an area of 0.5 ha.

KVK intervention

One day he along with his friends came to KVK Bishnupur district, Utlou and met SMS- Horticulture and discussed about the Commercial cultivation of Watermelon. After a thorough discussion, it was decided to arrange an Off Campus training programme under Horticultural crops to be organized by KVK Bishnupur district, Utlou. The programme was with Hands on Scientific cultivation of Watermelon. After participating in the training programme, he was interested to start vegetable cultivation by adopting Improved package of practices of high value crops based on market demand including Maize cultivation for vegetable purpose ie. not for grain purpose. He started cultivation of Watermelon,Tomato, French bean and Maize in the year 2023. Under the guidance of the Subject Matter Specialist-Horticulture, in the year 2024, he could increase the cropping intensity by cultivating Broadbean, Garden pea, Cabbage, Rajma, etc. in addition to the previous year crops. Subject Matter Specialist – Horticulture of the Kendra supervised all the practicing technologies adopting at his farm. And, the seeds of French bean Var. Arka Sukomol and Ayoka, Pea var. Kashi Ageti and Arkel, Tomato var. NS-501 and quality vegetable seedlings viz. Tomato and Cabbage were also handed over as an encouragement for his new venture. He was told to participate in all the on-campus training programmes under Horticulture conducted at KVK Bishnupur district. On the advice of the SMS - Horticulture, he attended skill development programmes by CAU, Imphal and other farmers' programmes conducted by the Department of Horticulture and Soil Conservation, Bishnupur district, Manipur.

Fig.1.Different types of intervention by KVK-Bishnupur, Manipur

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Sl. No.	Crop	Area (sq.m)	Yield	Cost of Production (Rs)	Gross Return (Rs)	Net Return (Rs)
1.	Watermelon	2500	3,500 kg	29,800	1,00,200	70,400
2.	Tomato	1,875	4,050 kg	38,100	1,18,000	79,900
3.	Frenchbean	600	20.5 kg	5,100	14,700	9,600
4.	Broadbean	600	210 kg	5050	20,250	15,200
5.	Gardenpea	600	254kg	4500	14,970	10,470
6.	Cabbage	625	1,600 kg	3850	16,000	12,150
7.	Rajma	625	295 kg	4850	11,100	6,250
8.	Maize	5,000	10,300 (cobs)	47,500	1,96,900	1,49,000

Input, Output and Outcome of the year 2023-24

Table 1. Cultivated Crops and Economics of the farm

Fig. 2. Adopting Scientific package of practices for high returns

Social Impact

During short span of time he could earn a net income of Rs 3,52,970 (Rupees three lakhs fifty-two thousand nine hundred and seventy) only. He could buy a Honda Activa from the showroom in the month of February 2024 and a second-hand diesel autorickshaw in May 2024. Now, he has self-confidence in farming and is leading a comfortable life and could manage all his family expenses from his farming enterprise. Her mother also started selling his farm produces as street vendor at the roadside of Maibam Lokpa Ching, Nambol. His parents, wife are assisting him in his farming operations. Inspired by his success, many unemployed youths and practicing farmers showed interest in farming and seeking information and advice from the KVK Bishnupur as well as from him. He has become a successful rural youth of his village and also recognized the role and activities of KVK Bishnupur district, Manipur. Now, his future target is to become a prominent agripreneur who can uplift the economic status of the poor farmers and for the livelihood security of the farming community.

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Impact of Mulches on Soil Health and Productivity

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Introduction

Soil is the foundation of agriculture and the lifeline for food security. It is a living ecosystem that supports billions of microorganisms and provides essential nutrients, water and anchorage for plants. Unfortunately, due to modern intensive farming, deforestation and climatic changes, soils are increasingly becoming degraded, losing fertility and structure. One of the most effective, affordable and eco-friendly techniques to restore and maintain soil health is mulching. Mulching is a practice of covering the soil surface with a layer of material. This layer acts as a protective blanket that shields the soil from direct sun, rain and wind, while improving its physical, chemical and biological properties. Mulching is not just a soil management practice; it is an investment in long-term soil sustainability and crop productivity.

Types of Mulches

Mulches can be categorized into organic and inorganic types, each with unique properties and benefits. The choice depends on crop type, availability of materials and objectives.

1. Organic Mulches: These include crop residues, straw, hay, dry leaves, grass clippings, sawdust, compost, farmyard manure, sugarcane trash and even green leaves from hedgerow trees. When applied, they gradually decompose and become part of the soil organic matter.

Advantages: Improve soil fertility, enhance microbial activity and maintain soil moisture.

Examples: Paddy straw mulch in vegetables, sugarcane trash mulch in orchards or dry leaves mulch in plantations.

2. Inorganic Mulches: These are synthetic or non-living materials such as black polyethylene sheets, silver mulch film, gravel, pebbles or stones. They are commonly used in commercial horticulture and high-value crops.

Advantages: Excellent weed control, efficient moisture conservation and temperature regulation.

Examples: Black plastic mulch in tomato and capsicum; silver-on-black films in cucumber and melon to repel pests.

3. Biodegradable Mulches: Recently, biodegradable plastic films made from starch or plant fibers are gaining popularity. They offer the benefits of synthetic mulches while decomposing naturally, reducing pollution.

Benefits of Mulching on Soil Health

a. **Moisture Conservation:** Mulch acts as a barrier to evaporation, reducing water loss from the soil surface. Studies indicate that mulching can reduce evaporation by 25–50%. This conserved moisture is crucial in rainfed areas and during dry spells. For instance, vegetable crops mulched with straw often require 20–30% less irrigation compared to unmulched fields.

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b. **Temperature Regulation:** Soil temperature affects seed germination, root growth and microbial activity. Mulches buffer the soil against extreme temperatures. In summer, they keep the soil cool, preventing root scorching. In winter, they retain warmth and promote early germination. Plastic mulches are especially useful for off-season vegetable production in temperate and subtropical regions.

c. **Soil Structure Improvement:** Organic mulches, as they decompose, form humus which binds soil particles into stable aggregates. This improves porosity, aeration and water infiltration. Loamy and sandy soils, which are prone to compaction or rapid drying, particularly benefit from this enhanced structure.

d. **Reduction in Soil Erosion:** Bare soil is easily eroded by rain splash and surface runoff. Mulch provides a protective layer that cushions the soil from raindrop impact, reduces runoff velocity and promotes water infiltration. This is especially valuable on sloping lands and in hilly agriculture.

e. **Weed Suppression:** Weeds compete with crops for nutrients, water and light. Mulches block sunlight from reaching weed seeds, preventing germination. Black plastic mulch, for instance, almost completely eliminates weed growth, reducing the need for manual weeding or herbicide application.

f. **Enhanced Microbial Activity and Soil Biology:** Beneath the mulch, soil moisture and temperature remain stable, creating an ideal environment for beneficial organisms like earthworms, nematodes and decomposer fungi. These organisms improve soil aeration, decompose organic matter and release nutrients. Earthworms thrive especially well under organic mulches, helping to form rich, friable soil.

g. **Improved Soil Fertility:** As organic mulches decompose, they release nutrients such as nitrogen, phosphorus and potassium into the root zone. This slow and continuous nutrient supply enhances plant nutrition and reduces the dependency on chemical fertilizers. Additionally, mulching helps maintain a balanced soil pH and reduces nutrient leaching.

h. **Reduced Soil Compaction:** The cushion effect of mulch protects the soil surface from the compacting effect of raindrops and machinery movement, preserving a friable soil texture ideal for root development.

Impact on Crop Productivity

Influence of mulching on crop performance is visible from sowing to harvest.

- Better Germination and Early Growth: By moderating temperature and conserving moisture, mulches promote uniform seed germination and healthy early growth.
- Enhanced Nutrient Uptake: Improved root health and microbial activity increase nutrient availability to plants.
- Higher Yields: Many field studies have reported yield increases ranging from 10% to 40% depending on the crop and mulch used. For example, black plastic mulch in tomato and watermelon enhances fruit yield and quality.
- Improved Quality and Appearance: Mulching reduces soil splashing on fruits and vegetables, improving their marketable appearance.
- Reduced Crop Stress: Plants under mulch experience less drought stress and

temperature fluctuation, leading to stronger growth and resilience.

In perennial crops such as banana, citrus and mango, mulching improves root spread and water retention around the root zone, which is crucial for consistent fruiting.

Environmental and Economic Significance

Mulching contributes directly to sustainable and climate-resilient agriculture:

- Water Use Efficiency: By conserving soil moisture, mulching reduces irrigation frequency and total water requirement.
- Energy Savings: Fewer irrigation cycles mean lower energy costs for pumping water.
- Reduced Fertilizer Loss: Mulch prevents nutrient leaching during heavy rains and promotes efficient fertilizer use.
- Carbon Sequestration: Organic mulches increase soil carbon content, playing a role in mitigating climate change.
- Reduced Pollution: Biodegradable mulches and natural materials minimize environmental hazards associated with plastic residues.

Economically, though the initial cost of mulching (especially for synthetic materials) can be high, the long-term benefits like improved yield, reduced labor for weeding and better soil health.

Challenges in Mulch Use

Despite numerous benefits, some challenges limit widespread adoption:

- Cost of Materials: High-quality plastic or biodegradable mulches may be expensive for small farmers.
- Labor Requirement: Applying, maintaining, and later removing mulch requires time and labor.
- Disposal Problems: Non-biodegradable plastics can create pollution if not properly managed.
- Pest and Disease Concerns: In humid conditions, organic mulches may harbor pests like slugs or fungal pathogens if not applied correctly.
- Limited Awareness: Many farmers are still unaware of proper mulching techniques and potential benefits.

To overcome these issues, extension services and research institutions should promote low-cost, locally available mulch materials and educate farmers on proper application methods.

Conclusion

Mulching is a powerful yet simple technique to protect and rejuvenate soil. It enhances soil moisture, fertility and microbial life while suppressing weeds and erosion. Whether through natural organic matter or innovative biodegradable films, mulching ensures that the soil remains productive and resilient. In the face of climate uncertainty, dwindling water resources and soil degradation, mulching offers a path toward sustainable, profitable and environmentally responsible farming. Adopting mulching is not just a practice; it is a step toward nurturing the soil for future generations.

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Algae and Mycoprotein: As a Plant-Based and Eco-Friendly Proteins Shaping Tomorrow's Diets

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The article explores algae and mycoprotein as sustainable, protein-rich alternatives to animal-based proteins. Algae such as *Spirulina* and *Chlorella* and mycoprotein derived from *Fusarium venenatum* offer high-quality amino acids and support muscle health. They also contribute to metabolic benefits like improved glucose and lipid control. From an environmental perspective, both require less land, water and energy, making them vital for sustainable food systems. Algae cultivation and mycoprotein fermentation have low carbon footprints and can help meet rising global protein demands. Their applications include meat substitutes, nutraceuticals and plant-based foods, with products like Quorn already popular in the market. While challenges such as consumer acceptance and allergenicity persist, these alternative proteins hold great potential to enhance nutritional diversity and reduce the ecological burden of traditional protein production.

Introduction

Algae and mycoprotein are emerging as significant protein-rich food sources, offering sustainable alternatives to traditional animal-derived proteins. Both sources are rich in essential amino acids and have been shown to support muscle protein synthesis, making them viable options for dietary protein supplementation. Algae, such as Spirulina and Chlorella and mycoprotein, derived from fungi like Fusarium venenatum, are gaining attention for their nutritional benefits and environmental sustainability. The growing interest in these protein sources reflects a shift towards more environmentally friendly food systems, which is crucial given the increasing global demand for sustainable nutrition (Wu et al., 2023). Moreover, the unique compositions of these protein sources can enhance dietary diversity while addressing the environmental challenges associated with conventional protein production (Wu et al., 2023) (Kumar et al., 2022). This overview explores the nutritional value, health benefits and sustainability of algae and mycoprotein as alternative protein sources.

Nutritional Value and Health Benefits

- **Algae**: Spirulina and Chlorella are microalgae known for their high protein content and essential amino acids. They have been shown to increase myofibrillar protein synthesis rates in both resting and exercised muscles, comparable to mycoprotein, despite different plasma amino acid responses (Heijden et al., 2023). Algae also contain lipids, fatty acids, and pigments, contributing to their nutritional profile (Severo et al., 2024). Additionally, the incorporation of algae into diets may provide beneficial effects on metabolic health, including improved glucose and lipid homeostasis (Wu et al., 2023). This highlights the potential of algae not only as a protein source but also as a functional food component.
- **Mycoprotein**: Derived from the fermentation of Fusarium venenatum, mycoprotein is a complete protein source rich in dietary fiber. It has been associated with reduced cholesterol levels, improved glycaemic control, and increased satiety (Coelho et al., 2020) (Derbyshire & Delange, 2021).

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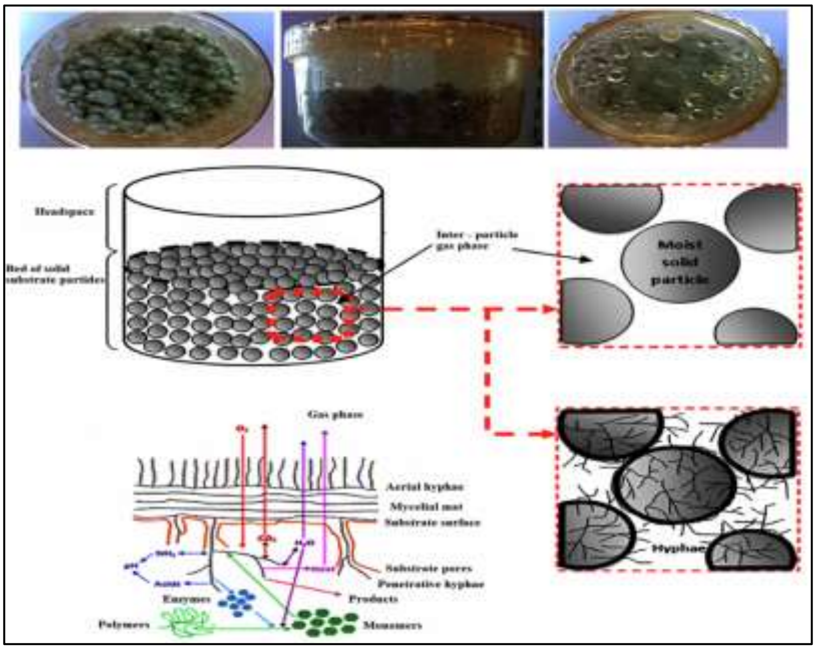
Mycoprotein is also effective in stimulating muscle protein synthesis, supporting muscle health and adaptation (Derbyshire et al., 2023). Further research is essential to fully understand the long-term impacts of incorporating algae and mycoprotein into diets, particularly regarding their effects on overall health and metabolic processes.

Sustainability and Environmental Impact

- **Algae**: Algae can be cultivated in open and closed systems, making them a sustainable protein source. They require less land and water compared to traditional agriculture, and their production can be scaled to meet global protein demands (Severo et al., 2024). Furthermore, algae's negligible land needs compared to conventional protein sources make them a compelling option for sustainable food production (Procházka et al., 2023). This adaptability positions algae as a key player in addressing the protein demands of a growing population while minimizing environmental impacts.
- **Mycoprotein**: The production of mycoprotein is environmentally friendly, using significantly less land and water than animal protein sources. It has a lower carbon footprint and is projected to be net positive by 2030, contributing positively to the environment and economy (Derbyshire & Finnigan, 2022) (Finnigan et al., 2024). Incorporating algae and mycoprotein into mainstream diets not only promotes nutritional diversity but also supports sustainable practices in food production, addressing the urgent need for eco-friendly protein sources (Wu et al., 2023) (Dajana et al., 2013).



Source: (Li et al., 2024)

Fig. 1: Recent advances and challenges in single cell protein (SCP) technologies for food and feed production

Applications and Market Potential

- **Algae**: Algae proteins are used in various food products, including meat substitutes and nutraceuticals. Their sensory attributes and health benefits make them suitable for seafood analogues and other plant-based foods (Karimidastjerd et al., 2024). The potential for algae to enhance food applications is significant, particularly in the European market, where consumer awareness and demand for sustainable protein sources are rapidly growing (Procházka et al., 2023). This trend indicates a promising future for algae as a major component in alternative protein products.
- **Mycoprotein**: Commercially available as Quorn, mycoprotein is used in a variety of food products such as mince, nuggets, and sausages. It is particularly appealing to vegetarians and those seeking to reduce meat consumption due to its nutritional benefit and low environmental impact (Garodia et al.,

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2017). The transition towards these alternative protein sources is essential for fostering a more sustainable food system that can adequately support the nutritional needs of a growing global population. Research into algae and mycoprotein highlights their potential to significantly contribute to sustainable food systems, addressing both nutritional needs and environmental concerns in the face of population growth (Wu et al., 2023) (Lohakar et al., 2024).

Conclusion:

Algae and mycoprotein offer promising alternatives to animal-derived proteins, challenges remain in terms of consumer acceptance and potential allergenicity. Some individuals may experience adverse reactions to mycoprotein, particularly those allergic to molds (Garodia et al., 2017). Additionally, the sensory attributes of algae-based products may require further refinement to meet consumer preferences. Despite these challenges, the growing interest in sustainable and health-promoting protein sources suggests that algae and mycoprotein will play an increasingly important role in future dietary guidelines and food systems.

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Biostimulants role in Vegetable Production

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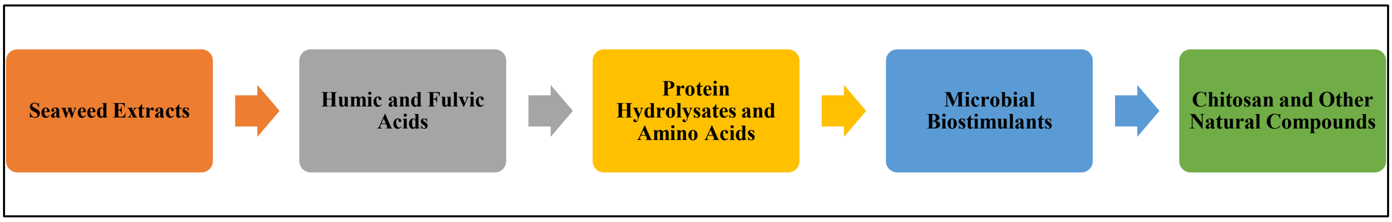
The growing global demand for safe, sustainable and high-quality vegetables has intensified the search for eco-friendly alternatives to chemical fertilizers and pesticides. Biostimulants have emerged as a promising solution to enhance crop productivity, improve stress tolerance, and promote soil health without adverse environmental impacts. This article discusses the types, mechanisms, and applications of biostimulants in vegetable cultivation, emphasizing their role in sustainable agriculture.

Introduction

Vegetables are an essential component of the human diet, providing vital nutrients, vitamins and minerals. However, intensive cultivation practices, declining soil fertility and climatic challenges often limit vegetable productivity. Nowadays farmers are more inclined to get benefited by the various alternate systems therefore indiscriminate use of chemicals is more popular. In recent years, biostimulants have gained importance as a sustainable tool to boost growth and yield in vegetables while maintaining ecological balance. Biostimulants are the natural formulation extracted from different seaweeds, plants and other materials. According to the European Biostimulants Industry Council (EBIC), biostimulants are substances or microorganisms that stimulate natural processes in plants, improving nutrient uptake efficiency, abiotic stress tolerance and crop quality.

Types of Biostimulants

Biostimulants encompass a broad range of products derived from natural sources. Major categories include:



- **Seaweed Extracts**: Rich in phytohormones (cytokinins, auxins, gibberellins), minerals, and polysaccharides; enhance seed germination, root development, and fruit quality in vegetables like tomato and cucumber.
- **Humic and Fulvic Acids**: Derived from decomposed organic matter; improve nutrient uptake and soil structure, particularly beneficial for root crops like carrot and radish.
- **Protein Hydrolysates and Amino Acids**: Supply organic nitrogen and stimulate enzyme activity, improving chlorophyll synthesis and yield in leafy vegetables like spinach and lettuce.
- **Microbial Biostimulants**: Include beneficial microorganisms such as Azospirillum, Bacillus, and Trichoderma species that enhance nutrient availability and disease resistance.
- **Chitosan and Other Natural Compounds**: Induce plant defense responses and improve tolerance to environmental stresses like drought and salinity.

Mechanisms of Action

Biostimulants act through multiple physiological and biochemical pathways:

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• Enhanced Nutrient Uptake: Stimulate root growth and nutrient absorption.

• Improved Photosynthesis: Increase chlorophyll content and enzymatic efficiency.

• Stress Tolerance: Activate antioxidant systems to combat drought, heat, and salinity.

• Improved Soil Microbiome: Support beneficial microbial communities that enhance soil fertility.

• Quality Enhancement: Improve flavor, color, vitamin content, and shelf life of vegetables.

Application in Vegetable Crops

Crop	**Type of Biostimulant Used**	**Observed Effect**
Tomato	Seaweed extract, humic acid	Increased fruit yield and lycopene content
Cucumber	Microbial inoculants	Enhanced nutrient uptake and disease resistance
Onion	Protein hydrolysate	Improved bulb size and shelf life
Capsicum	Chitosan	Better stress tolerance and fruit firmness
Spinach	Amino acid formulations	Higher chlorophyll content and leaf area

Advantages of Using Biostimulants

• Environmentally friendly and biodegradable

• Reduce dependence on chemical fertilizers and pesticides

• Enhance soil health and fertility

• Improve crop yield and quality

• Compatible with organic farming practices

Challenges and Future Prospects

Despite their potential, the use of biostimulants faces certain challenges such as product standardization, variable field performance, and limited awareness among farmers. Future research should focus on:

• Molecular mechanisms of biostimulant action

• Development of crop-specific formulations

• Integration with precision agriculture technologies

• Regulatory frameworks to ensure quality and efficacy.

Conclusion

Biostimulants represent a revolutionary approach in modern vegetable production, promoting sustainable and resilient farming systems. Their integration into conventional and organic vegetable cultivation can significantly improve productivity, quality, and environmental sustainability. With continued research and awareness, biostimulants can play a pivotal role in achieving the goals of climate-smart and eco-friendly agriculture.

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A comprehensive solution of aggressive root-knot nematode, *Meloidogyne spp*. in Guava

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Introduction

Guava (*Psidium guajava* L.) is an economically important fruit crop of the Myrtaceae family. It is one of the commercial and important fruits of India widely grown in tropical and sub-tropical regions of the world and hence it is referred to as the 'poor man's apple' and 'the apple of tropics' due to the low cost of production and high nutritional value. In Rajasthan, farmers have been facing a unique problem in guava trees that showed sudden yellowing followed by bronzing and marginal necrosis of leaves, delayed and poor flowering, shedding of leaves, reduction in fruit size, and decline of guava trees leading to complete destruction of the orchards within a short span of time of one to two years. Root-knot nematode infestation especially in southern Rajasthan have been reported as major problem in Guava growing area of Rajasthan. The nematode was confirmed to be mix population of *Meloidogyne incognita, M. enterolobii* and *M. javanica,* through morphological and molecular means. Many studies showed that all the guava cultivars (Psidium guajava L.) are susceptible to *Meloidogyne* spp. and also the root exudates of guava cultivars increased the egg hatching ability and decrease the infective juvenile J2 mortality rate and were directly proportional to the time and concentration. Among *Meloidogyne* spp., *M. enterolobii* is regarded as the most aggressive species in comparison to other tropical species of root-knot nematode (Brito et al., 2004) in view of its high reproduction rate, induction of large galls and a very wide host range, and their combinations has become a threat to guava production worldwide leading to the decimation of several guava orchards. The optimal temperature for growth and development of *M. incognita* & *M. enterolobii* is 28°C which coincides with the temperature of most of the Tropical and subtropical regions of Country especially Rajasthan to high infestation. Various approaches such as physical, cultural, chemical, and biological practices have been used to manage the incidence of root-knot nematode. Cultural practices such as soil solarisation and crop rotation showed limited value in managing nematode infestation due to its broad host range. Hence, there has been an urgency to tackle the destruction caused in guava by this nematode by identifying suitable integrated management practices to control the root-knot nematode.

Symptoms:

They cause the formation of galls or knots on the roots, disrupting the plant's ability to absorb water and nutrients. These nematodes invade the root system, establish feeding sites and manipulate plant cellular processes to create a conducive environment for their reproduction. The primary symptom of *Meloidogyne* spp. infection in guava is the formation of large galls or knots on the roots leading to several above-ground symptoms, including:

- ✓ Stunted growth
- ✓ Chlorosis (yellowing of leaves)
- ✓ Drying of branches
- ✓ Reduced plant vigour
- ✓ Wilting, especially during hot days
- ✓ Reduced fruit yield and quality

In severe infestations, the entire root system can become severely galled, resulting in plant death.

Impact of yield loss on farmers and the economy in India: The significant yield losses caused by nematode diseases in guava have far-reaching

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implications for farmers and the agricultural economy in India. The following points highlight the impact:

1. **Economic Losses for Farmers:** Yield losses directly translate to reduced income for guava farmers. With yield reductions ranging from 10% to 80%, farmers face substantial financial setbacks. Increased production costs due to the need for additional inputs like nematicides, organic amendments, and resistant varieties further strain farmers' finances.
2. **Reduced Export Potential:** Guava is an important export commodity for India. Nematode diseases leading to lower yields and poor fruit quality can reduce the export potential of Indian guava, affecting foreign exchange earnings.
3. **Food Security Concerns:** Guava is a nutritious fruit that contributes to the food security of many communities in India. Yield losses due to nematodes can impact the availability of this vital food source.
4. **Impact on Agro-Based Industries:** Guava is used in various agro-based industries, including the production of juices, jams, and other processed foods. Reduced guava yields can affect the supply chain, impacting these industries and their associated livelihoods.
5. **Environmental Impact:** Increased use of chemical nematicides to control nematodes can lead to environmental degradation, affecting soil health and biodiversity. Sustainable management practices are essential to mitigate these impacts.
6. **Social Impact:** The financial strain caused by yield losses can lead to increased indebtedness among farmers, affecting their socio-economic status and overall well-being.

Management Strategies

Managing the guava root-knot nematode, requires a comprehensive and integrated approach to mitigate its devastating impact on guava crops. Cultural practices form the backbone of nematode management, with crop rotation being particularly effective. Rotating guava with non-host crops can significantly reduce nematode populations in the soil. Soil solarisation, which involves covering the soil with clear plastic to trap solar radiation, helps sterilize the soil and reduce nematode levels. Sanitation measures, such as removing and destroying infected plant material, are crucial in preventing the spread of nematodes within and between fields. Biological control offers an environmentally friendly approach. Introducing beneficial nematodes that prey on harmful nematodes can help reduce populations of harmful nematodes.Chemical control, though often necessary, should be used judiciously to minimize environmental impact. Nematicides such as carbofuran 3G, fenamiphos and oxamyl can effectively reduce nematode populations when applied correctly. Advances in molecular biology and genomics offer new opportunities for nematode management. Research into the genetic basis of nematode resistance and the development of genetically modified guava plants could provide long-term solutions. Additionally, exploring organic amendments and enhancing soil health through microbial diversity are promising areas for future study.

Integrated Nematode Management:

- Use nematode free grafts and layers for planting by checking for galls if any
- Planting marigolds (*Tagetes* spp.) around the guava trees can serve as a trap crop, as their roots produce compounds that are toxic to nematodes.
- Liquid and talc based formulation of novel biocontrol agent *Bacillus subtilis* (IIHR BS-

- 2, NAIMCC – B-01211). Highly effective against eggs and juveniles of root knot nematodes (*Meloidogyne incognita*)
- Enrich with *Purpureocillium lilacinum*: Mix 1 kg of the bio-agent *Purpureocillium lilacinum* (formerly known as *Paecilomyces lilacinus*) with 100 kg of Farm Yard Manure (FYM) or bio-compost and apply @ 500 g - 1 kg / plant every 3 months.
- Application of Carbofuran 3G @ 60g / plant on onset of symptoms such as yellowing, bronzing and stunting

Conclusion:

Nematode diseases, especially those caused by root-knot nematodes, present considerable challenges for guava farming in India and specifically in Rajasthan. The yield losses incurred have far-reaching economic, social, and environmental consequences. For sustainable guava production, it is essential to adopt an integrated management strategy that combines cultural practices, biological control, chemical treatments, and resistant varieties. Guava growers can lessen the effects of nematode diseases, maintain the health and productivity of their orchards, and protect their livelihoods by adopting these management practices. To devise effective strategies for fighting these ubiquitous pests and fostering the development of India's guava industry, ongoing research and innovation are essential.

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Biochar: Next Generation Material in Plant Protection and Agronomic Practices

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Introduction

Agriculture is currently facing dual challenges: maintaining high crop productivity and ensuring sustainability of natural resources. Conventional methods relying on chemical fertilizers and pesticides have boosted yields but created problems such as soil degradation, pest resistance, and environmental pollution. Biochar, a carbon-rich solid material produced by pyrolysis of crop residues, wood chips, animal manure, and other biomass under limited oxygen, has emerged as a promising innovation in agronomy and plant protection (Lehmann and Joseph, 2015). Unlike simple organic amendments, biochar is: Highly porous, Stable in soil for hundreds of years, and provide a micro habitat for beneficial microbes. Thus, biochar represents a next-generation material in agriculture combining soil fertility improvement, pathogen suppression, and climate change mitigation.

Properties of Biochar Relevant to Agriculture

Biochar's effectiveness in plant protection and agronomy depends on its physical, chemical, and biological properties, which are influenced by feedstock type and pyrolysis temperature.

- Porous Structure: Acts as a sponge, absorbing water and nutrients while giving habitat to microbes.
- High Surface Area: Provides binding sites for toxins, pesticides, and heavy metals.
- Cation Exchange Capacity (CEC): Retains nutrients (N, P, K, Ca, Mg) and prevents leaching losses.
- pH Buffering: Neutralizes acidic soils, improving nutrient availability.
- Stable Carbon: Remains in soil for decades, reducing CO_2 emissions and sequestering carbon.
- Microbial Colonization: Supports plant growth-promoting rhizobacteria (PGPR), *Trichoderma*, and mycorrhiza (Elad *et al.*, 2011).

Example: Biochar from rice husk has high silica content, improving disease resistance in rice. Similarly, wood-derived biochar has better pH buffering capacity than crop residue biochar.

Biochar in Agronomic Practices: Soil Health and Fertility Improvement

i) Enhances nutrient availability:

- N is adsorbed in micropores, reducing volatilization losses.
- P solubility increases in acidic soils due to liming effect of biochar.

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- Reduces fertilizer dependency by increasing nutrient use efficiency.
- Acts as a slow-release fertilizer carrier when combined with urea or compost.

Example: Application of 10 t/ha of maize-stalk biochar increased maize yield by 25–30% by improving N retention.

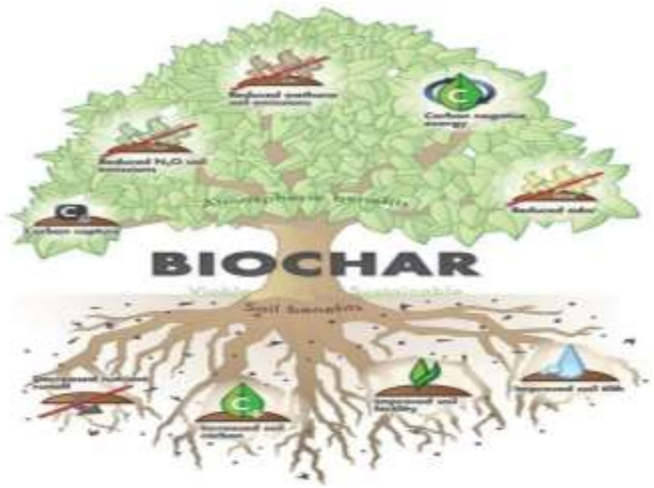
ii) Crop Productivity and Stress Tolerance

- Improves water holding capacity by 15–25%, crucial in dryland farming.
- Reduces salt stress by adsorbing Na^{+} ions.
- Chelates heavy metals (Cd, Pb, Zn), reducing their uptake by crops (Singh *et al.,* 2020).

Example: In tomato fields, biochar application reduced Na uptake and improved fruit yield under saline irrigation.

iii) Climate-Smart Agronomy

- Reduces greenhouse gas (GHG) emissions:
- Decreases N_2O emission by immobilizing nitrate.
- Reduces CH_4 from paddy fields by improving aeration.
- Provides carbon sequestration, earning carbon credits in some countries.



Source: International Biochar Initiative, 2025

Biochar in Plant Protection

i) Suppression of Soil-Borne Pathogens

- Biochar adsorbs and neutralizes fungal toxins and pathogen propagules.
- Enhances beneficial microbial populations that outcompete pathogens.
- Induces systemic resistance:
- SAR (Systemic Acquired Resistance) against fungal pathogens.
- ISR (Induced Systemic Resistance) mediated by rhizobacteria (Elad *et al.*, 2011).

Example: In cucumber, biochar reduced severity of Fusarium wilt by 35–50%.

ii) Synergy with Biocontrol Agents

Biochar acts as a carrier medium for beneficial microorganisms:

- *Trichoderma* spp.: suppress root-rot pathogens and enhance root growth.
- *Pseudomonas fluorescens*: produces antibiotics and siderophores, limiting pathogen growth.
- *Bacillus subtilis*: forms biofilm on biochar pores and induces ISR.
- *Azotobacter / Azospirillum*: fix atmospheric nitrogen

Example: "Biochar + Trichoderma" formulations have shown superior results in controlling *Rhizoctonia solani* in rice.

iii) Pest and Weed Management

- Biochar modifies soil volatiles, altering insect attraction and behavior.
- Improves crop vigor, making plants more tolerant to insect attack.
- Suppresses some weed seed germination by changing soil moisture and pH conditions.

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Innovative Applications of Biochar

1. **Nano-Biochar**

Produced by grinding or special pyrolysis: nano-sized particles.

Enhances adsorption capacity and delivery of nutrients/pesticides.

Binds pesticide residues, reducing contamination in soil and food.

2. Biochar-Based Formulations

Biochar + Compost: enriches organic matter and microbial activity.

Biochar + Fertilizers: improves nutrient efficiency (INM approach).

Biochar + Biopesticides: increases survival and shelf life of microbial inoculants (Jaiswal *et al.,* 2014).

Challenges and Limitations

Variability: Properties differ with feedstock and pyrolysis conditions (e.g., rice husk vs. poultry manure biochar).

High Cost: Large-scale biochar production is still expensive.

Application Rates: Lack of uniform guidelines (recommendations vary 2–20 t/ha).

Farmer Awareness: Low adoption due to insufficient extension services.

Future Prospects

- Standardization of biochar formulations for specific crops and soils.
- Development of nano-biochar technologies for precision agriculture.
- Integration of biochar with Integrated Nutrient Management (INM) and Integrated Disease Management (IDM).
- Policies for carbon credit schemes to encourage adoption.

Conclusion

Biochar is not merely a soil conditioner, it is a multi-dimensional, next-generation agricultural input. By enhancing soil fertility, promoting beneficial microbes, inducing systemic resistance, and mitigating climate change, biochar stands out as a sustainable tool bridging agronomy and plant protection.

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How Aeroponics is Reshaping Modern Agriculture

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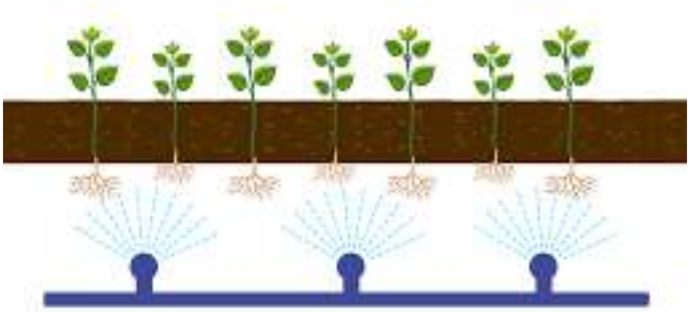
Aeroponics represents a revolutionary soilless cultivation technology that grows plants by delivering nutrient-rich aerosol directly to expose root systems. This advanced agricultural method offers unprecedented water efficiency, achieving up to 95% water conservation compared to traditional farming, while increasing crop yields by 30-50%. Current research indicates that aeroponic systems integrate IoT sensors, AI monitoring *and* precision nutrient delivery to optimize plant growth parameters. The technology addresses critical challenges in food security, urban agriculture *and* sustainable farming practices, positioning itself as a viable solution for next-generation agricultural systems with applications ranging from leafy greens to medicinal crops.

Introduction

The global agricultural landscape faces mounting pressure to produce sufficient food for an estimated 9.7 billion people by 2050, while simultaneously addressing water scarcity, soil degradation *and* climate change impacts. Traditional farming methods consume approximately 70% of global freshwater resources and occupy 50% of habitable land, yet struggle to meet increasing food demands (Chen *et al.*, 2023). Aeroponics is a soilless agricultural technique that grows plants by misting their roots with a nutrient-rich solution, emerging as a transformative solution that addresses these challenges through innovative cultivation methods.



The etymology of aeroponics derives from the Greek words "aero" (air) and "ponos" (labor), literally meaning "working with air." This sophisticated growing technique suspends plant roots in air while delivering nutrients through fine mist droplets, typically ranging from 5-50 micrometers in diameter. Unlike hydroponic systems that submerge roots in nutrient solutions, aeroponic systems provide enhanced root oxygenation and precise nutrient control, resulting in accelerated plant growth and superior crop quality.

Technological Framework and System Components

Modern aeroponic systems integrate sophisticated technological components that enable precise environmental control and automated plant management. The core infrastructure consists of growing chambers, high-pressure pumps generating 60-80 psi, ultrasonic foggers *and* computer-controlled nutrient delivery systems. Advanced installations incorporate Internet of Things (IoT) sensors that continuously monitor pH levels (optimal range 5.5-6.5), electrical conductivity (1.2-2.0 mS/cm), temperature (18-24°C) *and* humidity levels (60-80%).

The proposed methodology is used to identify the parameters that affect plant growth and their correlations with the plant performance indicators, demonstrating how artificial intelligence algorithms optimize growing conditions in real-time. Contemporary systems utilize machine learning models to predict nutrient requirements, adjust

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misting frequencies *and* prevent disease outbreaks through pattern recognition analysis.

The misting cycle typically operates on 5-second spray intervals every 2-5 minutes, delivering precisely calibrated nutrient solutions containing essential macronutrients (nitrogen, phosphorus, potassium) and micronutrients (iron, manganese, zinc, boron). This precision delivery mechanism ensures 100% nutrient availability to root systems, compared to 30-40% efficiency in soil-based agriculture.

Performance Metrics and Agricultural Benefits

Aeroponic cultivation demonstrates remarkable productivity improvements across multiple performance indicators. Research data reveals that lettuce (*Lactuca sativa*) grown in aeroponic systems achieves harvest maturity 25-30% faster than soil cultivation, with fresh weight increases of 40-60%. Tomato (*Solanum lycopersicum*) production shows yield improvements of 3-4 times per square meter compared to traditional greenhouse cultivation, while maintaining superior fruit quality with enhanced vitamin C content (15-20% higher) and reduced pesticide residues.

Water efficiency represents the most significant advantage of aeroponic systems, achieving 95% water conservation compared to conventional irrigation methods. Traditional farming requires approximately 250 liters of water per kilogram of leafy greens, while aeroponic systems utilize only 20 liters for equivalent production. This dramatic reduction results from precise nutrient delivery, minimal evaporation losses *and* closed-loop water recycling systems.

Root development in aeroponic environments exhibits enhanced characteristics including increased root hair density (300-400% higher than soil cultivation), improved nutrient absorption capacity *and* accelerated secondary root formation. These physiological improvements contribute to stronger plant immune systems and increased resistance to pathogens, reducing crop losses by 70-80% compared to traditional farming methods.

Crop Diversity and Application Potential

Aeroponic technology demonstrates versatility across diverse crop categories, from leafy greens to high-value medicinal plants. Commercial installations primarily focus on fast-growing crops including lettuce, spinach (*Spinacia oleracea*), basil (*Ocimum basilicum*) *and* cilantro (*Coriandrum sativum*), which complete growing cycles in 21-35 days. These crops achieve optimal growth rates due to enhanced root oxygenation and continuous nutrient availability.

Recent agricultural research explores aeroponic cultivation of traditionally soil-dependent crops including strawberries which demonstrate 200-250% yield increases and extended fruiting periods. Root vegetables such as radishes (*Raphanus sativus*) and carrots (*Daucus carota*) show promising results, though require specialized growing containers and modified misting techniques.

NASA has been researching aeroponics for growing food in space, highlighting the technology's potential for extreme environments and resource-limited applications. Space agriculture research indicates that aeroponic systems can maintain plant growth in zero-gravity conditions, opening possibilities for long-duration space missions and planetary colonization projects.

The pharmaceutical industry increasingly adopts aeroponic cultivation for medicinal plant production, particularly cannabis (*Cannabis sativa*) and ginseng (*Panax ginseng*), achieving enhanced cannabinoid concentrations and ginsenoside content respectively. These applications demonstrate aeroponics' capability for producing high-value crops with superior biochemical profiles.

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Economic Considerations and Market Dynamics in India

The Indian aeroponic market has witnessed remarkable expansion from 2020-2024, with partnership agreements boosting the adoption of advanced aeroponic technology in India and the Middle East regions. Early adopters concentrated on high-value crops like leafy greens, herbs, and medicinal plants, while government initiatives and private investments accelerated technological advancement and cost reduction programs.

Initial capital investments for commercial aeroponic installations range from ₹60 lakhs to ₹2.2 crore per acre, including infrastructure, control systems, and environmental equipment. The substantial cost variation depends on land acquisition, material quality, automation levels, and regional market conditions. Operating costs average ₹8-12 per square meter annually, primarily attributed to electricity consumption (45%), nutrient solutions (25%), maintenance expenses (20%), and skilled labor (10%). Despite higher upfront investments compared to traditional farming, aeroponic systems achieve break-even points within 24-30 months through premium crop pricing, multiple harvest cycles, and reduced resource consumption.

Labor requirements decrease by 50-60% compared to conventional Indian farming practices, as automated systems manage irrigation, nutrient delivery, and environmental monitoring functions. Skilled technical operators can supervise 2-3 aeroponic units simultaneously, significantly improving labor productivity in regions facing agricultural workforce shortages. Quality premiums for aeroponically-grown produce range from 25-40% above conventional products in Indian urban markets, driven by pesticide-free cultivation, extended shelf life, and growing consumer awareness about sustainable agriculture practices.

Aeroponics Market was valued at USD 1.1 billion in 2023 and is estimated to register a CAGR of over 15% between 2024 and 2032. The market is witnessing a surge in growth, propelled by the growing demand for sustainable agricultural practices. A notable trend is the traction in vertical farming adoption, optimizing both space and output. In July 2023, according to the USDA, vertical farming can increase crop yields by up to 70%. Moreover, advancements such as automation and IoT integration are enhancing aeroponic systems, boosting their precision and productivity. The market is further fueled by the rising consumer preferences for pesticide-free, organic-produced crops supported by aeroponic cultivation.

Challenges and Limitations

Despite significant advantages, aeroponic systems face technical challenges that require ongoing research and development. Power dependency represents a critical vulnerability, as system failures lasting 2-3 hours can cause irreversible root damage and complete crop loss. Backup power systems and redundant equipment increase installation costs but remain essential for commercial viability.

Nutrient solution management requires precise monitoring and adjustment, as imbalanced EC levels or pH fluctuations can rapidly impact plant health. Biofilm formation in misting lines poses contamination risks, necessitating regular cleaning protocols and antimicrobial treatments. Technical expertise requirements limit adoption among traditional farmers, highlighting needs for comprehensive training programs and simplified system designs.

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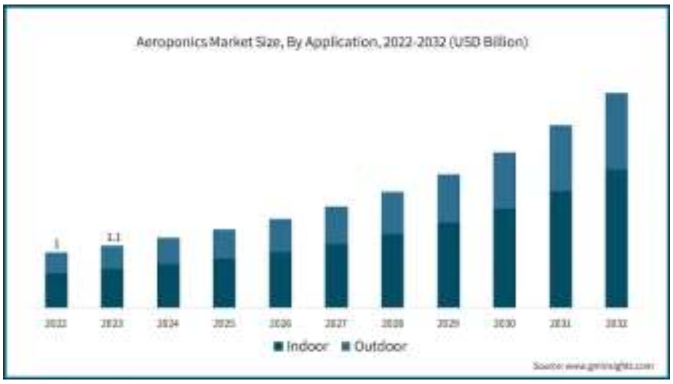
Root diseases, particularly *Pythium* and *Fusarium* species, can spread rapidly through aeroponic systems due to shared nutrient delivery networks. Preventive measures include UV sterilization, ozone treatment *and* biological control agents, adding complexity and operational costs to system management.

Future Directions and Innovations

Emerging technologies promise to address current limitations and expand aeroponic applications. Aeroponic systems accelerate plant growth rates, improve root oxygenation *and* significantly enhance water use efficiency, particularly when paired with both low- and high-pressure misting systems, indicating continued technological refinement and optimization.



Artificial intelligence integration enables predictive analytics for crop management, disease prevention *and* yield optimization. Machine learning algorithms analyze plant growth patterns, environmental data *and* nutrient uptake rates to develop customized growing protocols for specific cultivars. Blockchain technology facilitates traceability systems, ensuring food safety and quality verification from seed to consumer.

Vertical farming integration with aeroponic systems maximizes land use efficiency in urban environments, potentially producing 365 harvest cycles annually in climate-controlled facilities. Research initiatives explore plasma treatment applications for seed germination enhancement and pathogen control, while nanotechnology develops advanced nutrient delivery systems with improved absorption efficiency.

Conclusion

Aeroponics represents a paradigm shift in agricultural production, offering unprecedented efficiency in water utilization, space optimization *and* crop yields. The technology's integration with artificial intelligence, IoT sensors *and* precision agriculture principles positions it as a cornerstone of sustainable food production systems. While technical challenges and capital requirements present adoption barriers, ongoing research and market developments continue to improve system reliability and economic viability, making aeroponics an increasingly attractive solution for addressing global food security challenges.

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Herbal Gardens in Human Stress Management

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Stress is the body's reaction to challenge or demands. It can be affecting mood, sleep and overall health. Common causes of stress: work pressure, health issues and personal life matter etc. Too much stress can harm our body and mind. In today's fast and competitive world, stress has become a silent enemy of our health but nature always gives us solutions and one of them is Herbal Gardens.

What is an Herbal Gardens?

Herbal gardens are special spaces where different medicinal and aromatic plants are grown such as Tulsi, Mint, Aloe vera, Lavender and Jasmine etc. Grown at home, in schools, parks or hospitals. These plants are not only useful for curing various diseases but also play a major role in reducing stress and anxiety naturally. Herbal gardens are not just green spaces, but also natural therapy zones.

How to start your own herbal garden?

- Choose a sunny spot- balcony, backyard
- Choose easy to grow herbs like Mint, Tulsi, Lemon grass etc.
- Use plots or small containers if space is limited and care daily, water regularly and place in sunlight.
- Enjoy the fresh fragrances and natural beauty daily.

How herbal gardens help with stress?

Herbal gardens are not just green spaces, they are natural stress relievers. Smell of herbs like lavender or mint helps reduce anxiety.

Now let us see how herbal gardens help in stress management –

First, Act of gardening is a therapeutic. When we spend time with plants, watering them, touching the soil and watching them grow – it relaxes our mind and makes us feel peaceful.

Second, Many herbal plants release natural fragrances that have a calming effect. The fragrances of certain herbs like Lavender and jasmine has been proven to calm the nervous system, improve mood and promote sound sleep.

Third, Herbal gardens create a green and positive environment around us. Gardening itself is a form of therapy- it teaches patience, mindfulness and a sense of nurturing.

Conclusion: -

Herbal gardens represent a beautiful blend of traditional wisdom and modern science. In a world full of tension and digital distractions, they remind us of the healing power of nature. Herbal gardens is a simple way to improve mental well-being.

Herbal gardens create a healthy environment with a pleasant atmosphere and pure oxygen. It promotes mental clarity and emotional balance.

If anyone can grow herbal gardens, he can get great peace with small efforts .

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E-NAM (Electronic National Agriculture Market) and Its Influence on Farmers

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The Electronic National Agriculture Market (e-NAM) has been initiated by the Government of India in April 2016, which is a pan-India online trading platform aimed at computerizing agricultural marketing and integrating a common national market. Through linking Agricultural Produce Market Committees (APMCs) on an online platform, e-NAM enables transparent price discovery, diminishes the interference of intermediaries, and lowers transaction costs, hence enhancing farmers' income and market reach. The platform provides electronic bidding, unified licences, quality grading, and direct electronic payment. Although e-NAM has increased price realization, market transparency, and interstate trade opportunities, there are challenges such as low digital literacy, poor connectivity, and opposition from conventional intermediaries. The digital infrastructure should be strengthened, farmers trained, mandis and commodities expanded, and FPOs encouraged to reap its maximum benefits. In all, e-NAM can revolutionize agricultural marketing in India, empower farmers, and help the country achieve its national goal of doubling farmers' incomes.

Introduction

The Electronic National Agriculture Market (e-NAM) is a pioneering initiative of the Government of India in April 2016 to modernize and revamp the agricultural marketing system. It is a pan-India electronic trading platform that electronically links existing Agricultural Produce Market Committees (APMCs) to create a single national market for agricultural products. By bringing together several mandis in one online platform, e-NAM seeks to eliminate market fragmentation and offer farmers greater access to buyers from other states.

The mechanism fosters price transparency, curtails the control of middlemen, and lowers transaction costs via competitive online auctions. Meanwhile, it boosts efficiency through the ability of farmers to sell their crops beyond local markets, thus making interstate trade possible. With online payments and instantaneous sharing of information, e-NAM not only facilitates honest trade practices but also helps in the broader goal of doubling farmers' income and advancing "Digital India." As a whole, e-NAM marks an important step towards making agricultural marketing more transparent, efficient, and farmer-friendly in the nation.

Objectives of e-NAM (Electronic National Agriculture Market)

The main goal of e-NAM is to consolidate Agricultural Produce Market Committees (APMCs) from various states and form a single national market for agricultural commodities. Through this, it decreases the disjointedness of local markets and gives farmers access to a larger base of buyers outside their local mandis. Another significant objective is to allow real-time price discovery, in which prices are set openly on the basis of demand

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and supply so that farmers have the ability to make rational choices regarding where and when they sell what they produce.

The platform also aims for fair and transparent trading through the introduction of online bidding and e-payment systems, which cut down on corruption, price manipulation, and exploitation by middlemen. Moreover, e-NAM minimizes the involvement of middlemen, thus cutting down on transaction costs and ensuring that the farmer receives a larger share of the consumer price, ultimately enhancing their profitability.

In addition, the system encourages interstate trade by dismantling the customary restrictive state-level APMC barriers, enabling farmers to sell their crops to other-state buyers and hence expand market opportunities. Along with these, e-NAM encourages digitalization of agricultural marketing by familiarizing farmers with online trading platforms, registration formalities, and electronic payment facilities, thereby positioning agriculture with the objectives of the Digital India mission.

In general, the program aims to empower farmers by increasing their market coverage, strengthening their bargaining position, and raising their incomes while ensuring efficiency, transparency, and inclusiveness in the marketing of agricultural produce all over the nation.

Main Features of e-NAM

The e-NAM offers an online trading facility which could be accessed with ease through both web portal and mobile app, facilitating farmers and traders to engage in agricultural marketing remotely. Its key feature is the open auction system running through electronic bidding, thus ensuring competitive price discovery while minimizing the scope for manipulation.

The platform also comes with a single license, which facilitates buying and selling of commodities on several markets within a state or even across states, thus transcending the conventional hindrances. In a bid to expedite and secure transactions, payments are made electronically straight into farmers' bank accounts, thus eradicating delays and minimizing reliance on cash transactions. Also, e-NAM offers quality testing facilities in mandis for standardization and grading of farm produce, which not only leads to greater confidence between buyers and sellers but also allows farmers to get better prices for quality produce.

Impact on Farmers

Implementation of e-NAM has had a major impact on farmers by enhancing their market opportunities and income prospects. A prominent benefit is enhanced price realization, as farmers can now cross-check prices in different mandis and opt to sell the produce at most convenient rates. The system has also introduced increased market transparency in the form of electronic auctions, which minimize opportunities for exploitation by middlemen and facilitate fair competition among buyers.

By reducing the involvement of intermediaries, e-NAM has reduced transaction costs, freeing up farmers' time and resources. It has also provided access to countrywide markets, allowing farmers to sell their produce outside the local mandis and access buyers across states. Moreover, the availability of standardization and grading facilities has motivated farmers to concentrate on quality produce, thus ensuring better returns on their farm products.

Challenges

Although having numerous benefits, the e-NAM platform is also challenged in its implementation. There is limited digital literacy, particularly on the part of marginal and small farmers, which limits their capacity to access the full potential of the platform. Uncordial internet connectivity in most rural areas presents a big bottleneck in the process of making online transactions more seamless. Further, reluctance from traditional go-betweens, fearing loss of their grip on mandi operations, tends to hamper the implementation of the system. A lack of knowledge

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and inadequate training among farmers regarding how to use e-NAM effectively is still a concern, necessitating the need for improved extension support and capacity-building measures.

Way Forward

To achieve the full potential of e-NAM, rural digital infrastructure needs to be strengthened through ensuring dependable internet connectivity and availability of digital devices at remote locations. Periodic training and awareness programs should be organized to increase farmers' digital literacy and introduce them to the working of the platform. Increasing the coverage of e-NAM by connecting more mandis and adding more commodities will further enhance its performance. Moreover, encouraging Farmer Producer Organizations (FPOs) can enable small and marginal farmers to undertake collective bargaining, thus making them more powerful in the market and better negotiators.

Conclusion

The Electronic National Agriculture Market (e-NAM) can transform Indian agricultural marketing by ensuring transparency, efficiency, and improved price realization for farmers. Though there may be hurdles in the form of digital literacy, infrastructure deficiencies, and opposition from conventional intermediaries, these issues can be addressed with effective policy interventions and robust institutional backing. With increased awareness, robust digital infrastructure, and active participation of farmers, e-NAM can significantly improve the socio-economic status of the farming community and play a crucial role in achieving the national goal of doubling farmers' income.

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Role of Cooperatives in Strengthening Smallholder Farmers

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Smallholder farmers are central to agriculture and rural livelihoods in many developing countries, including India, yet they face challenges such as limited access to credit, markets, modern inputs, and technology. Cooperatives, as member-owned and democratically managed organizations, play a vital role in addressing these challenges by providing affordable financial services, collective input procurement, market access, value addition, technical support, risk sharing, and social empowerment. They enhance farmers' productivity, income, and resilience while promoting gender inclusion and youth participation. Despite challenges such as limited managerial capacity, weak infrastructure, and policy constraints, strengthening and expanding cooperative networks, including Farmer Producer Organizations (FPOs), can significantly empower smallholder farmers and contribute to sustainable agricultural development, improved rural livelihoods, and national food security.

Introduction

Smallholder farmers are the backbone of agriculture in many developing countries, including India, contributing significantly to food security, rural livelihoods, and the national economy. Despite their crucial role, these farmers often face multiple challenges, including limited access to credit, modern agricultural inputs, advanced technology, and reliable markets for their produce. In this context, cooperatives member-owned and democratically managed organizations serve as an important mechanism for empowering smallholder farmers. By aggregating resources, sharing information, and collectively accessing markets, cooperatives assist farmers in overcoming these limitations, raise productivity, increase income, and increase bargaining power in the agricultural supply chain.

Access to Credit and Financial Services:

Smallholder farmers can usually not access loans from formal banks because they lack collateral, which restricts their capacity to invest in seeds, fertilizers, machinery, and other farm inputs. Agricultural cooperatives fill this gap by offering low-cost credit, savings schemes, and insurance products specific to smallholders' needs. By providing financial services at reduced interest rates and with greater flexibility, cooperatives cut down farmers' reliance on moneylenders who charge excessive interest. For instance, dairy cooperatives such as Amul extend loans to their members for cattle purchase and dairy machinery, allowing farmers to increase production and enhance incomes.

Principal Roles of Cooperatives in Enhancing Smallholder Farmers

Collective Input Procurement:

Cooperatives allow farmers to buy agricultural inputs in large quantities, like seeds, fertilizers, pesticides, and machinery, at lower costs. Through aggregated demand, they not only reduce the cost of inputs but also provide timely supply of good quality products, which is important at peak cropping seasons. This group purchasing system enhances the bargaining power of smallholders and prevents delays that might impact crop production. Indian fertilizer cooperatives, for example, offer fertilizers at a subsidized price to their members, making them affordable and improving productivity.

Market Access and Fair Pricing:

One of the greatest benefits of cooperatives is that they ensure collective marketing of crops, which removes exploitation of farmers by middlemen. With cooperative marketing, smallholder farmers are able to access local, national, and even overseas markets where they can sell at reasonable prices. Farmer Producer Organizations (FPOs), say, sell fruits and vegetables directly to retail chains, eliminating intermediaries and making sure the farmers get a bigger chunk of the consumer price. It makes market linkages stronger and increases the income security of farmers.

Value Addition and Processing:

Cooperatives can run processing facilities for commodities like milk, fruits, grains, and vegetables to help farmers benefit from value addition and earn extra income. Farmers cannot sell raw products at cheap prices but can process them to produce marketable products like cheese, butter, jams, and packaged grains. Dairy cooperatives, for example, process milk into diverse products like cheese, butter, and yogurt, improving farmers' profitability and minimizing post-harvest losses.

Capacity Building and Technical Support:

Cooperatives play a critical role in the dissemination of knowledge by conducting training courses on innovative agricultural practices, organic cultivation, post-harvest handling, and climate-resilient methods. Such activities impart skills to farmers to adopt new technologies and enhance productivity. Through dissemination of knowledge and extension services, cooperatives enable smallholders to take well-informed decisions and respond to changing market and environmental trends.

Risk Sharing and Insurance:

It is naturally risky because of reasons like crop loss, pest attack, and market price variability. Cooperatives mitigate this risk by allowing farmers to share resources and take crop insurance schemes together. This risk-sharing reduces vulnerability at an individual level and acts as a cushion, helping smallholders rebound from unexpected loss without getting caught in debt traps.

Empowerment and Social Inclusion

In addition to economic gains, cooperatives encourage decision-making by groups, social empowerment, and inclusiveness among rural communities. Cooperatives provide forums through which women and the youth are actively engaged in governance and leadership. Women farmers especially get opportunities to be involved in cooperative management, decision-making, and accessing financial and technical resources that were not available before. Through promoting social inclusion, cooperatives enhance community unity and empower marginalized groups to enhance their livelihoods.

Advantages of Cooperatives to Smallholder Farmers

There are several economic, social, and technical advantages that cooperatives bring to smallholder farmers. On an economic level, cooperatives enhance income and lower costs through access to cheaper credit, purchase of inputs in bulk, and higher prices for products from collective marketing. Value addition and processing units enable farmers to get more money from their produce than selling raw materials at a low price. Socially, cooperatives empower underprivileged groups, such as women and the youth, by engaging them in decision-making and leadership positions, thus fostering inclusivity and community development. Technically, they promote knowledge transfer and capacity building via training on new farming methods, climate-resilient agriculture, organic farming, and post-harvest management. Generally, cooperatives enhance farmers' bargaining power, enhance resilience to market shocks, and support sustainable rural livelihoods.

Challenges Facing Cooperatives

Even with their advantages, cooperatives are confronted with a number of challenges that constrain their performance. Small cooperatives are often limited by limited financial and managerial capabilities, which constrain their ability to expand operations and offer full-range services to members. Weak access to markets, technology, and high-quality infrastructure limits competitiveness and efficiency. Weak governance, lack of transparency, and poor member participation constrain some cooperatives, sometimes resulting in mismanagement and corruption. Resistance to adopting new technologies or online tools by farmers may hold back modernization. Also, policy and regulatory constraints, such as delayed subsidies and cumbersome registration processes, occasionally hinder growth and sustainability. Meeting these issues is paramount to ensure cooperatives remain effective in supporting smallholder farmers.

Way Forward

To achieve the full potential of cooperatives, it is important to enhance their institutional, financial, and technical capacities. Offering training to cooperative leaders and members in areas of governance, financial management, marketing, and digital tools will increase efficiency and transparency. Increasing access to credit, new inputs, and processing infrastructure will give the smallholders the strength to enhance productivity and profitability. Encouraging the establishment of Farmer Producer Organizations (FPOs) and federations will increase collective bargaining, access to markets, and scalability of operations. Policy encouragement, including ease of registration, timely subsidization, and value addition incentives, will further empower cooperatives. Cooperatives can become a transformative force empowering smallholder farmers and enhancing rural livelihoods by overcoming present drawbacks and embracing new practices.

Conclusion

Cooperatives are an effective tool for empowering smallholder farmers by improving their access to finance, quality inputs, markets, technology, and vital social support systems. Through collective effort, such organizations allow farmers to gain increased productivity, earn improved prices for their crops, and develop insurance against farm risks like crop loss, price fluctuations, and climate unpredictability. Beyond economic returns, cooperatives support social equity, gender empowerment, and community development, which ensures that marginalized communities are actively involved in decision-making and sharing benefits from pooled resources. Strengthened existing cooperatives, promoting the establishment of new Farmer Producer Organizations (FPOs), and extending policy, technical, and infrastructural support can dramatically increase their reach and impact. On balance, cooperatives can play a transformative role in sustainable agricultural development, enhancing rural livelihood, and helping national food security and economic growth.

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Are Ethanol Blending and EVs Really the Solution to India's Pollution Problem?

J. Akshaykumar Badal

India has made substantial progress in its quest for cleaner air and lower carbon emissions most significantly by encouraging electric vehicles (EVs) and mandating ethanol blending in petrol (20% by 2025-26). Although these steps are laudable, a closer examination discloses that they may not be the final solution to India's pollution problem.

The broader ecosystem—from fuel production to industrial emissions—still suffers from non- stringent environmental norms, and pollution control at the source remains weak or altogether absent.

1. Ethanol Blending: A Water-Starving and Resource-Intensive Solution

The government's policy of blending gasoline with ethanol relies greatly on sugarcane, which in turn uses 1500–2000 litres of water per kg of yield. Blending ethanol into gasoline can certainly lower tailpipe emissions, but it also creates an environmental trade-off: high water use, monoculture farming, and soil degradation.

The plan demands over 1,000 crore litres of ethanol per year —and while grain-based ethanol is being explored, India lacks surplus agricultural feedstock to support such massive demands sustainably. In fact, no holistic life-cycle emissions study has been undertaken to analyse the actual carbon gains from ethanol blending for the Indian context.

2. EVs: Zero Tailpipe, But Not Zero Emissions

EVs are marketed as "zero-emission" vehicles, but that classification comes only from tailpipe emissions. Their manufacture and use still produce huge indirect emissions, particularly when:

- Lithium, cobalt, and nickel—critical battery materials—are extracted from the ground using environmentally destructive methods. Lithium mining alone takes almost 1.9 million litres of water per ton.
- India's power grid remains 70% coal-dependent, so EVs are, in most instances, running on fossil fuels.

Unless the grid is decarbonized and battery recycling facilities are bolstered, EVs only transfer the pollution from roads to power plants and mines

3. The Underestimated Players: Refineries, Fuel Stations, Fertilizer & Chemical Plants

Whereas transportation takes centre stage, some of India's most polluting industries run under weak or poorly implemented regulations, producing huge quantities of toxic gases without strong control mechanisms.

3.1 *Petroleum Refineries*

- India has 23 petroleum refineries, all of which release significant amounts of Sulphur dioxide (SO_2), nitrogen oxides (NOx), carbon dioxide (CO_2) and harmful volatile organic compounds (VOCs).
- Emission standards are superseded or poorly enforced, with few real-time checks. Often flaring and venting is underreported, causing air quality deterioration near refinery towns.

3.2 *Fuel Stations: The Missing Vapor Recovery Systems*

- India has more than 75,000 petrol pumps, the nation experiences huge evaporation losses of benzene, toluene, xylene, and other VOCs.
- In developed nations, Vapor Recovery Systems (VRS) are obligatory to recover fuel vapors at the time of underground tank refuelling at fuel station and terminal depots.

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In India, VRS are largely absent in many areas. Despite binding orders from the National Green Tribunal (NGT) and the Supreme Court (SC) mandating their installation, agencies are not prioritizing their implementation.

- This generates a poisonous micro-environment around fuel pumps, particularly in urban agglomerations, leading to chronic respiratory ailments and long-term cancer risk.

3.3 *Fertilizer and Chemical Industries*

- India's fertilizer factories, particularly urea and ammonia producers, emit large quantities of ammonia, carbon dioxide (CO_2) and nitrous oxide (N_2O).
- Most factories function with outdated pollution control machinery, and non-adherence to emission standards usually goes unnoticed.
- The chemical industry, particularly small and medium enterprises in industrial clusters, regularly lets out toxic gases and untreated effluents, usually without environmental clearance renewals.

4.Agriculture and Waste: Emissions from the Shadows

The agricultural sector accounts for 14% of India's GHG emissions, mainly through methane emissions from rice paddies and livestock and nitrous oxide emissions from fertilizers. Nevertheless, sustainable practices such as alternate wetting and drying in rice crop cultivation or using biofertilizers are not widespread.

Moreover, waste burning in urban areas, raw sewage, and landfill gases still emit methane and other poisonous gases—with minimal public investment in decentralized composting and waste-to-energy systems.

5. A Holistic Environmental Governance Call

While the shift to ethanol and EVs is crucial, their benefits are short-circuited without systemic reforms in other significant emission sectors. To effectively battle carbon emissions, India needs to:

Implement stricter emission standards and make real-time monitoring compulsory in petroleum, fertilizer, and chemical industries.

It should be mandatory to install VRS at all retail fuel stations, terminals, and chemical plants where necessary, with penalties imposed for non-compliance.

Upgrade industrial clusters with shared effluent treatment plants (CETPs) and pollution control retrofits.

Encourage sustainable agriculture, organic waste treatment, and grid decarbonization.

Conclusion: Beyond Tailpipes and Tanks

Ethanol blending and electric vehicles are just part of the solution to India's environmental crisis. Focusing exclusively on transportation emissions dangers ignoring the bigger, frequently filthier sectors that still keep polluting because there are weak norms and lax enforcement.

India needs to make a transition from end-of-pipe thinking to source-level intervention— reducing emissions where they are created, not merely where they can be seen.

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Assessing the Key Constraints to ICT Adoption in Agriculture

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ICT, or information and communications technology(s), is the infrastructure and components that enable modern computing. Although there is no single, universal definition of ICT, the term is generally accepted to mean all devices, networking components, applications and systems that combined allow people and organizations (i.e., businesses, non-profit agencies, governments and criminal enterprises) to interact in the digital world. When it comes to use ICT in agriculture then we called it as E-agriculture that is synonyms for ICT in Agriculture.

The application of Information and Communication Technology (ICT) in agriculture is increasingly important. E-Agriculture is an emerging field focusing on the enhancement of agriculture and rural development through improved information and communication processes. More specifically, E-agriculture involves the conceptualization, design, development, evaluation and application of innovative ways to use information and communication technologies (ICT) in rural domain, with a primary focus on agriculture. E-Agriculture is a relatively new term. The ICT used from sowing of seed to the plate of consumer.

All stakeholders of agriculture industry need information and knowledge about these phases to manage them efficiently. Any system applied for getting information and knowledge for making decisions in any industry should deliver accurate, complete, concise information n time or on time. The information provided by the system must be in user-friendly form, easy to access, cost-effective and well protected from unauthorized access. Information and Communication Technology (ICT) can play a significant role in maintaining the abovementioned properties of information as it consists of three main technologies. They are Computer Technology, Communication Technology and Information Management Technology. These technologies are applied for processing, exchanging and managing data, information and knowledge.

Apart from all these goods, it also has some critical constraints too that should be manage in such a manner to use optimum level of efficiency and effectiveness of ICT tools in agriculture. Some of most important factors are:

- Technology itself is not sufficient, a well-trained team is also required,
- Complex ICT or complex platforms are not necessarily essential and
- Data integrity and security.

Through this article, we try to cover whole in short, that there is dire need of considering these factors to reduce the resistance and suggest the optimization of ICT tools in efficient manner.

Introduction

ICT in agriculture is a demanding field focusing on the enhancement of agriculture and rural development. It involves applications of innovative ways to use ICT in rural domain. The up- gradation in ICT can be utilised for providing right information at right time and right place and services to the farmers, thereby facilitating a platform for more rewarding agriculture.

However, all the ICT initiatives are not empirical it is change with time, place & situation with disparities between localities in the level and quality of telecommunications, information and the effort of individuals, public and private organizations, and differentiated nature of demand of the farmers in different areas? Or in Lehman words, It's the matter of tailoring, not just a case of manufacturing. As we know very well, India is the country of variation for which we have dire need to tailored the need of agriculturist to facilitate them. The word tailored is used here in the sense of "Need based" action. As a result, there have been many successes, failures, lessons learned and experience gained, so far. While these steps are intended to address the needs of the agriculturist through ICT, their real usage and their ability to bring significant impact on the farm productivity and socio-economic development of the intended beneficiaries actually use the facilities provided for them fruitfully to meet their needs. The key problems in adoption of ICT in rural segments are ICTs "4A" Here, It is Accessibility, Availability, Affordability & the last one is the Accountability. Critical constraints in the usage of ICT's for farmers and their surroundings, as seen in the some of the ICT driven initiatives, Technology itself is not sufficient, a well-trained team is also required; Complex ICT or complex platforms are not necessarily essential; local factors such as the lack of adequate resources must be taken into account beforehand and Data integrity and security.

Thus, there is a need to understand as to how efficient the ICT initiatives are able to address the farmers need so that better solutions can be developed to address those constraints. The proposed research aims to study the past and present major ICT initiatives in agriculture. This paper attempted to try and better understand the ICT adoption issues involved and the barriers to effective ICT uptake for agriculture, agriculture development and rural viability.

Research Methodology

The study is based on analysis of secondary data collected from records/data of the extension institutes, the view of extensionists & from the websites of different ICT agencies like RML, M&M, BIORE & Agri.Tech etc. The collected data has been analyzed and interpreted with simple tools for sketch out the Recommendations.

Key Issues of ICT in Agriculture

This Paper discussed on key constraint for implementing the ICT in agriculture. Specifics comments and insights were collated under the following major groupings that moves around the 4A of ICT:

1. Communal Issues.
2. Capacity building initiatives
3. Policy beakers.
4. Adoption Barriers

1. Communal Issues

ICTs in rural have conventionally been "based on indigenous forms of storytelling, song and theatre, print media and radio." But the arrival of modern ICTs – especially mobile technology and the Internet – has changed the way information is shared and the speed of communication all over the continent. It has also reduced the cost of accessing information and new knowledge, and is creating many new opportunities in different sectors of rural economies, including agriculture.

Traditional media, such as radio, TV, print, and video, are still relevant communication channels for agriculture. Apart from email and websites, the use of which are becoming commonplace, even in the agricultural sector, modern ICT devices and applications used in agriculture now include computers, tablets, mobile phones, TV, satellites, office software, short messaging services (SMS),

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social media, geographical information systems (GIS), and drones Not all forms of ICTs are yet fully applicable to agriculture in the rural context. Some are more relevant than others based on factors like cost, accessibility, applicability, user profile, and so on.

Describing how to incorporate "community" into the ICT adoption process drop downed a long list of success and failures. Magnification brought to light the following issues and constraints:

a. Communal involvement before engaging in efforts to adopt (tailored) new technologies – ICT adoption is not an exception.

b. ICT should be empirical it is for Communities not just individuals. This dictates a more holistic view of the communities as prerequisite to identify the best fit, empower leaders to effectuate them ensure relevant local content.

c. Strong leadership from the community is essential for the success of any ICT project. Undertaking and taking on board the key requirement for users in terms of end user skills, motivation and their realties in terms of access must be factored into the ICT adoption process.

d. ICT will not affect the tradition of the rural communities. Rather they will introduce new methods of doing the same traditional activities and/or enable new activities.

2. Capacity building initiatives

This point discusses about how to customize ICT to be user friendly (research) and how to bind with training, education and research. Training and Research focused on the following issues:

a. Problem assessment has not done properly to identify solutions for effective adoption of technological innovation including ICT.

b. Compulsion of pre requisite knowledge leads to obstacle for ease of doing.

c. Use of simpler technologies may get better results, can take projects forward and trigger learning that leads to adopting more advanced ICT.

d. Consideration of users after use response to counter the issue with the coming technology.

3. Policy breakers

The country like India, where the economy is depend on agriculture & country has huge pressure to meet the demand & supply of food for their drastically increasing population for which the government prioritized the agriculture, this is the one side on other hand, governments today have no choice but to prioritize agriculture and rural viability as the only sustainable solution to the current, explosive rural migration, the need for ensured food security, food quality and urgency to minimize environmental abuse. With that noted the following were outlined for consideration and action:

a. ICT infrastructure for rural areas must be part and parcel of all national infrastructure planning and programs.

b. Utilization of ICT for strengthening the linkages between agriculture policy, research and extension institutions, communities and individuals is a political issue as well as an organizational option. Encompassing digital inclusion can have tangible benefits including a favourable ICT impact on productivity, GDP and quality of life. This is especially important for rural communities during the current generational and technological transition.

c. The need for Public Private Partnership (PPP) to alleviate funding and resource scarcities for investments in physical and human capital.

d. It is governmental responsibility to ensure linking of ICT adoption in -

- National policies, long term strategies and universal involvement.

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- Mainstream thinking concerning digital inclusions.
- Professional bodies, NGOs, private initiatives, international collaborations, community responsibilities influencing thinking.

4. ICT Adoption Barriers

The following lists several – not necessarily specific to agriculture or rural communities. They

include –

a. Improper database management system between the apex ICT developers because of that there is not any specific network by the user can opt the best fit.

b. The lack of physical and human resource infrastructure which was repeatedly cited as a major impediment. Comments identifying wireless connectivity as an alleviating factor for example did not contribute to the understanding of this issue since wireless facilities need infrastructure as well. Infrastructure was related to technology in general.

c. Too much innovation can be an obstacle by blocking the use of older technologies which can often be more effective and/or by imposing an unacceptable cost and it leads to deteriorate the accountability of technology developers & the users.

d. ICT adoption based on working within communities takes longer in many cases because of the lack of understanding and awareness of the needs and challenges of small-scale farmers, lack of understanding what ICT can do including unexpected deviations from initials farmer and community expectations.

e. Ensuring leadership within the political and governmental environment.

f. Developing leadership and agents of change at all levels including communities. Sharing ICT adoption funding including public/private partnership. Sharing details of successful projects including business opportunities and their benefits.

AgriNet: An Initiative by Government

Agriculture Network Information Centre has to be formed for providing internet access to quality, authoritative agriculture information, and specialized reference services. In this we can use technologies like satellite remote sensing (SRS) which will help in mapping and monitoring features and processes on earth's surface while Geographical Information System (GIS) stores, retrieves, analyses, and displays spatial a non-spatial attribute data in a computer to support decision-making. Seamless integration of GIS, SRS, GPS etc. Holds the key for effective utilization of spatial technologies to solve agriculture problem. Unlike most science and technology disciplines, agriculture has a mechanism for distilling and distributing research to those who need it.

Following objective can be made by this AgriNet:-

a. It can strengthen agriculture research and accelerate technology transfer through establishing regional network on agriculture and allied disciplines, particularly among agriculture research and extensions centres, professionals, policy advisors and stakeholders.

b. To provide inputs for developing regional policies, strategies and programmers, primarily through developing networks in the crop, livestock and fisheries sectors and for efficient utilization/management of soil, water and other resources.

c. To promote new and innovative techniques and systems in agriculture include production, post-harvest and food processing.

d. To facilitate collaborative studies on agriculture marketing and distribution systems, harmonization of agriculture related standards, promotion of agricultural trade, food security, and risk and disaster management agriculture.

e. To facilitate and undertake collaborative capacity building programmers in agriculture and allied sectors with focus on skill development and research in frontier areas.

f. To collate and disseminate information for agricultural advancement in the region.

Recommendations

The recommendations for the identification of key constraint in use of ICT along with

initiative by government to facilitate the users. ICT enabled Information Systems for Agriculture

Development is straightforward. They were concentrated mainly on the need to

- Focus and consolidate all national and public ICT policies, budgets and investments for agriculture and rural sector.
- Involve all ICT stake holders in setting of the technology commercialization guideline and the measures needed to attain the successful transfer of these technologies.
- Strengthen the "Agriculture technology management" curriculums in the formal and informal educational and training programs even at school level too.
- Focus ICT training for teachers/researchers/extension and farmers on practical implementations.
- Link village knowledge centres and agri-clinics to farmer's needs. Where possible involve unemployed university graduates in this activity.
- Assurance for the 4A (Accessibility, Availability, Affordability & Accountability for technology) of ICT at grass root level.

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Year-Round Floral Magic: Designing Gardens That Never Sleep

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Designing a garden that maintains color, texture, and life throughout the year requires strategic planning, plant diversity, and seasonal foresight. A "never-sleeping" garden integrates structural evergreens, seasonally blooming perennials, ornamental shrubs, bulbs, and grasses that collectively sustain visual appeal and ecological function across all seasons. This approach combines principles of succession planting, microclimate manipulation, and ecological design to achieve year-round aesthetics and biodiversity. Proper soil management, maintenance scheduling, and the use of pollinator-friendly species ensure long-term sustainability and continuous interest. Such landscapes not only enhance beauty but also contribute to urban ecology and environmental resilience.

1.Introduction

A year-round flowering garden represents the harmonious blend of **horticultural science and artistic expression**, designed to offer continuous visual and ecological value throughout all seasons. Unlike conventional gardens that emphasize spring or summer displays, a four-season garden integrates **plant succession, ecological diversity, and structural design** to maintain color, texture, and form every month of the year (Kingsbury, 2016). Such gardens are rooted in the principle of **phenological sequencing** understanding how plants transition through their life cycles in response to seasonal changes. By aligning plant choices with climatic cues such as temperature, daylight length, and soil moisture, designers can sustain an evolving palette that mirrors nature's rhythm (Hitchmough, 2017). The use of evergreen foliage, ornamental bark, fruiting shrubs, and seedheads extends aesthetic appeal beyond flowering periods, ensuring year-round interest (Dirr, 2019). Furthermore, these landscapes play an important **ecological role**, providing nectar and shelter for pollinators, supporting soil organisms, and improving urban microclimates (Proietti, Meijer, & Heuvelink, 2022). The concept of the "garden that never sleeps" thus merges functionality with sustainability transforming outdoor spaces into living systems that evolve with the seasons while minimizing environmental impact.

2. Principles of Year-Round Design

Creating a garden that offers continuous bloom and vitality requires strategic planning based on plant behavior, structural diversity, and site-specific conditions. The core principles guiding such design include succession planting, layered planting structure, microclimate utilization, and maintenance for continuity. Each principle complements the others, ensuring that both biological and aesthetic processes remain active throughout the year.

2.1 Succession Planting

Succession planting is the deliberate sequencing of species to ensure uninterrupted bloom and foliage display across the seasons. It involves selecting plants with overlapping flowering periods so that as one fades, another reaches its peak. For example, early spring bulbs such as *Crocus vernus* and *Narcissus pseudonarcissus* are followed by spring perennials like *Primula vulgaris* and *Helleborus orientalis*, which in turn give way to summer performers such as *Echinacea purpurea* and *Salvia nemorosa* (Floret Flowers, 2018).

Autumn interest can be sustained using *Aster novi-belgii*, *Sedum spectabile*, and ornamental grasses, while winter color and structure come from *Hamamelis mollis*, *Cornus alba*, and evergreen groundcovers (Kingsbury, 2016). The goal is to choreograph seasonal transitions—each plant taking its turn in the spotlight to produce an evolving tapestry of form and color.

From a management perspective, succession planting also improves **pollinator availability**, ensuring that bees and butterflies find forage across extended periods (Hitchmough, 2017). Additionally, the strategy distributes maintenance demands more evenly through the year, reducing peak labor intensity in any single season.

2.2 Layered Planting Structure

Layered planting mimics the **vertical stratification** found in natural ecosystems—comprising trees, shrubs, perennials, bulbs, and groundcovers. This structural complexity enhances spatial depth, biodiversity, and visual coherence (Dirr, 2019).

- **Canopy layer (trees)** provides height, shade, and seasonal color through blossoms or autumn foliage (e.g., *Acer palmatum*, *Magnolia × soulangeana*).
- **Shrub layer** offers intermediate structure and texture; species like *Hydrangea paniculata* and *Viburnum tinus* bridge gaps between woody and herbaceous layers.
- **Herbaceous layer** contributes color diversity and dynamic movement, while **bulbs and groundcovers** fill voids and suppress weeds.

Combining evergreens with deciduous plants ensures that when flowering ceases, foliage, stems, or bark continue to sustain visual interest (Hitchmough, 2017). Furthermore, layered designs support ecological functions such as habitat creation, soil stabilization, and efficient moisture use through canopy shading and root-zone stratification.

2.3 Microclimate Utilization

Microclimates localized variations in temperature, light, and humidity—are crucial for extending bloom periods and enhancing plant performance. South- or west-facing walls absorb heat and radiate it at night, creating warmer niches that allow tender perennials or late-flowering species to thrive (Proietti, Meijer, & Heuvelink, 2022). In contrast, shaded north-facing areas are ideal for woodland or moisture-loving plants like *Hosta* and *Ferns*, which provide lush greenery even in low-light conditions.

Windbreaks, hedges, and water features also modify local conditions, mitigating frost, conserving soil moisture, and stabilizing temperature fluctuations (Dirr, 2019). Gardeners in cooler regions can use **cold frames, cloches, or mulching** to extend flowering seasons, while those in warmer climates can utilize shade sails and strategic planting to buffer heat stress. Thoughtful microclimate manipulation transforms challenging sites into diverse, high-performing plant zones.

2.4 Maintenance for Continuity

Consistent maintenance ensures the garden's longevity and balance across seasons. Practices such as deadheading encourage repeat flowering in perennials like *Salvia* and *Rosa* species, while seasonal pruning enhances air circulation and rejuvenates shrubs. Mulching and compost incorporation improve soil fertility, moisture retention, and root insulation (RHS, 2020).

Dividing crowded perennials every 3–5 years prevents decline in vigor and maintains proportionality within planting compositions. Winter care involves removing diseased debris to reduce pest incidence and safeguarding tender species with organic mulches. Maintenance also includes periodic redesign replacing underperforming species with varieties better suited to evolving climatic conditions. This adaptive management approach ensures that the garden remains both visually engaging and ecologically stable throughout the year.

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3. Seasonal Design Strategies

A garden that maintains interest through all four seasons must be carefully orchestrated to highlight different plant groups as the year unfolds. Each season contributes its own palette of colors, textures, and ecological interactions. The key to success lies in strategic plant selection, succession planning, and intentional contrast between dormant and active elements (Kingsbury, 2016; Dirr, 2019).

3.1 Spring Awakening

Spring marks the **rebirth of the landscape**, transforming the garden from dormancy to vibrant life. The early months often cold and unpredictable demand resilient species capable of emerging through frost and low soil temperatures. Bulbous plants such as *Tulipa gesneriana*, *Narcissus pseudonarcissus*, and *Crocus vernus* herald this renewal, offering bright colors and fragrance at a time when few other species bloom (Dirr, 2019).

Helleborus orientalis (Lenten rose) and *Pulmonaria officinalis* (lungwort) add early-season texture and nectar sources for pollinators awakening from hibernation (Hitchmough, 2017). The inclusion of *Primula vulgaris* (primrose) enhances continuity between bulbous and herbaceous phases, maintaining a seamless floral display.

Designers often combine early-blooming bulbs beneath deciduous trees, allowing flowers to receive maximum sunlight before the canopy leafs out. Groundcovers such as *Vinca minor* and *Ajuga reptans* stabilize soil while adding contrasting foliage hues. Together, these layers create a **living mosaic** that reflects both renewal and ecological synergy.

3.2 Summer Splendor

Summer is the **climactic crescendo** of the garden year, characterized by full foliage, bold blooms, and maximum biomass. Perennials such as *Rudbeckia hirta*, *Echinacea purpurea*, and *Salvia nemorosa* dominate the landscape with radiant yellows, purples, and pinks (Floret Flowers, 2018). Their extended flowering periods ensure sustained color from early to late summer, while **deadheading** stimulates secondary blooms and maintains tidiness.

Annuals such as *Zinnia elegans*, *Cosmos bipinnatus*, and *Petunia hybrida* can be succession-sown every few weeks to bridge gaps between perennial flowering cycles. Ornamental grasses—like *Miscanthus sinensis* and *Pennisetum alopecuroides* add movement and texture, softening transitions between color blocks (Kingsbury, 2016).

Incorporating flowering shrubs such as *Hydrangea paniculata* and *Buddleja davidii* enhances the **vertical dimension** and supports butterfly populations through nectar availability. Proper irrigation and mulching are essential to sustain the high metabolic activity of plants during this season, ensuring vigor and preventing stress-related dieback.

3.3 Autumn Radiance

Autumn is a period of **maturity and transformation**, where warmth in hue replaces the freshness of spring and summer. The interplay of golden, crimson, and russet tones signals both beauty and biological preparation for dormancy. Late-blooming perennials such as *Aster novae-angliae* (New England aster), *Sedum spectabile* (stonecrop), and *Chrysanthemum indicum* maintain color well into cooler months, attracting pollinators seeking final nectar sources (Kingsbury, 2016).

Shrubs such as *Viburnum opulus* (guelder rose) and *Ilex aquifolium* (holly) extend ornamental interest through **berries and foliage persistence**, providing both aesthetic contrast and wildlife food (Hitchmough, 2017). The inclusion of ornamental grasses like *Calamagrostis acutiflora* contributes vertical structure and golden plumes that persist into winter.

This season is also a time for **ecological stewardship**: leaving seedheads uncut supports birds and beneficial insects, while allowing natural decay recycles nutrients into the soil. Strategically placed deciduous trees such as *Acer palmatum* and

Liquidambar styraciflua create striking color backdrops, framing perennial borders with seasonal drama (Dirr, 2019).

3.4 Winter Structure and Subtlety

Winter, though subdued, possesses its own **aesthetic vocabulary of form, texture, and tone**. When flowers retreat, the garden's framework—bark, stems, seedheads, and evergreens comes to the forefront. *Cornus alba* (red-stem dogwood) introduces vibrant stem color, while *Betula utilis var. jacquemontii* (Himalayan birch) adds architectural elegance through stark white bark (Dirr, 2019).

Hamamelis mollis (witch hazel) blooms in midwinter, defying the season with fragrant yellow flowers that brighten dormant landscapes. Evergreen species such as *Buxus sempervirens* and *Ilex crenata* maintain structure and continuity, serving as anchors amid bare perennials.

Frost, snow, and low winter light can enhance textures highlighting ornamental grasses, sculptural seedheads, and the geometry of pruned shrubs. In well-designed gardens, winter becomes not a void but a **canvas of serenity**, reflecting the interplay between permanence and transience (Hitchmough, 2017). The season's quiet beauty completes the cyclical narrative of the year-round garden.

4. Ecological and Aesthetic Benefits

Beyond their ornamental value, year-round gardens function as **integrated ecosystems** that nurture biodiversity, regulate microclimates, and enhance environmental resilience. The use of native and pollinator-friendly species supports bees, butterflies, and birds throughout the year, providing sequential sources of nectar, pollen, and shelter (Hitchmough, 2017). Groundcover diversity also promotes soil health by reducing erosion, improving infiltration, and fostering beneficial microbial activity.

Perennial-based designs, with their deeper and denser root systems, contribute to carbon sequestration and reduce the need for frequent replanting, aligning ornamental gardening with sustainability goals (Proietti, Meijer, & Heuvelink, 2022). In urban and peri-urban settings, year-round gardens mitigate heat islands and buffer temperature extremes, improving local microclimates and air quality (Dirr, 2019).

From an aesthetic and psychological perspective, the constantly evolving palette of color, texture, and form offers **emotional restoration** and seasonal mindfulness (RHS, 2020). The visual rhythm emergence in spring, vibrancy in summer, warmth in autumn, and calm in winter nurtures a sense of connection between humans and natural cycles. Thus, a garden that never sleeps is not merely decorative; it is a living, dynamic organism that celebrates continuity, adaptation, and ecological harmony across the year.

5. Conclusion

A garden that "never sleeps" is both a visual and ecological triumph. Through thoughtful plant selection, seasonal layering, and adaptive maintenance, it is possible to create living art that evolves across time. Integrating ecological principles with aesthetic sensibility transforms gardens from static landscapes into dynamic, sustainable habitats (Dirr, 2019). Such designs not only celebrate seasonal rhythm but also restore balance between human creativity and natural cycles.

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A Probabilistic Gaussian–Gamma Framework for Rainfall Variability Assessment in Drought-Prone Regions of North East India

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Rainfall variability is one of the most significant climatic factors influencing agricultural productivity and water resource management in monsoon-dependent regions. North East India, despite being one of the wettest parts of the world, often experiences highly uneven rainfall distribution, resulting in localized droughts and prolonged dry spells. Such variability directly impacts rain-fed agriculture, soil moisture availability, and crop yield stability. This article presents a theoretical exploration of a Probabilistic Gaussian–Gamma Framework for assessing rainfall variability in the drought-prone areas of North East India. The framework integrates the Gaussian distribution, suitable for normally distributed rainfall, with the Gamma distribution, which captures skewed and extreme rainfall events. By combining these two probabilistic approaches, the model offers a more comprehensive representation of rainfall behavior, providing valuable insights for agricultural planning, drought preparedness, and climate-resilient farming systems across North East India.

Introduction

North East India (NEI) is characterized by remarkable climatic diversity, complex topography, and a predominantly agrarian economy. The region, comprising states such as Assam, Meghalaya, Nagaland, Manipur, Mizoram, Tripura, and Arunachal Pradesh, contributes significantly to India's agricultural production yet remains highly vulnerable to climatic variability. Although NEI receives abundant rainfall, ranging from 1500 mm in certain valleys to over 10,000 mm in the hill slopes of Meghalaya, its spatial and temporal irregularity has emerged as a critical challenge for the agricultural sector. Agriculture in NEI is largely rain-fed, with over two-thirds of the cropped area dependent on monsoon rainfall. However, the monsoon's erratic nature, characterized by delayed onset, premature withdrawal, and uneven intra-seasonal distribution, often leads to both flooding and droughts within the same season. In recent decades, localized meteorological droughts have been reported in parts of Assam, Nagaland, and Manipur, adversely affecting the region's major crops such as rice, jute, pulses, and oilseeds. The unpredictability of rainfall not only influences crop yields but also affects soil moisture balance, irrigation scheduling, and pest incidence. Given this climatic uncertainty, understanding the probabilistic structure of rainfall is vital for improving agricultural planning and drought management. Deterministic models, which rely on fixed values and averages, often fail to represent the random and skewed nature of rainfall. Probabilistic models, in contrast, describe rainfall as a stochastic process, accounting for variability and uncertainty. The Gaussian–Gamma mixture framework provides an advanced probabilistic approach that captures both the normal and extreme components of rainfall distribution, making it particularly suitable for analysing the climatic behavior of North East India.

Rainfall Variability and Agricultural Vulnerability in North East India

The hydroclimatic setting of North East India is governed by the southwest monsoon, which contributes nearly 80% of the region's annual rainfall. The combination of mountainous terrain and shifting weather systems produces a highly uneven rainfall pattern across short spatial scales. For example, while the southern slopes of Meghalaya

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receive rainfall exceeding 10,000 mm annually, districts such as Nagaon or parts of Karbi Anglong in Assam often face seasonal droughts despite their proximity to humid zones.

Such irregularity has serious implications for agriculture. The primary rain-fed crop, sali rice, is particularly sensitive to moisture stress during its reproductive phase. Even a brief dry spell during the monsoon can lead to significant yield reduction. Crops like pulses, maize, and vegetables also suffer from erratic rainfall and unpredictable soil moisture conditions. In upland and jhum (shifting cultivation) areas, insufficient pre-monsoon showers delay land preparation and sowing, while heavy post-monsoon rains cause soil erosion and nutrient loss. In this context, a probabilistic approach to rainfall assessment can help quantify the likelihood of drought occurrence and rainfall deficits. Understanding rainfall in terms of probability distributions rather than averages provides more realistic insights for crop calendar planning, irrigation scheduling, and drought risk management.

Theoretical Basis of the Gaussian–Gamma Framework

The Gaussian–Gamma framework is based on the principle that rainfall data typically exhibit two dominant statistical behaviours—moderate variability around a mean (which can be modelled using a Gaussian distribution) and pronounced asymmetry or skewness due to extremes (best captured by a Gamma distribution). By combining these two distributions, the framework provides a comprehensive representation of rainfall variability.

The **Gaussian (Normal) distribution** is expressed as:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

where “μ” is the mean rainfall and “σ” the standard deviation. This model is appropriate for representing consistent rainfall patterns where deviations from the mean are symmetric.

The **Gamma distribution**, on the other hand, is given by:

$$g(x) = \frac{1}{\Gamma(k)\,\theta^k}\, x^{k-1}\, e^{-x/\theta}$$

where “k" is the shape parameter and "θ" the scale parameter. The Gamma model is asymmetric and defined only for positive rainfall values, making it ideal for representing data with long right tails — typical of rainfall datasets in monsoon regions.

By combining these, the **Gaussian–Gamma mixture model** can be defined as:

$$h(x) = w \cdot f(x) + (1 - w) \cdot g(x)$$

where $w(0 \le w \le 1)$ denotes the weighting factor that determines the contribution of each distribution. This hybrid model thus captures both the regular and extreme behavior of rainfall in a single probabilistic framework.

Conceptual Methodology

In a theoretical application, the framework involves several stages. First, long-term rainfall data are compiled for multiple stations across North East India to ensure spatial representation. The data are then analyzed for statistical properties such as mean, variance, skewness, and kurtosis. The Gaussian and Gamma components are fitted separately, and their parameters (μ, σ, k, θ are estimated using Maximum Likelihood Estimation (MLE) or Bayesian inference methods. The final step involves combining these components through an optimal weighting factor w, determined by minimizing the error between the observed and modelled distributions. The resulting mixture model provides a probabilistic representation of rainfall occurrence and intensity. From this model, probabilities of rainfall deficit or excess can be derived, which in turn can be linked to drought indices, crop water requirements, and rainfall reliability for agricultural planning.

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Applications and Agricultural Significance

The Gaussian–Gamma probabilistic framework offers substantial utility in the agricultural context of North East India by providing a systematic and quantitative understanding of rainfall variability. Its applications extend to several key areas:

Drought Assessment and Risk Mitigation:

The model enables the estimation of probabilities for rainfall deficits and prolonged dry spells, thereby facilitating the identification of drought-prone regions. Such information is critical for early warning systems, targeted drought mitigation strategies, and contingency planning in agriculture.

Optimized Crop Planning:

Probabilistic rainfall projections derived from the framework can inform the timing of sowing, transplanting, and harvesting activities. This supports the selection of crop varieties suited to expected moisture conditions, enhancing yield stability and reducing the risk of crop failure.

Efficient Water Resource Management:

By quantifying the likelihood and severity of dry periods, the framework assists in the scheduling and allocation of irrigation resources. This ensures optimal use of limited water supplies and contributes to sustainable watershed management.

Enhancement of Agrometeorological Advisory Services:

Integration of the Gaussian–Gamma model into agrometeorological advisory systems can improve the reliability of weather-based advisories. Farmers benefit from probabilistic guidance on rainfall variability, enabling informed decisions regarding crop management, fertilizer application, and pest control.

Policy and Planning Support:

The probabilistic outputs of the model provide a scientific basis for agricultural policy formulation, including the design of crop insurance schemes, allocation of drought relief funds, and prioritization of resource management interventions.

Spatial Planning and Climate Resilience:

When combined with GIS and remote sensing data, the framework can produce spatially explicit maps of rainfall probability, drought risk, and moisture reliability. Such maps are valuable for regional agricultural planning, disaster risk reduction, and the development of climate-resilient farming systems.

In summary, the Gaussian–Gamma framework not only enhances the understanding of rainfall variability but also directly supports decision-making in agricultural planning, resource management, and climate adaptation initiatives across North East India.

Conclusion

The Probabilistic Gaussian–Gamma Framework offers a theoretically sound and practical approach for understanding rainfall variability in North East India’s drought-prone regions. By integrating two complementary probability distributions, the model effectively captures both normal and extreme rainfall behavior, offering a nuanced understanding of climatic variability. For agriculture, this framework holds immense potential in improving drought forecasting, crop planning, and climate adaptation strategies. As rainfall becomes increasingly unpredictable under changing climatic conditions, probabilistic models such as the Gaussian–Gamma mixture will play a vital role in ensuring sustainable agricultural development and food security in North East India.

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From Farm to Market: Leveraging PPPs and Contracts for Food Security

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Introduction

Food security goes beyond producing enough food - it is about ensuring that food is accessible, affordable, and nutritious for everyone. In many parts of the world, especially in developing countries, farmers grow abundant crops yet struggle to bring them to the market place. Poor infrastructure, lack of cold storage, fluctuating prices, and weak bargaining power often leave them vulnerable. As a result, while millions of farmers remain trapped in poverty, consumers in urban areas face rising food costs and inconsistent supply. This paradox highlights the urgent need for new models that strengthen the entire agricultural value chain - from seeds in the soil to food on the table. Two promising strategies have gained global attention: contract farming and public-private partnerships (PPPs).

Contract farming creates direct agreements between farmers and agribusiness companies, guaranteeing markets, prices, and technical support. This reduces risk for farmers and ensures companies have reliable supply. Public-private partnerships (PPPs) bring together governments, private investors, and sometimes development agencies to finance and manage critical infrastructure like irrigation systems, storage facilities, transport networks, and processing units.

Together, these approaches can transform agriculture into a more inclusive, profitable, and resilient sector. They not only improve farmers' livelihoods but also enhance national food security by reducing post-harvest losses, stabilizing supply chains, and encouraging investment in modern technologies.

What are PPPs?

Public-Private Partnerships (PPPs) are collaborative agreements between governments and private sector players designed to deliver agricultural services, infrastructure, and innovations. Instead of the government working alone, PPPs share risks, responsibilities, and investments with private companies to strengthen the agricultural sector.

Importance of PPPs in Agriculture:

- ✓ Agriculture in many countries suffers from low investment. PPPs bring in private capital for infrastructure like irrigation, cold storage, processing units, and logistics.
- ✓ Private firms introduce modern farming technologies, while governments ensure accessibility for small farmers.
- ✓ PPPs help farmers move from raw production to processing, packaging, and exports.
- ✓ By improving productivity and reducing post-harvest losses, PPPs strengthen food availability and affordability.

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Types of PPP Models:

1) **Infrastructure PPPs** – Investments in irrigation, storage, and roads (e.g., cold chain networks).
2) **Service Delivery PPPs** – Extension services, training, and technical support for farmers.
3) **Market-Oriented PPPs** – Creating direct market linkages and export opportunities.
4) **Research & Innovation PPPs** – Joint R&D for new crop varieties, biotechnology, and climate-smart practices.

Examples of PPPs in Agriculture:

- **Nigeria's Staple Crop Processing Zones (SCPZs):** Government partners with private investors to set up processing plants near production areas, reducing transport costs and food losses.
- **Kenya's PPP Irrigation Schemes:** Boost horticultural production for domestic and export markets.
- **India's Mega Food Parks:** Joint government-private investment in processing, warehousing, and logistics for farm produce.
- **Global Example - FAO-led PPP initiatives:** Partnering with corporations like Nestlé and Unilever to promote sustainable sourcing and smallholder integration.

Challenges of PPPs:

1. Unequal Benefit Distribution

- Large agribusinesses may gain most benefits, while smallholders are left out.
- Rural poor may not access new infrastructure if costs are high.

2. Governance and Transparency Issues

- Corruption, weak regulations, or unclear roles can derail projects.
- Lack of accountability may reduce farmer trust.

3. Financial and Sustainability Risks

- PPP projects depend on both government and private investment—if either side fails, projects collapse.
- Political instability or policy shifts can discourage private investors.

4. Exclusion of Vulnerable Groups

- Women, landless laborers, and marginal farmers may be overlooked in PPP planning.
- Projects may prioritize export crops or cash crops over local food needs.

5. Capacity Gaps

- Many governments and farmer groups lack the expertise to manage complex PPP contracts.
- Mismatch between private profit motives and public welfare goals can lead to conflicts.

Why PPPs Matter for Food Security:

- Reduce post-harvest losses (currently up to 30–40% in some regions).
- Improve storage and processing, ensuring year-round food availability.
- Strengthen rural economies through job creation and market access.
- Enhance resilience to climate change via modern irrigation and technology adoption.

What Is Contract Farming?

Contract farming is a system where farmers and buyers (agribusiness firms, food processors, or exporters) enter into a formal agreement before production begins. The contract typically specifies:

a) Crop/commodity type to be produced,
b) Quantity and quality standards,
c) Price to be paid, and

d) Support provided by the buyer (inputs, training, credit, or technical assistance).

It essentially transforms farming into a market-driven activity, reducing uncertainty for both farmers and buyers.

Benefits of Contract Farming:

For Farmers: -

- Assured market and price stability.
- Access to high-quality seeds, fertilizers, and new technologies.
- Reduced marketing risks and costs.
- Technical training and extension services from companies.

For Buyers (Companies):-

- Consistent and reliable supply of raw materials.
- Better control over product quality and standards.
- Reduced procurement costs (no middlemen).
- Stronger relationships with local producers.

Challenges of Contract Farming

1. Power Imbalances

- ❖ Large companies often have stronger bargaining power, which can lead to unfair contract terms.
- ❖ Smallholders may feel "locked in" with little negotiation capacity.

2. Price & Quality Disputes

- ❖ Companies may reject produce citing poor quality, leaving farmers with losses.
- ❖ Farmers may "side-sell" (sell to other buyers) if open-market prices rise, breaking trust.

3. Legal and Enforcement Issues

- ❖ In many countries, there are weak legal frameworks to enforce contracts.
- ❖ Farmers may lack literacy or awareness to fully understand contract terms.

4. Farmer Dependency

- ❖ Reliance on one buyer makes farmers vulnerable if companies withdraw or change policies.
- ❖ Over-specialization (e.g., only growing one contracted crop) reduces crop diversity and increases risks.

5. Social Concerns

- ❖ Small and marginal farmers may be excluded if companies prefer large, organized farmers.
- ❖ Unequal benefits can increase rural inequality.

Conclusion:

Contract farming and public-private partnerships (PPPs) are powerful tools that can reshape modern agriculture. Contract farming provides farmers with secure markets, access to inputs, and stable incomes, while PPPs bring much-needed investment, infrastructure, and innovation into rural economies. Together, they strengthen the agricultural value chain from production to processing and distribution, reducing food losses and making food more accessible and affordable.

However, these models are not without challenges. Power imbalances, governance gaps, and the risk of excluding smallholders highlight the need for careful design and regulation. Governments must ensure fair contracts, transparent partnerships, and

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policies that protect farmer interests. At the same time, companies must adopt ethical practices and include small farmers, women, and youth in their supply chains.

When implemented inclusively, contract farming and PPPs can transform agriculture from a subsistence activity into a sustainable, market-driven sector. More importantly, they can help achieve the larger goal of food security—ensuring that every household has reliable access to safe, affordable, and nutritious food.

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Climate Resilient Agriculture: For an Eco-Friendly Future

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Climate-resilient agriculture involves all the techniques and strategies to help farmer tackle the negative impact of climate change on their crop production. Globally, India ranks second in farm outputs but is also highly vulnerable to the challenges of climate change. Despite having increased agricultural production, 62% of Indian agriculture still depends on the monsoon. This climate crisis and weather conditions have a direct impact on the agricultural community, with rising temperatures, irregular rainfall, and increasing CO2 levels reducing production and income of the farmers. Climate change has a 4-9% influence on agriculture each year. Since the agriculture sector contributes about 15 % to the country's GDP, this is only because of this influence that losses of about 1.5 % take place. The article below describes the importance of climate-resilient agriculture, which enables the farmer to adapt to the adversities of climate change for a better yield and healthy ecosystems, in contrast to conventional farming. This is possible due to the diversification of crops and livestock that have different tolerance levels to climate stresses. It also presents various initiatives taken by the government to boost the agricultural sector's resilience and productivity.

Introduction

The most vulnerable sector facing the severe impact of climate change is the agricultural sector. It employs nearly 46% of the population and contributes 15% to the GDP (FY24) of the nation. In India, the majority of the farmers (who are considered the strength of agriculture) are struggling with extreme weather events like fluctuations in temperatures, irregular rainfall patterns, droughts, and floods, all due to climate change, which ultimately impacts their crop yields. It has been reported that warmer temperatures, which are more than the threshold level, cause a significant decline in rice and wheat productivity (a 1 % increase in temperature reduces the productivity by 23 % and 9 %, respectively). There could be a decrease of 8% in the global crop yields by 2050 (MacPherson, 2025). Moreover, due to uneven rainfall, nearly 43 % of the farmers have lost their standing crops. Therefore, to adapt to or mitigate these challenges, climate-resilient agriculture (CRA) emerge as a solution, which combines the use of necessary strategies, *i.e.,* crop diversification, water harvesting, soil conservation, climate-smart crop varieties, etc., for sustainable farming practices and to safeguard food security.

Climate-Resilient Agriculture

CRA involves all the practices that can resist and adapt to the severe effects of climate change, like high temperatures, sudden changes in rainfall, and other extreme weather events. Since agriculture acts as both a contributor to and a victim of this global phenomenon, it can only be resolved through climate-resilient agriculture, which helps safeguard food security and the environment while improving the livelihoods of people at the same time. Farmers are, nowadays, moving towards following practices like crop diversification (by using drought/flood tolerant varieties), water harvesting, conservation tillage and integrated pest management to enhance resilience.

Key Objectives

Concerning the need for transformation and to rearrange the direction of agricultural systems, an integrated approach of CRA mainly involves the following key objectives

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1) To increase the agricultural productivity and income of the farmers
2) To sustain the capacity of the agricultural community to adapt to the adverse effects of climate change
3) Utilization of CRA to reduce greenhouse gas emissions.

Practices involved in CRA

To adapt to or mitigate the effects of climate change, CRA put forward the idea of sustainable practices and novel techniques, unlike traditional agriculture. It examines the long-term role of farming on the environment and provides solutions to various problems, such as degraded soil, water scarcity, and increased greenhouse gas emissions, with the help of digital farming technology. CRA encompasses promising approaches of crop rotation, cultivating drought-resistant crops, and smart irrigation that possess more resilience. The following are the practices that are included to implement CRA.

Fig.1. Strategies involved in Climate Resilient Agriculture (Arif *et al.,* 2025)

1) Adapt climate-resilient crop varieties: Since 2014, over 2,600 climate-resilient crop varieties have been developed and promoted by ICAR and SAUs to mitigate the effects of climate change. Examples include: flood-resistant rice (Scuba rice), heat-tolerant durum wheat, stress-tolerant millets, high-calcium finger millet, along with horticultural crop varieties like guava, mango, and tomato.

2) Soil Resilience: An eco-friendly management of soil is a vital component of CRA. It involves focusing on those techniques that improve the soil structure, increase soil organic matter, and augment the water retention capacity of the soil. All of this can be accomplished by adding compost, animal manure, green manure into the soil and implementing reduced tillage.

3) Implementing agroforestry practices: It employs the integration of trees and shrubs into agricultural landscapes to boost the resilience of farming systems to the effects of climate change. Trees provide many advantages, like carbon sequestration, act as windbreaks and shade, encourage biodiversity, and regulate the microenvironment, which are in harmony with climate-resilient agriculture.

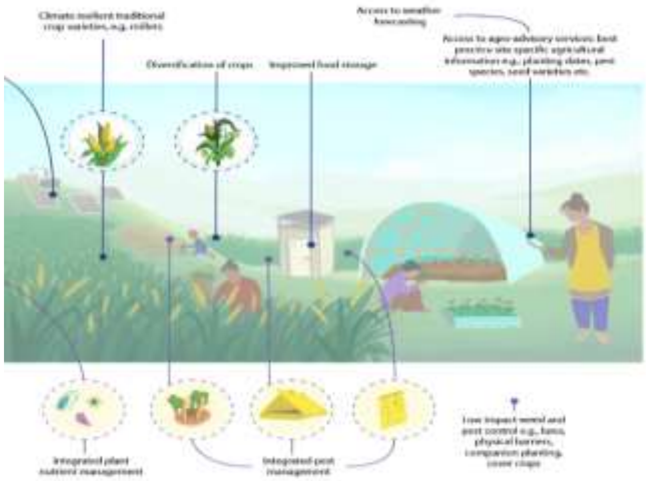

Fig. 2. Resilient Farm Management (Dhakal *et al.,* 2025)

4) Adapting a good livestock system: Focusing on heat-tolerant Indigenous breeds like Gir, Red Sindhi, and Sahiwal cattle helps to mitigate the effect of heat surge due to their larger body surface area.

National and Global Impact

India ranks 5th as the most vulnerable nation, according to the Global Climate Risk Index (2020). The most vulnerable sector to climate change is agriculture, which faces challenges such as irregular rainfall and harsh weather events, resulting in a

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reduction in crop yields and livestock output by 2050. Across the country, the following initiatives have been taken by the government to promote CRA.

1) National Innovations in Climate Resilient Agriculture (NICRA): It aims to boost the resilience of crops, along with livestock and fisheries, through the development of risk management technologies. Launched in 2011, it demonstrates site-specific technology packages in the field to help farmers adopt new tools to tackle the vulnerabilities of climate change.

2) National Mission for Sustainable Agriculture (NMSA): Introduced in 2014-15, it promotes the productive and profitable CRA by strengthening location-specific integrated farming systems. It enhances the agricultural productivity, particularly in rainfed areas, through soil health management and diversified farming.

3) All India Coordinated Research Programme on Integrated Farming Systems (AICRP-IFS): The project aims to build Indian agriculture more resilient in 25 states/UTs by developing low/negative emission farming systems that include efficient cropping systems, organic and natural farming to tackle the effects of climate change. ICAR has developed 76 models of IFS, which include 8 integrated organic farming system models and organic farming packages for 80 cropping systems as a means of sustainable farming practices.

4) Crop Diversification Programme under Pradhan Mantri- Rashtriya Krishi Vikas Yojana (2007): It facilitates sustainable agriculture by focusing on infrastructure development, adoption of modern tools/techniques, and marketing initiatives to advance the agricultural supply chain.

On a global scale, the World Bank has also made a significant contribution to climate-smart agriculture. It has identified agriculture, food, land, and water as one of the five key shifts in its formulated climate change action plan (2021-2025) to support the Paris Agreement. The World Bank has increased funding for CRA by eight times, nearly reaching $3 billion annually.

Case Studies Involving CRA

CRA encompasses all strategies that enhance resilience to climate variability by improving agricultural viability. Below are some of the real-world cases that promotes resilience practices

1) Shree Anna Abhiyan: Formerly known as Odisha Millets Mission. The primary objective of this initiative is to promote climate-resilient and nutritionally rich crops (millets that are drought-resistant), thereby enhancing the livelihoods of farmers and ensuring food security.

2) Prakritik Kheti Khushhal Yojana: It is another initiative launched by the Government of Himachal Pradesh to promote sustainable agriculture by incorporating non-chemical, affordable, and climate-resilient practices.

Conclusion

The sustainability of agricultural production is regularly impacted by climate change variability, the most challenging concern, which influences national food production. Climate-resilient agriculture (CRA) is not merely a set of practices but also a holistic approach that helps to safeguard food systems against the harmful effects of changing climate by adopting climate-smart technologies. Moreover, the major initiatives taken by the government at the national level, like NICRA, NMSA, and NAFCC, also protect Indian agriculture from the adversity of climate change. However, in recent years, researchers and policymakers have only focused on resilience practices rather than emphasising adaptation measures. but with the support of collaborative actions and further research from the stakeholders involved, India can lead in the CRA approach for the sustainable utilisation of existing natural resources to attain long-term balance and higher productivity.

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Antimicrobial Peptides in Lepidopteran insects

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Antimicrobial peptides (AMPs) are oligopeptides with a varying number (from five to over a hundred) of aminoacids which have antimicrobial activity against a broad spectrum of pathogens. Natural AMPs can be found in both prokaryotes (e.g., bacteria) and eukaryotes (e.g., protozoan, fungi, plants, insects, and animals. Antimicrobial peptides (AMPs) are endogenous polypeptides produced by multicellular organisms in order to protect a host from pathogenic microbes. Most AMPs are produced by specific cells at all times, while the production of some AMPs is inducible. AMPs are also defined as host defense peptides because of their essential role in constituting the innate immunity system. In general, when AMPs are folded in membrane mimetic environments, one side of AMPs is positively charged (mainly due to lysine and arginine residues) and the other side contains a considerable proportion of hydrophobic residues. These peptides are considered as probable candidate for forthcoming drugs, because of their broad range of activity, lesser toxicity and decreased resistance development by target cells. The smaller size of AMPs helps in the rapid diffusion and secretion outside the cells, which is mandatory for evoking immediate response against pathogenic microbes. Antimicrobial peptides are widely distributed in nature and they have been found in every organism in which that they have been looked for. The main sources of AMPs are microorganisms, plants, invertebrates and vertebrates.

Need of AMPs

The rate of spread of multi resistant microbial strains is becoming a source of lethal infections. The antimicrobial drug resistance is due to the high rate of genetic mutations of bacteria, making them resistant to treatments formerly effective. Antimicrobial drug resistance arises due to high rate of genetic mutation in microbes that make them resistant to formerly used antimicrobial agents which were found to be effective earlier. The property of bacterial strains for rapid transfer of their genes suggests that bacterial resistance to antibiotics occurs quickly in the evolution of bacterial development. According to antimicrobial resistance report by World Health Organization, common type of drug resistant bacteria includes *Escherichia coli*, *Klebsiella pneumonia*, *Staphylococcus aureus*, *Neisseria gonorrhoeae*, *Streptococcus pneumonia*, *Shigella* species that are acquired resistant against common antibiotics like cephalosporins, fluoroquinolones, carbapenems, methicillin, penicillin, including resistance onferred to extended spectrum beta lactamases (ESBL). The World Health Organization (WHO) report also stated that this serious threat is no longer a prediction for the future; it is happening right now in every region of the world and has the potential to affect anyone, of any age, in any country. To combat with the present multi drug resistance predicament, the use of AMPs from insects becoming a major area of interest for the discovery of new antibiotics which is biologically active, less toxic and reduction of resistance. Insect AMPs become a major area of interest for the discovery of new antibiotics which are biologically active and less toxic to combat with the present multi drug resistance predicament.

AMPs from Lepidoptera

In insects, a large number of antibacterial proteins have been isolated and these antibacterial proteins are classified in five major groups. Cecropins, lysozyme and prolin-rich antibacterial

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proteins have been reported from immunized haemolymph of silkworm, *B. mori*. The detergent properties of these antimicrobial proteins disrupt the cell membranes of the invading microbes and enzymatically attack bacteria by hydrolyzing their peptidoglycan cell walls. Antimicrobial proteins play an important role in eliminating invaders. Antimicrobial proteins are amphiphilic, positively charged molecules that protect the host from infection. Various AMPs from Lepidoptera and other insects were described below.

Cecropins

Cecropins are cationic antimicrobial peptides, first isolated from the immunized haemolymph of the giant silk moth, *Hyalophora cecropia.* In insects three principles cecropins are present, *viz.* A, B and D having a length of 35 to 37residues which lacks cysteine with a strong basic N-terminal linked to a neutral C-terminal by a flexible glycine proline link. Cecropin was also recognized as a part of immune response in two silkworm *B. mori* and *Antherea peryni*. Many families of cecropin have been isolated in lepidopteran and dipteran insects. Members of cecropins family include, sarcotoxin-I, papiliocin, stomoxyn, hinnavin, SB-37 and Shiva (synthetic derivatives of cecropins). Cecropins have broad range of antimicrobial activity against Gram-positive and Gram-negative bacteria and also to fungi. The antimicrobial property of cecropin is governed by the amidation at the C-terminus and amidation is necessary for the interaction of cecropin with liposomes. Besides antimicrobial property cecropin and cecropin derivatives (SB-37 and Shiva) are active against parasites like *Plasmodium* and *Trypanosoma* and can inhibit the replication of HIV-1 virus and proliferation of cancerous cells.

Defensins

Bm Defensin B a homolog of defensin was indentified in the silkworm *B. mori.* The presence of six cysteine residues in conserved sequence is a crucial characteristic of all defensins. *Bm* Defensin B has low amino acid similarity (about 27%) with that of *Bm* Defensin A. The *Bm* Defensin B gene was expressed in the fat body and it was found that it is strongly activated by bacteria such as *Escherichia coli* and *Bacillus subtilis*, and also by *Beauveria bassiana*.

Moricin

Moricin was isolated from the haemolymph of *Bombyx mori* which was found out to be active against *Staphylococcus aureus*. The basic nature of moricin may be important for the attachment of positively charged peptides to the negatively charged bacterial surfaces through electrostatic interaction. Moreover, the presence of amphiphatic α-helix is mainly responsible for antibacterial activity.

Gloverins

Gloverin is a basic insect inducible antibacterial protein isolated from the pupae of giant silk moth *Hyalaphora cecropia*. It contains large number of glycine residues (18.5%) but no cysteine residues and has a distinct amino acid sequence that reveals no strong degree of identity with any known proteins. Till now gloverin have been identified only in Lepidoptera including, *Helicoverpa armigera*, T*richoplusia ni*, *Galleria mellonella*, *Antheraea mylitta*, *Manduca sexta*, *Diatraea accharialis*, *Salix exigua*, and *Bombyx mori*. Gloverins were found to be active against *E. coli,* mutant strains of (Df21f2, D21 and D22) containing Lipopolysaccharide (LPS). Gloverin from *T. ni* is active against virus and *S. exigua* is active against *Flavobacterium* sp.

Attacins

The presence of two sub domains in the G domains in *B. mori, Hyalophora cecropia* attacins and *Sarcophaga peregrine* sarcotoxin IIA, suggests that common amino acid residues in the subdomains are conserved during evolution and seems to play an important role in the activity of antibacterial proteins. The expression level of attacin quickly induced when injected with *Escherichia coli* cells into *B. mori* larvae and continued for 48 hours in the fat body and hemocytes.

Lebocin

It is an antibacterial peptide rich in proline and O-glycosylated consisting of 32 amino acids isolated from by the haemolymph of silkworm, *B. mori* immunized with *Escherichia coli.* The glycosylation in the amino acid residue (15-Thr) is an essential feature for antibacterial activity. The primary structure and antibacterial activity of this peptide mainly coincides with abaecin. Biological significance of lebocin is still remains doubtful because it shows very weak antibacterial activity under physiological conditions and requires low ionic strength for full expression.

Advantages of AMPs

- Broad-spectrum activity (antibacterial, antiviral, antifungal)
- Rapid onset of killing
- Potentially low levels of induced resistance
- Cidal activity and
- Concomitant broad anti-inflammatory activities

Disadvantages of AMPs

- Discovery costs of synthesis and screening
- Patent exclusivity for economic viability
- Susceptibility to proteolysis
- Sensitization and allergy after repeated application
- Confounding biological functions
- High manufacturing costs

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Intercropping of medicinal and aromatic crops with dragon fruits: a sustainable approach for enhanced productivity and profitability

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Climbing epiphytic cacti belonging to the genus Hylocereus, commonly called dragon fruit, pitaya, or strawberry pear, have recently gained global popularity among growers due to their high economic value as a food crop and their remarkable nutritional and medicinal properties. The fruit is known to aid in managing diabetes, arthritis, heart ailments, asthma, obesity, and even slowing the ageing process. These cacti are vigorous, branched climbers that require sturdy support structures to sustain their growth and ensure high fruit yield. As dragon fruit plants generally begin fruiting within 8 to 12 months after planting, adopting intercropping practices during this initial non-productive phase can help generate additional income.

Dragon fruit is categorized into three main types based on the colour of its peel and flesh:

i. **Red-white:** This variety has a pink outer skin with white flesh containing small black seeds — *Hylocereus undatus*.
ii. **Pink:** In this type, both the outer peel and the edible inner flesh are pink, interspersed with black seeds — *Hylocereus costaricensis*.
iii. **Yellow:** This variety features a bright yellow outer peel and white flesh filled with black seeds — *Hylocereus megalanthus*.

Agro-climatic requirement of dragon fruit cultivation:

Climate: Dragon fruit plants can tolerate a broad range of temperatures, though tropical regions offer the most favourable conditions for their growth. They thrive best in areas receiving at least 50 cm of annual rainfall and temperatures ranging from 20°C to 35°C. In regions with intense sunlight, providing partial shade can enhance fruit yield.

Soil: The crop grows well in various soil types, from sandy loam to clay loam, but well-drained sandy soils enriched with organic matter are ideal. A soil pH between 5.5 and 7.0 is considered optimal for successful dragon fruit cultivation.

Land Preparation: The field should be deeply ploughed to achieve a fine tilth and ensure it is free from weeds. During land preparation, the recommended amount of organic compost should be incorporated, and the land should be levelled properly before planting.

Propagation: Dragon fruit is mainly propagated through stem cuttings, as this method ensures quicker establishment and true-to-type plants. Although seed propagation is possible, it is not preferred for commercial farming since seedlings take longer to reach the fruiting stage and often lack the desired traits of the parent plant.

Planting: Cuttings should be selected from healthy, disease-free mother plants of superior quality. Each cutting should be around 30 cm long and treated with a fungicide to prevent infections, followed by dipping in a rooting hormone (IBA) to promote root formation. The treated cuttings can either be planted directly in the field or first rooted in polythene bags (12×30 cm) containing a mixture of dry cow dung, topsoil, and sand in a 1:1:2 ratio. These bags should be kept under partial shade until the cuttings are ready for field transplantation.

Training: For proper vertical growth and structural support, plants should be trained using concrete pillars measuring about 2.13 m in length, with 0.76

m embedded in the soil. Young stems need to be tied to these supports to ensure upright growth. Lateral branches should be pruned, allowing only 2–4 main stems to develop. A circular metal frame is recommended at the top of each pillar to help form a well-balanced canopy or "dragon bush." Under this ring system of training, approximately 1,600 pillars per hectare are required, supporting a plant population of 3,200–6,400 per hectare.

Intercropping:

Intercropping is a traditional yet effective farming technique that involves cultivating two or more crops together on the same land, arranged strategically to optimize space and resource use. This method improves soil fertility, enhances resource efficiency, and boosts overall farm income. In recent years, integrating medicinal and aromatic plants (MAPs) with fruit crops such as dragon fruit (*Hylocereus* spp.) has emerged as a sustainable and profitable land-use practice. Being a perennial cactus with shallow roots and wide spacing, dragon fruit provides ample inter-row space and partial shade — ideal conditions for growing many short-duration MAPs.

Dragon fruit plants usually begin fruiting 8 to 12 months after planting, reaching full economic productivity after about three years. Under favourable conditions, most of the active roots remain within a one-meter radius, leaving a significant portion of the land underutilized in mono-cropping systems. Introducing suitable medicinal and aromatic intercrops can make better use of this space and provide farmers with an additional source of income, helping to offset the high initial investment in dragon fruit cultivation.

Criteria for Selecting Suitable Intercrops:

1. The intercrop's economic lifespan should be shorter than that of the main crop.
2. The subsidiary crop should remain shorter in height than the dragon fruit plant.
3. Its root system should explore different soil layers than the main crop.
4. It should not be more prone to diseases than dragon fruit.
5. Crop selection should align with local soil type, rainfall pattern, irrigation facilities, and climatic conditions.
6. Intercrops should be chosen based on the availability and accessibility of marketing channels.

Suitable Medicinal and Aromatic Crops for Intercropping

The choice of intercrop depends on soil type, climate, and shade level within the dragon fruit orchard. Some suitable MAPs include:

Catagory	Name of the Crops	Benefits
Medicinal Plants	Ashwagandha (*Withania somnifera*), Kalmegh (*Andrographis paniculata*), Aloe vera, Brahmi (*Bacopa monnieri*), Tulsi (*Ocimum sanctum*), Stevia (*Stevia reboudiana*), Vasaka (Adhatoda vasika)	Improve soil organic matter and provide medicinal raw materials for pharma and herbal industries
Aromatic Plants	Lemongrass (Cymbopogon flexuosus), Citronella (Cymbopogon winterianus), Vetiver (Vetiveria zizanioides), Palmarosa (Cymbopogon martinii), Mint (Mentha sp), Patchouli (Pogostemon patchouli) etc.	Emit essential oils that repel pests, suppress weeds, and improve microclimate
Leguminous MAPs	Senna (Cassia angustifolia), Shatavari (Asparagus racemosus)	Add nitrogen to soil, reducing fertilizer needs.

These crops are short to medium duration, have minimal canopy spread, and do not compete heavily with dragon fruit for sunlight or nutrients.

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Spacing: - An ideal spacing of 3 meters between rows and 2.5 meters between plants ensures healthy growth and optimum productivity of dragon fruit. Pits of 60 cm × 60 cm × 60 cm should be prepared and filled with topsoil, 100 g of superphosphate, and compost before planting. Medicinal and aromatic crops can be intercropped either in single or double rows between the dragon fruit rows.

Manures and Fertilizers: - Organic manures play a crucial role in promoting vigorous growth and productivity of dragon fruit plants. Apply 10–15 kg of organic compost or manure around each supporting pillar, increasing the amount by 2 kg annually. Inorganic fertilizers are also essential, with a recommended dose of N:P_2O_5:K_2O at 450:350:300 g per pillar per year. Additional fertilizer application can be adjusted based on the nutritional requirements of the intercrops.

Stages	Percent of nutrient application		
	N	P_2O_5	K_2O
After pruning	30	20	30
Before flowering	10	10	30
At fruit set	20	40	25
3 months after harvesting	40	30	15

Irrigation:

Dragon fruit requires less water compared to most fruit crops. However, adequate irrigation is crucial during planting, flowering, fruit development, and dry or hot weather conditions. Annual water requirement ranges from 1145 to 2540 mm, with soil moisture maintained at about 65% of field capacity. Drip irrigation is the most efficient method, ensuring optimal water use for both main and intercrop plants.

Mulching and Weed Control: - Applying organic mulches or maintaining living cover crops helps suppress weed growth, retain soil moisture, and enhance soil health.

Harvesting: - Dragon fruit begins to bear fruits within the first year of planting, with commercial yield achieved after 2–3 years. Plants remain productive for 5–7 years. Flowering occurs from May to June, while fruiting takes place from August to December. Fruits mature about a month after flowering. The change in fruit colour from bright green to red indicates ripening. Since dragon fruit is non-climacteric, harvesting should be done 3–4 days after the colour change for best quality.

Yield: - Each fruit weighs about 300–600 g. On average, yields range between 5–6 tons per acre. With a market price of ₹150–₹200 per kg, dragon fruit cultivation can generate significant income for growers.

Pests and Diseases: - Dragon fruit plants are generally free from major pests and diseases. However, ants and birds can pose problems during flowering and fruiting. Spraying neem oil or kerosene oil helps control ants, while bird nets or bagging can protect fruits. Intercropping aromatic plants such as lemongrass and basil can further repel pests naturally due to their volatile oils.

Cost and Profit from 1 Acre Dragon Fruit Cultivation: - The estimated cost of establishing a one-acre dragon fruit farm in the first year is around ₹5.1 lakh, which includes expenses for seedlings, land lease, labor, support structures, pesticides, fertilizers, intercultural operations, and irrigation. However, establishment costs like support structures, land lease, and initial labor (~₹4.1 lakh) are one-time investments. Thus, the effective recurring cost in the first year is approximately ₹1 lakh.

In the first year, farmers can harvest around 6–8 quintals (700–800 fruits) per acre, generating an income of ₹1.5–2 lakh. After deducting expenses, the net profit in the first year is around ₹50,000–₹60,000. From the second year onward, as yields increase by nearly 70% annually, farmers can earn up to ₹4 lakh

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per acre. Additionally, intercropping with medicinal and aromatic plants provides supplementary income, helping offset initial establishment costs.

Cultivating multiple acres of dragon fruit can significantly enhance profitability, making it one of the most lucrative commercial horticultural ventures.

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Ecological Significance and Control of Ostracod Populations in Aquaculture

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Ostracods are tiny, bivalved crustaceans that inhabit almost all aquatic environments globally, ranging from shallow lakes to deep-sea habitats. Their calcareous exoskeletons, extremal adaptability, and varied reproductive modes have led them with over 17,000 described species worldwide. Ecologically, ostracods have a dual function: they are a nutrient-dense food source that connects lower trophic levels with fish stocks and can be good indicators of water quality. Excessive populations of ostracods, on the other hand, can be adverse, competing with larvae of fish for food, being vectors of parasites, and piling up pollutants that can cause harm to the water ecosystem. Controlling ostracod outbreaks is all about reducing organic accumulation, routine substrate cleaning, the addition of natural predators, enhancing filtration systems, and chemical controls. Implementing an integrated, ecosystem-oriented approach is crucial for ensuring healthy fish populations and ecological balance in aquatic ecosystems.

Introduction

Ostracods are minute crustaceans that inhabit almost every type of aquatic environment across the globe. They are easily identified by their hard, two-part shell that closes like a clam, and hence called as “seed shrimps” or “mussel shrimps.” Due to the presence of calcified carapace, these hardy organisms can survive in warm tropical shallows and freshwater ponds to icy polar seas and the deep ocean floor several thousand meters below. Most species reproduce sexually, though some have adopted asexual reproduction through parthenogenesis. They measure only about 0.2 to 2 millimeters long, but a few can grow up to 3 centimeters. Their compact bodies carry up to eight pairs of limbs that serve multiple purposes such as feeding, swimming, and sensing their surroundings (Brandão et al., 2025).

Classification and diversity of ostracods

Ostracods belong to the phylum Arthropoda and the subphylum Crustacea. Within this group, they occupy a distinct taxonomic rank as the class Ostracoda, which is further divided into two major subclasses- Myodocopa and Podocopa. Members of the subclass Myodocopa are predominantly marine, inhabiting both benthic and pelagic zones, while Podocopa includes species adapted to freshwater, brackish, and some marine environments. Globally, more than 46,000 ostracod species and subspecies have been described. Of these, around 17,000 species are currently recognized as valid in taxonomic databases. Their diversity and ecological range make ostracods one of the most successful crustacean groups, thriving from mountain streams to ocean trenches (Brandão et al., 2025).

Ostracods as food for fishes

Ostracods thrive in almost all types of aquatic environment and primarily feed on algae, diatoms, and detritus. Thus, rich in essential fatty acids and proteins. Fish that feed on ostracods benefit from their high nutritional content, which supports better growth and health. In aquatic food web, ostracods play a crucial role by transferring energy from primary producers lie algae and bacteria to higher consumers like fish, thus maintaining balance of the ecosystem and productivity. These can also serve as bio-indicators, as they are sensitive to pollutants and environmental changes. Healthy ostracod populations reflect good water quality that indirectly support healthier fish communities. Additionally,

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ostracods can help in controlling nutrient cycling and organic matter decomposition which promotes the overall habitat condition for fishes and other aquatic organisms (Chakravarthy and Balamurugan, 2024).

Overpopulation and competition with fish larvae

Ostracods can pose serious problems for fish populations, especially when their density is greater than ecological limits. Excessive populations of ostracods in aquaculture and aquatic ecosystems can subject fish larvae and juveniles to competition for food resources, thus compromising growth rates and survival in certain species like *Arapaima gigas*. Their high reproductive capacity can rapidly contribute to population explosions, which may further destabilize fragile food webs and have an impact on the dynamics of fish recruitment.

Intermediate hosts of fish parasites

One of the major issues involving ostracods is their role as vectors of parasitic life stages of trematodes and nematodes. When fish consume ostracods that have parasitic stages, they are susceptible to infections, which can present in several forms of symptoms, ranging from tissue damage to metabolic dysfunctions and haemorrhaging in severe cases. These parasitic infections have the potential to impair immune status, decrease overall fish fitness, and even cause death in highly affected populations. Such issues are of particular concern in closed aquaculture systems where the transmission of parasites is enhanced by high stocking densities.

Bio accumulators of pollutants and ecological implications to fish

In addition, ostracods are known to be able to bioaccumulate heavy metals and pollutants from polluted water bodies, including cadmium, copper, and lead. When fish feed on ostracods that have bioaccumulated harmful contaminants, the potential for secondary exposure to these pollutants increases, causing damage to fish growth, development, and immunocompetence. Ostracods become overpopulated due to anthropogenic activities or enrichment with nutrients. This can also intensify organic matter loading and oxygen depletion, further stressing fish populations and leading to adverse ecological consequences (Irizuki et al., 2008, Sao Mai., 2014, Gonçalves et al., 2019 & Chakravarthy and Balamurugan, 2024).

Prevention and treatment of ostracod outbreaks

Reducing ostracod food sources and substrate cleaning

In order to control and eliminate ostracod infestations when they become problematic in aquaculture or aquarium settings - reducing excess organic waste and overfeeding are the key steps. Since ostracods feed on rich detritus and leftover food sources- keeping tanks or ponds free from nutrients can effectively restrict their numbers. Regular siphoning and cleaning of substrates is recommended, as ostracods mostly live within or near the substrate where they can hide and reproduce. Routine removal of detritus and debris limits ostracod populations and prevents population explosion in density.

Biological and Physical Controls for Ostracod Populations

Biological control is another choice, where small fish species like tetras, rasboras, or killifish will naturally feed on ostracods and control their population. Balance needs to be maintained in introducing these predators with the cultured aquatic species, as certain natural predator fish might not be ideal for every system. In hatchery or high-value breeding systems, adding filtration upgrades or UV sterilization can continue to decrease ostracod larval survival, and quarantine procedures for new plants, substrate, or equipment prevent accidental introductions or reinfestations of ostracods.

Chemical Treatments and Best Practices for Long-Term Ostracod Management

Chemical treatments, such as the selective use of trichlorfon or other approved antiparasitic medications in crustaceans, may be considered in

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severe outbreaks in commercial systems, but with caution given against non-target organisms and environmental safety. In the end, the optimal management of water quality, periodic cleaning routines, and integrated biological and mechanical measures represent the most viable and efficient options for reducing ostracod nuisance in aquatic systems.

Conclusion

Ostracods are a dynamic and ecologically relevant group of microcrustaceans that play a significant role in aquatic food webs as grazers and also as prey. Though their existence usually indicates healthy water quality and increases fish diet, their unchecked population explosion can result in competition for larval fish, spread of parasitic diseases, and biomagnification of toxic pollutants. Proper management includes nutrient control, cleanup of habitat, biological control mechanisms, and proper use of chemical controls. Sustained monitoring and prudent aquaculture management are critical to maximizing the ecological benefits of ostracods without minimizing their possible risks to fish health and aquatic ecosystem.

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Transformation of Indian Agricultural Value Chains: Challenges, Opportunities and Future Policies

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Introduction: The Shift Towards High-Value Agriculture (HVA)

Indian agriculture is at a pivotal juncture, transitioning from a subsistence and production-focused system to one increasingly oriented toward high-value, nutrient-rich products. Historically, Indian agricultural policies prioritized stabilizing staple food production, ensuring food security and maintaining buffer stocks. Today, however, growing urban populations, rising disposable incomes and shifting dietary preferences are driving demand for high-value crops such as fruits, vegetables, pulses, milk and meat.

Small and marginal farmers, who account for **86.1% of all landholders in India**, represent the backbone of this transformation. Yet, despite record production, the average income of these farmers remains low, highlighting the disconnect between output and profitability. Successful cases in the dairy sector, exemplified by the Amul cooperative model and the poultry industry, through integrated production and improved breeds, demonstrate the potential for inclusive growth and value capture. Nonetheless, replicating these models across other high-value chains remains a significant challenge.

The Problem: Fragmentation and Value Erosion

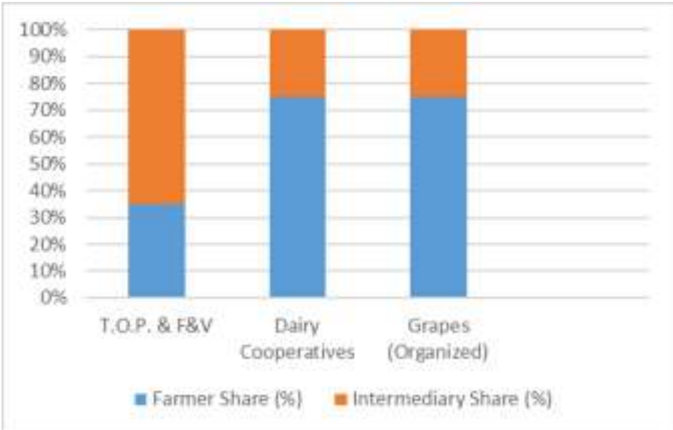
Fragmented Value Chains

Indian agricultural value chains remain highly fragmented. Multiple intermediaries and weak logistics infrastructure contribute to **post-harvest losses of 15–20% in fruits and vegetables** and **10–12% in cereals**, leading to price volatility and reduced returns for producers.

Competitiveness and Farmer Share

Farmers' share of the consumer rupee starkly illustrates these inefficiencies:

- **Tomatoes, onions, potatoes (T.O.P.) and other F&V:** Farmers capture **26.6–45%** of the final retail price.
- **Dairy cooperatives and organized grape producers:** Farmers can retain up to **75%** of the final consumer price.



This data underscores systemic inefficiencies in fragmented chains and the value retained by intermediaries rather than producers.

Inclusiveness and Market Access

While Agricultural Produce Market Committees (APMCs) provide physical market access, smallholders have limited influence over price discovery. Initiatives such as **Grapenet** and **Anarnet** for grapes and pomegranates have improved traceability and participation, but scaling similar solutions requires a stronger role for **Farmer Producer Organizations (FPOs)**. FPOs can enhance aggregation, strengthen collective bargaining and provide a counterbalance to contract

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farming arrangements that often favor larger producers.

Sustainability, Scalability and Finance Bottlenecks

Economic and Environmental Sustainability

- **Price sensitivity:** Crops like T.O.P. and pulses are vulnerable to market fluctuations due to dependence on traditional marketing.
- **Dairy cooperatives:** Many face governance challenges and financial instability, compounded by national fodder shortages.
- **Environmental footprint:** Dairy production is water-intensive and contributes significantly to **greenhouse gas emissions (~4% of India's GHG from agriculture)**. Pulses, fruits and vegetables, by contrast, are generally water-efficient and environmentally sustainable.

Scalability and Finance

The expansion of high-value crops is constrained not by land availability but by yield limitations. Adequate financing is critical:

- Approximately **80% of T.O.P. farmers rely on informal moneylenders**, paying monthly interest rates of **2–5%**, which severely restricts adoption of improved seeds, irrigation and post-harvest technologies.
- Limited access to institutional credit remains a major bottleneck to vertical growth, value addition and supply chain efficiency.

Policy Imperatives for Transformation: The Four Pillars

To unlock the full potential of high-value agriculture, policy reforms must focus on **Technology, Markets, Institutions and Finance**.

1. Technology

- Dedicate **1% of Agri-GDP to R&D and infrastructure development**, ensuring access to improved seeds, digital farm advisory and post-harvest technologies.
- Promote acquisition and adaptation of advanced agricultural technologies from private and global R&D institutions to benefit smallholders.

2. Markets

- Implement a **uniform marketing fee structure** across APMCs to streamline trade, akin to the GST framework.
- Develop **futures markets for perishables**, including T.O.P., to enhance price discovery and risk management.
- Introduce **direct income support**, preferentially targeting small and marginal farmers, to buffer against market volatility.

3. Institutional

- Reform **land lease markets** to facilitate consolidation and achieve economies of scale necessary for aggregation, storage and value addition.
- Empower **FPOs and cooperatives** with easier access to credit and common marketing infrastructure.
- Adopt **global food safety and quality standards** to enhance export potential and consumer confidence.

4. Finance

- Leverage **FinTech and modern NBFCs** to provide institutional credit directly to farmers, bypassing high-interest informal channels.
- Create a **dedicated agricultural equity investment vehicle** to support startups and growth-stage enterprises building robust value chains.
- Introduce **market-oriented hedging products**, including tailored futures and

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- collateral-based financing, to mitigate price and credit risks.

Conclusion

The transformation of Indian agriculture requires moving beyond a production-centric paradigm toward a **value-centric model**. Coordinated reforms in technology, markets, institutions and finance can dismantle structural bottlenecks, improve farmer share of the consumer rupee and reduce dependency on informal finance. By systematically addressing these challenges, Indian farmers particularly smallholders cultivating T.O.P., pulses and other high-value crops can realize the full economic potential of their produce, achieve sustainable livelihoods and contribute to a resilient agricultural economy.

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Ranikhet Disease (Newcastle Disease) Avian Influenza (Bird Flu) disease of Poultry and their management

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Introduction

A significant amount of the world's meat and egg production comes from poultry farming, making it an essential part of the agricultural industry. Diseases that impact avian health, production, and profitability, however, present serious obstacles for the sector. Poultry diseases can spread quickly and result in significant financial losses. These diseases might be bacterial, viral, or parasitic. Vaccination, biosecurity precautions, routine monitoring, and timely treatment are all crucial components of effective disease management. Minimizing outbreaks requires an understanding of illness signs, causes, and control strategies. In this introduction, prevalent chicken diseases are examined, along with sustainable methods for managing and preventing them in contemporary poultry systems.

Both domestic and wild birds are susceptible to the highly contagious viral disease known as avian influenza, or bird flu. Some strains of influenza type A viruses, which cause severe disease and significant mortality in chicken, can range from low to high pathogenic forms. Serious public health concerns have been raised by the human infections of several subtypes, including H5N1 and H7N9. Direct touch, infected equipment, and migratory birds are the main ways that the disease spreads quickly. Strict biosecurity, surveillance, culling of affected flocks, and vaccination campaigns are necessary for effective control and prevention. Controlling avian influenza is essential for both food safety and animal health.

1. **Ranikhet Disease (Newcastle Disease)**

Ranikhet disease is a viral threat that has plagued poultry farms leading to mass devastation, for decades. Research shows that it is highly contagious, causes severe respiratory, digestive and neurological symptoms in affected birds and even the poultry faces 100% mortality rate, particularly in intensive farming operations.

Cause: Ranikhet disease is caused by the Newcastle disease virus (NVD), a highly contagious Paramyxovirus. The disease is highly contagious and it spreads through direct contact between birds, contaminated feed, water, equipment or even through people.

Symptoms: Respiratory distress (gasping, coughing), neurological signs (twitching, paralysis) and digestive issues (diarrhea) may be visible in infected birds. Other symptoms include a drop-in egg production, soft-shelled eggs and sudden death.

Prevention

1. Follow strict vaccination schedule using live and inactivated vaccines.

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2. Primary vaccination with Lasota or F strain, followed by boosters.
3. Restrict farm access and movement.
4. Use disinfectants for equipment, housing, and water.
5. Isolate new or sick birds.
6. Provide balanced nutrition and clean water.
7. Control stress factors like overcrowding and poor ventilation.
8. Regular flock health checks.
9. Immediate culling and proper disposal of infected birds.

2. **Avian Influenza (Bird Flu)**

Avian Influenza, commonly called Bird Flu, is a viral disease, have a recuring threat to global poultry populations. This disease primarily affects birds, but can also rarely spread to humans. It is a silent killer lurking in the skies, with the potential to mutate and spark global pandemics, a deadly threat to humanity.

Cause: It is caused by different strains of influenza virus, notably H5 and H7. As being a contagious disease, it can spread through direct contact with infected birds, their secretions or contaminated surfaces.

Symptoms: In mild cases, birds may show symptoms like ruffled feathers, decreased egg production, and mild respiratory sufferings. In severe outbreaks, the disease can cause respiratory failure, internal bleeding and death.

Prevention

1. Restrict entry of visitors and vehicles.
2. Regular disinfection of poultry houses and equipment.
3. Control movement of birds and products
4. Monitor for clinical signs and sudden mortality.
5. Report suspected cases immediately.
6. Follow government guidelines on vaccination.
7. Use approved vaccines if applicable.
8. Immediate culling of infected and exposed birds.
9. Proper disposal by deep burial or incineration.
10. Maintain healthy nutrition and stress-free environment.
11. Avoid contact with wild or migratory birds.

Conclusion: Shaping the failure of poultry health in agriculture. As global agriculture evolves to meet the demand of growing population, safeguarding poultry from disease is more crucial than ever. Poultry health is a linchpin in sustainable food systems, and the integration of solutions. Protecting poultry to strengthen the resilience of agriculture as a whole, ensuring a stable, efficient and sustainable food supply for future generations.

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The Horticultural Imperative: Efficacy of Crop in Climate Change

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Introduction

Climate change-related extreme weather occurrences, such as heat waves, droughts, and frosts, have a negative impact on the output and quality of horticultural products. This lists the unique vulnerabilities of important horticultural plants like mango, citrus, grapes, cashew, tomato, chili, onion, potato, and lettuce to a wide range of abiotic stresses. The paper then outlines crucial adaptation measures that are being implemented to mitigate these consequences. These include the development and usage of resilient rootstocks and stress-tolerant cultivars, the implementation of protected cultivation methods (greenhouses, shade houses), and improved agricultural practices such as precision irrigation, moisture retention, and optimal planting dates. The main goals are to improve food security, productivity stability, and crop resilience in the face of an increasingly unpredictable environment.

Factors affecting Horticultural crops

Despite hurdles, the horticulture industry has made significant progress and is now at a point where it is critical to launch sustainable development projects. This involves managing plant health, utilizing novel plant species, implementing water monitoring, and making the most of nutrients. Strategies to minimize post-harvest losses are being implemented. However, climate change-related challenges, such as changes in the seasonal timing of extreme weather occurrences, such as severe rain, floods, frosts, high temperatures, hailstorms, and droughts, which have the potential to negatively impact crop production yield, are impeding the growth of horticultural output.

Impact of Climate Change in Horticulture;

Climate change presents a significant environmental challenge that will profoundly influence horticulture. Horticultural crops need ideal conditions for optimal production and cultivation quality. Changes in climate conditions have a direct effect such as;

Mango *(Mangifera indica)*

In mango trees, both those that bear fruit and those that do not suffer from leaf scorching and twig dieback as a result of heat stress. Additionally, a significant outcome reported by AVRDC is the transformation of reproductive buds into vegetative parts of the plant.

Citrus *(Citrus sp.)*

Citrus fruits in India are primarily collected during the winter season, meaning that the flowering phase typically occurs before winter, around December to January. Abundant winter rainfall tends to promote vegetative growth rather than the development of flower buds, which can result in decreased production. Implementing *Hastha bahar* treatment can diminish flowering in October, allowing for a summer harvest. Furthermore, water stress in citrus trees can lead to a decline in leaf initiation, a reduction in leaf size, and the development of thick, leathery leaves.

Vines *(Vitis vinifera)*

Temperatures exceeding 42ºC can lead to a decline in both enzyme activity and chlorophyll levels, resulting in reduced photosynthesis and inefficient use of radiant energy by vine plants. The levels of anthocyanins in wine grapes are influenced by variations in day and night temperatures ranging from 15ºC to 20ºC.

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Cashew (*Anacardium occidentale)*

Lack of adequate and consistent rainfall, along with high temperatures and strong winds, results in cashew trees yielding fewer fruits, with a noticeable amount of leaves dropping. Additionally, the flowers end up wilting. In severe situations, this can lead to a complete lack of productivity.

Tomato (*Solanum lycopersicum)*

Prior to flowering, tomatoes subjected to temperature stress experience developmental changes in their anthers, such as uneven flower opening, insufficient pollen production, and abnormalities in the epidermis and endothecium. Tomato crops demonstrate a 30-45% decrease in blooms when exposed to temperatures over 28°C, according to the IPCC. High temperatures lead to tipburn and blossom end rot.

Chilli *(Capsicum annuum)*

Drought conditions account for 50–60% of the decreased chilli production, which has a significant effect on rainfed farmers.

Onion *(Allium cepa)*

Onion crops experience a decrease in bulb size at 38ºC and a decrease in the number of bulbs at 40ºC.

Potato *(Solanum tuberosum)*

For optimal growth and physiological processes, potatoes need temperatures between 2°C and 30°C. Frost damage reduces tuber yield by 10–20%, whereas high-temperature stress results in a 1–20% decrease in the production of marketable potatoes. A cool night temperature between 15°C and 20°C is necessary for inducing tuberization (the creation of tubers), which is being impacted by fluctuating night temperatures above 22°C. (Anupama singh 2015)

Lettuce *(Lactuca sativa)*

Tip burn in lettuce is caused by heat-induced disturbance, which affects calcium distribution within plants, and by inadequate water absorption from the soil, which leads to insufficient calcium absorption.

Growing indicator cultivars in lettuce that are susceptible to tip burn can serve as an early warning system, aiding in the prevention of harm to the main crop. Studies indicate that the use of indicator plants can increase lettuce yields by 4% to 70%. Additionally, calcium supplements applied through foliar and subsurface drip irrigation can help alleviate stress. (Gouthami Y. 2023)

Other crops

- Strawberries will produce more runners at the cost of fruit.
- At higher temperatures, ripening will occur more quickly, particularly for fruit that will be stored for less time on trees or plants.
- At an elevated temperature of 27°C, which is different from the typical strong red pericarp produced under ideal 17°C conditions, apples will have a weakly coloured pale green pericarp.

Adaptation Practices to Changing Climate- A Growth Arc

The farming community is being observed with a variety of adaptation methods, such as creating resistant hybrids or varieties, and tolerant varieties. The impact may also be mitigated by innovation in agronomical adaptation, crop management, and input management practices. However, some straightforward strategies, like changing the sowing date, implementing drip irrigation, and adopting moisture conservation practices, can be quite effective.

Protected cultivating practices

The protected cultivation of horticultural crops has become a vital method in contemporary agriculture, providing several advantages, including increased yield, improved quality, and protection against pests and harsh weather conditions. In addressing global food security issues such precipitation management, temperature, humidity, and carbon dioxide levels, various forms of structures like greenhouses, high

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tunnels, and shade houses have importance in protected cultivating techniques. Protected farming enables the cultivation of crops throughout the year, regardless of outside weather factors. (James M. Chacha 2023)

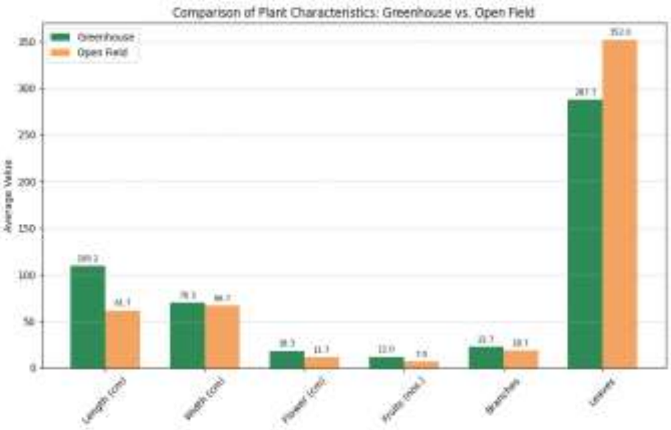

Figure 1. Comparison of Tomato Characteristics: Greenhouse vs. Open Field

Stem girdling technique in vine crops

Stem girdling involves removing the ring of bark from a section of a grapevine's main trunk or branches. This process stops the accumulates such as sugars and anthocyanin collected above the girdled area from moving away from the berries, which increases their availability and results in grapes that are larger, sweeter, have better color, and can be harvested earlier. In cooler climates, girdling and appropriate fruit load can help the negative effects on berry development.

Figure 2. Improvement of skin color by girdling and appropriate fruit load in Grapes

Moisture conservation practices in citrus and guava

Plastic mulching with drip irrigation is the most effective of all methods for addressing water stress in citrus, which has an impact on fruit quality.

Farmers in drought-prone areas like Nashik, where grapes are one of India's main export crops, have widely embraced drip irrigation in conjunction with fertigation. This resulted in water savings of more than 40% and a 24–30% increase in production. The National Research Center for Grapes Pune has published on how precision irrigation is changing water-stressed horticultural areas.

Other methods

- Selecting fruit or vegetable varieties that are appropriate for the climate. Some crops, like pineapples, have a CAM pathway that allows them to tolerate changing conditions.
- Growing lettuce in hydroponic system using Nutrient Film Technique (NFT) yields in just 21 days with 90% less water consumption compared to field grown lettuce.
- Under the National Mission for Sustainable Agriculture (NMSA), Climate-Smart Horticulture is included in India's National Action Plan on Climate Change.

Climatic Change Mitigation Efficacy

Carbon Sequestration

One of the primary methods for mitigating the significant negative impacts of climate change is carbon sequestration. In order to evaluate the mitigation potential, the PROCAMP model was used in Indian Institute Of Science (IISc) Bangalore to assess the planting of Farm Forestry Fruit Orchard Blocks (FFCOB) using indigenous crops such as *Mangifera indica, Tamarindus indica, Manilkara zapota, Azadirachta indica, Psidium guajava and Artocarpus heterophyllus* The sequestration potential was estimated to be 47.42 tons of carbon per hectare, and the total mitigation potential for the 5381-hectare area was calculated to be 81750 tons of carbon.

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Horticultural Efficacy

Resistant Rootstock

The increasing effects of climate change, such as severe heat and drought, call for adaptable strategies for fruit production. The essential component is a hardy rootstock that allows fruit trees to survive in variable environments by providing resistance to abiotic stresses like heat, drought, and salinity. Choosing the right rootstock-scion combinations is essential for sustaining productivity and ensuring agricultural sustainability.

Crop	Variety/Rootstock	Trait(s)
Mango	13-1, Kurakkan, Nileshwar dwarf and Bappakai	Salinity tolerant
Guava	*P. cujavillis*	Tolerant to drought, sodic soils
Grape	Dogridge, 110R, SO-4	Drought, salinity tolerant
Citrus	Cleopatra mandarin	Salinity tolerant
Sapota	Khirni	Drought tolerant
Anona	Arka Sahan	Drought tolerant
Lime	Rangpur lime, Cleopatra mandarin	Salinity tolerant
Pomegranate	*Punica granatum* (variety: Ruby)	Drought tolerant

Table 1. Fruit crop cultivars and rootstocks that are resistant to biotic and abiotic stressors

The top priority should be to implement recommended and most suitable variety or hybrid to the changing growing condition and adapt to hot and dry conditions.

Crop	Variety	Abiotic Stress Tolerance
Tomato	Arka Vikas and ArkaMeghali	Drought
	Thar Anant and Pusa Sadabahar	Heat
	Pusa Sheetal	Fruit set up to 8°C
	Pusa Hybrid 1	Fruit set up to 28°C
Eggplant	Pragati and Pusa Bindu	Salinity
Chili	G4, Arka Lohit and LCA334	Drought
Okra	Pusa Sawani	Salinity
Cucumber	Pusa Barkha	High temperature
Bottle gourd	Pusa Santushti	Heat and cold
Onion	Arka Kalyan	Excessive soil moisture
Radish	Pusa Chetki	High temperature
Potato	Kufri Surya	Heat
Cowpea	Arka Garima, Arka Samrudhi and Arka Suman	Water limiting condition
Dolichos bean	Arka Jay, Arka Sambhram, Arka	Water limiting condition

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	Amogh and Arka Soumya	

Table 2. List of vegetable cultivars that are resistant to abiotic stresses

Recent study on Potato-Adaptation

In Jalandhar, Punjab, the future climatic production predicts a favorable outlook for potato tuber harvests. According to stimulation using INCOCROP-Potato yield of tuber increases by 7.31% in 2020 under 1°C and 400 ppm CO2 and by 3.6% in 2050s under 3°C rise and 500 ppm CO2. Notably, the major potato productivity status shows that Punjab and Haryana are expected to see an increase in yield, but other states are predicted to see a decrease.

Recent study on Apple-Cultivation and Adaptation

In Shimla, one of the higher altitude crops is apples, and low chilling kinds or cultivars (Tamma, Early Shanburry, Parlins Beauty and King David) are taking the place of high chilling varieties like Royal Delicious. These higher altitude locations are now ideal for growing subtropical crops like kiwi, pears, and avocados. Because of climate change, Shimla's apple orchards are seeing a dramatic shift as traditional high-chilling types are replaced by low-chilling cultivars and subtropical crops like kiwi, pear, and avocado start to appear. This change has a direct effect on the area's food security and agricultural stability.

Conclusion

Climate change poses undeniable threats to horticulture, demanding quick adaptation. Progress with stress-tolerant varieties and protected cultivation is encouraging. A resilient future requires integrated water management, improved agro-climatic forecasting, and expedited breeding programs. Future advancement depends on supportive regulations, improved research-farmer ties, and accurate horticulture techniques. Giving these transformations top priority will protect horticulture, food security, and livelihoods worldwide.

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Global Best Agricultural Practices for India: A Path to Sustainable and Resilient Farming

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The health of our planet depends on the health of its ecosystems, and sustainable agriculture is key to maintaining that health." - Jules Pretty

Agriculture is the backbone of India's economy with a population projected to reach 1.5 billion by 2050, India faces the dual challenge of ensuring food security while combating environmental degradation, water scarcity, and climate change impacts. Despite significant strides through the Green Revolution, Indian agriculture grapples with issues such as declining soil fertility, over-reliance on chemical inputs, and fragmented landholdings, which hinder productivity and sustainability. The Gross Value Added (GVA) contribution from Indian agriculture sector is around 17.66% to the total GVA.

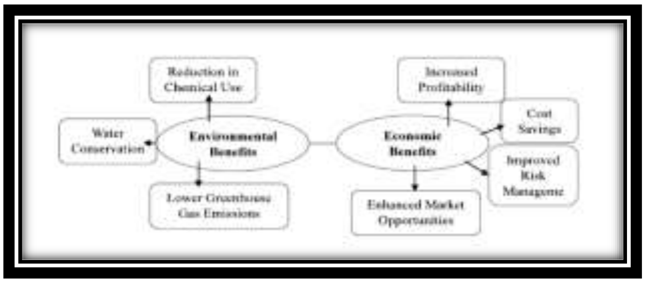
valued at approximately Rs. 47.25 lakh crore within India's total GVA of Rs. 267.62 lakh crore in FY24. Real GDP growth for agriculture in FY25 is projected at 3.8%, up from 1.4% in FY24, driven by record Kharif production and favourable monsoons. The sector employs about 46.1% of the workforce, underscoring its role as a key economic pillar despite a declining GDP share over decades due to rapid growth in industrial and service sectors.

Globally, innovative agricultural practices have emerged to address similar challenges, offering lessons that India can adapt to its diverse agro-climatic zones and socio-economic conditions. This article explores the best agricultural practices from around the world, focusing on precision agriculture, sustainable soil management, water-efficient irrigation, climate-resilient farming, and digital integration. By drawing on global examples and tailoring them to India's context, a roadmap is proposed for transforming Indian agriculture into a productive, sustainable, and inclusive sector.

1. Precision Agriculture: Optimizing Inputs with Technology: Precision agriculture, widely adopted in countries like the United States, Australia, and the Netherlands, uses technologies such as GPS, remote sensing, and data analytics to provide specific and calculated needs for cultivation such as water, manures, composts and insecticides or pesticides. In the U.S., farmers employ variable rate technology (VRT) to apply fertilizers based on soil nutrient levels, reducing waste and environmental impact. In the Netherlands, greenhouse farming leverages sensors and IoT devices to monitor crop health, ensuring optimal growth conditions and yields up to 20 times higher per hectare than traditional methods.

With an average landholding size of 1.08 hectares, Indian farmers face challenges in adopting capital-intensive technologies. However, precision agriculture can be scaled up using affordable tools like drones for crop monitoring and mobile apps for soil testing. For instance, India's Digital Agriculture Mission aims to integrate technology into farming, and startups like CropIn provide data-driven insights to smallholder farmers.

<u>A theoretical chart -Environmental and Economic Benefits of Precision Farming</u>



Source: https://www.researchgate.net/

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Implementation Strategy

- **Low-Cost Sensors and Drones**: Promoting Government-subsidized drones and soil sensors for cooperatives to monitor crops in rain-fed areas like Bihar and Odisha.
- **Mobile Applications:** Enhancing platforms such as Kisan Suvidha to deliver timely and accurate information on soil health, weather conditions, and pest management, with content tailored to regional languages and local agricultural contexts.
- **Public-Private Partnerships**: Collaborating with Agri-tech firms to provide precision tools at subsidized rates, as seen in the Agriculture Infrastructure Fund (AIF).

Adoption of precision agriculture upsurges crop yield by 10-15% and decrease the input costs by 20% improving farmers earnings with minimalistic harm to environment.

2. Workable Soil Supervision: Teachings from Conservation Agriculture: Conservation agriculture, widely practiced in countries such as Brazil, Argentina, and Canada, is based on the principles of minimal disturbance to the soil by suitably covering the soil and practicing rotation of crops with wide diversities. In Brazil, no-till farming is used on more than 32 million hectares of land, helping to reduce soil erosion by 90% and improve the soil's ability to retain water. This approach also increases the amount of organic matter in the soil, thereby enhancing its fertility and resilience during droughts. In Sub-Saharan Africa, integrated soil fertility management which combines organic and inorganic fertilizers has been shown to increase crop yields by as much as 36%.

India faces soil degradation, with 30% of its land affected by erosion and low Soil Organic Matter (SOM) levels (3.32% on average). Practices like zero tillage and crop rotation are already piloted in states like Punjab and Haryana, but adoption remains limited due to lack of awareness and mechanization.

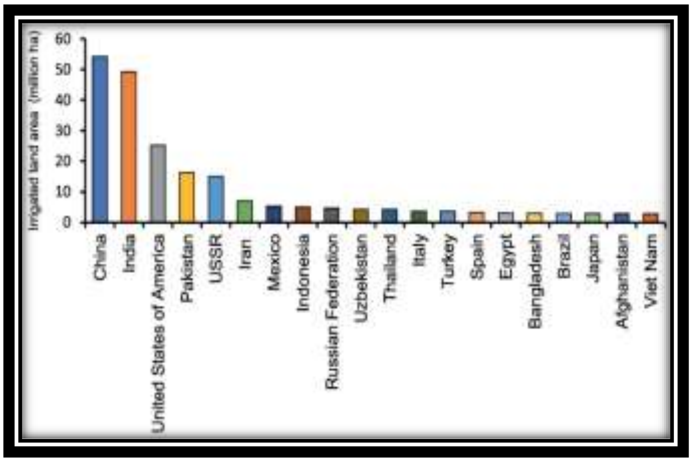
Implementation Strategy

- **Zero Tillage and Mulching**: Promoting zero-tillage machines through custom hiring centres, as seen in Bihar's adoption of direct-seeded rice (DSR).
- **Crop Rotation and Cover Crops**: Encouraging legumes and millets in rotation with cereals to improve nitrogen fixation, especially in rain-fed areas like Rajasthan.
- **Biofertilizers**: Scaling up initiatives like Paramparagat Krishi Vikas Yojana (PKVY) to promote biofertilizers, reducing chemical fertilizer subsidies (currently Rs. 1,400 billion annually).

Conservation agriculture can increase yields by 200-1000 kg/ha and save 50-300 mm of water annually, addressing water scarcity and soil degradation.

3. Water-Efficient Irrigation: Learning from Israel and Australia: Israel's drip irrigation systems, covering 90% of its farmland, deliver water directly to plant roots, achieving 95% water use efficiency. Australia's water management includes rainwater harvesting and laser land levelling, reducing irrigation needs by 30%. These practices are critical in water-scarce regions, ensuring sustainable crop production.

Countries with arable land area under irrigation (million hectares)



Source: https://www.sciencedirect.com

Agriculture consumes 69% of India's freshwater, with over-pumping causing groundwater depletion in states like Punjab. Micro-irrigation covers only 15% of India's irrigated land, despite Government schemes like the Per Drop More Crop initiative.

Implementation Strategy

- **Drip and Sprinkler Systems**: Expanding subsidies for micro-irrigation to smallholder farmers, targeting crops like sugarcane and cotton in Maharashtra and Gujarat.
- **Rainwater Harvesting**: Promoting farm ponds and check dams in rain-fed areas, as seen in Andhra Pradesh's natural farming initiatives.
- **Laser Land Levelling**: Scaling up laser levelling in northern India to reduce water use by 20-25%, building on pilot successes in Haryana.

Micro-irrigation and rainwater harvesting could save 30-50% of irrigation water, enhance water productivity, and enable crop diversification.

4. Climate-Resilient Farming: Adapting to a Changing Climate: Climate-resilient agriculture (CRA) is gaining traction in countries like Nepal and Ethiopia. Nepal's Good Agricultural Practices (GAP) reduce agrochemical use by 31% and increase yields by 36%. In Ethiopia, integrated practices like agroforestry and crop diversification improve livelihoods in drought-prone areas. Such practices bolster the land's ability to withstand climatic extremes, including floods and droughts.

India's vulnerability to climate change is evident in frequent droughts and floods, particularly in states like Andhra Pradesh. Farmers in Bundelkhand have adopted climate-smart strategies like drought-resistant varieties, but scaling remains a challenge.

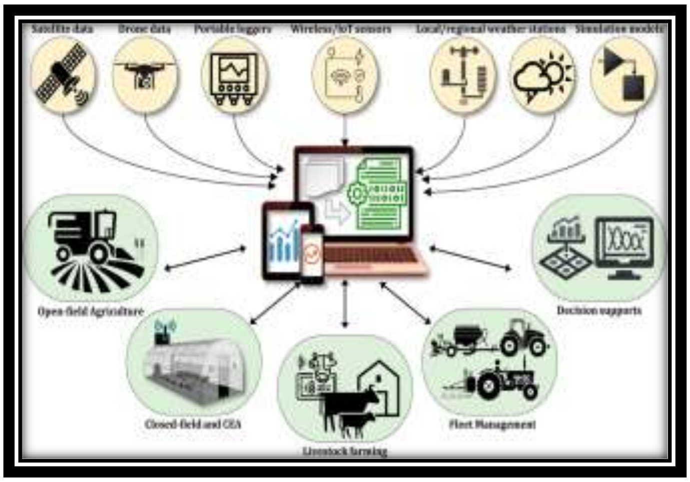
Implementation Strategy

- **Climate-Resilient Crop Diversification**: Promoting millets and pulses, which are drought-tolerant for example, in eastern India, building on Tamil Nadu's Rural Transformation Project.
- **Agroforestry**: Expanding agroforestry to 25 million hectares, as practiced by large cultivators, to sequester carbon and improve soil health.
- **Extension Services**: Strengthening agricultural extension through Rythu Bharosa Kendram (RBK) centres to disseminate climate-resilient technologies.

Adoption of Climate Resilient Agriculture (CRA) practices can upsurge flexibility to condense greenhouse gas emissions, climate shocks and improve farmer revenues by US$10-200/ha/year.

5. Digital Integration and Agri-Tech: The Future of Farming: Digital agriculture is transforming farming in countries like China and Kenya. China's Agri-tech market, projected to reach US$13.5 billion by 2025, uses AI and blockchain for supply chain transparency. In Kenya, M-Pesa enables farmers to access credit and insurance via mobile phones, improving financial inclusion.

<u>A conceptual representation of implementation of digital agriculture in farms</u>



Source: https://www.frontiersin.org/journals

India's Agri-tech sector is growing, with initiatives like the Farmer Connect Portal providing market linkages. However, shortcomings in digital literacy and infrastructure continue to impede adoption among smallholder farmers.

Implementation Strategy

- **Digital Platforms**: Expanding platforms like e-NAM to connect farmers to markets, reducing post-harvest losses (currently 30% for perishables).
- **Mobile Banking**: Promoting mobile-based financial services, as seen in Tamil Nadu's Rural Incubator, which supported 120,000 rural businesses.
- **Training Programs**: Launching digital literacy campaigns through Krishi Vigyan Kendras to train farmers on app usage.

Expected Impact is improved access to credit, enabling investment in modern technologies.

6. Organic and Natural Farming: Scaling Up Sustainable Practices: Organic farming is mainstream in countries like Denmark and New Zealand, covering 15-20% of their farmland. The best practices of New Zealand's organic dairy sector boost premium prices, furthering farmer incomes. In India, the organic farming is being practiced only on limited area of 2.8 million hectares i.e., 2% of net spread area, however, the natural farming is rising swiftly, with around 800,000 adopters.

India's traditional farming practices align with organic principles, and consumer demand for chemical-free produce is rising. States like Andhra Pradesh have pioneered natural farming, showing resilience during cyclones.

Execution Strategy

- **Authorisation, Certification and Labelling:** Simplifying the certification of Good Agricultural Practices (GAP) system and procedure process further through the National Accreditation Board for Certification Bodies (NABCB), thereby allowing farmers better access to first class premium markets.
- **Subsidies for Organic Inputs**: Redirecting chemical fertilizer subsidies (US$18 billion) to organic inputs, as recommended by sustainability reports.
- **Farmer Cooperatives**: Forming cooperatives to share organic input costs, as seen in Sikkim's organic farming model.

Expected Impact: Scaling up organic farming to 5% of net sown area could improve soil health, increase biodiversity, and raise farmer incomes by 20-30%.

Challenges: Despite the potential of these practices, India faces hurdles to espousal due to:

- **Lack of Knowledge:** Farmers lack admittance to extensive guidance and training on the best innovative and sustainable practices.
- **Rural Infrastructure:** Poor rural roads network, warehouse, mobile connectivity and grading, packing, labelling, and loading facilities hampering market entry.
- **Financial Constraints**: High initial costs deter smallholder farmers, who own 69% of landholdings.
- **Policy Inertia**: Slow reforms in agricultural research and extension systems limit innovation.

Policy Recommendations: To overcome these challenges, India needs:

- **Increasing Investment in R&D:** Allocating 1% of agricultural GDP to develop climate-resilient varieties and sustainable inputs.
- **Strengthening of Extension Services**: Revamping Krishi Vigyan Kendras to deliver hands-on training, as seen in Uruguay's Agro-Ecological Project.

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- **Subsidizing Green Technologies**: Offering incentives for drip irrigation and biofertilizers, following Israel's model.
- **Enhancing Credit Access**: Expanding credit lines, as piloted in Sierra Leone, to fund technology adoption.
- **Promoting Regional Strategies**: Adopting practices to agro-climatic zones, acknowledging India's diversity.

However, the widespread adoption of these practices hinges largely on access to adequate and timely financing. It provides treasured openings for banks to play a pivotal role in transforming Indian agriculture through innovative and inclusive financing models.

- Banks can develop specific credit facilities that outfit to meet the needs of sustainable agriculture. For example, low-interest or zero-interest green loans can be introduced for farmers adopting climate-resilient crops, drip irrigation systems, or organic inputs. Lending criteria can be revised to favour practices that promote soil health, biodiversity, and water conservation. Furthermore, banks can collaborate with agricultural universities, NGOs, and Government agencies to educate farmers on the economic viability of these practices, thereby increasing uptake and minimizing default risks. Government-backed credit guarantee schemes and interest subvention policies can be utilized to mitigate lending risks and encourage higher credit flow to the sector.
- By offering credit to FPOs rather than individual farmers, banks can ensure collective bargaining, economies of scale, and risk-sharing. This model also simplifies monitoring and reduces transaction costs. Banks can further explore value-chain financing, where credit is extended not only to farmers but also to input suppliers, processors, and retailers within the agricultural ecosystem. This holistic approach ensures that each stakeholder is financially empowered to contribute to a resilient food supply chain.
- Digital technologies offer another frontier for innovation in agricultural finance. Fintech integration can help banks assess farmer creditworthiness using alternative data such as satellite imagery, crop health indices, and mobile transaction histories. This can make loans more accessible to smallholders traditionally excluded from formal banking. Mobile banking and digital loan disbursement reduce administrative overhead and bring transparency. Additionally, integrating crop insurance products with credit can act as a financial cushion for farmers in case of climate-related crop failures.
- Banks can also issue green bonds aggressively or partner with international climate finance institutions to raise funds specifically for sustainable agriculture. These funds can be channelled into long-term infrastructure projects like cold storage, farm-to-market logistics, and renewable energy-based solutions for farms. Aligning agricultural lending portfolios with ESG (Environmental, Social, and Governance) criteria also enhances the bank's own sustainability credentials and aligns with national and global climate targets.

Financing sustainable and resilient agriculture in India is not just a developmental imperative but also a strategic opportunity for banks. By aligning credit strategies with global best practices in agriculture, banks can foster rural prosperity, ensure food security, and position themselves as key drivers of India's green transition.

Conclusion: By adopting global best practices such as precision agriculture, sustainable soil management, water-efficient irrigation, climate-resilient farming, digital integration, and organic farming, India can transform its agricultural sector into a model of productivity and sustainability. These practices, when adapted to India's smallholder-dominated landscape, can enhance yields, improve farmer incomes, and ensure food security for a growing population. The success of pilot projects in states like Andhra Pradesh and Tamil Nadu demonstrates the potential for scaling up. With robust policy support, investment in research, and strengthened extension services, India can lead the way in sustainable agriculture, balancing economic growth with environmental stewardship.

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Standardization of Nursery technologies for climate-smart Turmeric (*Curcuma longa* L.) cultivation

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Turmeric (*Curcuma longa* L.) is a high-value spice crop, faces significant challenges under climate change, including erratic rainfall, disease outbreaks, and high seed rhizome requirements. Conventional cultivation methods exacerbate these issues, prompting the adoption of standardized nursery technologies as climate-smart alternatives. This review synthesizes research on nursery-based systems such as pro-tray, minisett, and micro propagation, highlighting their agronomic and environmental benefits. Key findings demonstrate that optimized media compositions (Coir pith: vermicompost at 3:1) combined with pre-treatments (*Trichoderma spp*, bio-priming or fungicide dips) enhance seedling vigor, reduce disease incidence, and improve water-use efficiency. Pro-tray systems achieve 60 - 70 % seed savings and enable early monsoon synchronization, while minisett techniques offer rapid multiplication and resilience to climate shocks. Organic soil-less media and micro propagation further contribute to pathogen free, uniform planting material with lower greenhouse gas emissions. These methods collectively yield 15 - 25% higher productivity compared to traditional practices. However, adoption barriers include limited farmer awareness, upfront costs, and the need for region-specific adaptations. This review emphasizes the potential of nursery technologies to align turmeric cultivation with Climate Smart Horticulture (CSH) goals by reducing input dependency, enhancing resilience, and mitigating emissions. Future research should prioritize life cycle assessments, participatory trials, and capacity-building to scale these innovations effectively.

1. INTRODUCTION

Turmeric (*Curcuma longa* L.) is a perennial rhizomatous spice crop of high economic and cultural significance in South and Southeast Asia. India is the largest producer and exporter, contributing over 80% of global production (National Horticulture Board 2022). Despite its adaptability to a range of agro-climatic zones, conventional turmeric cultivation relies heavily on bulky seed rhizomes, long crop duration, and high labour inputs (Nair 2019). These characteristics make the crop vulnerable to climate-induced stress, particularly erratic rainfall, prolonged dry spells, and outbreaks of rhizome rot diseases. In this context, nursery-based transplanting systems, particularly those employing standardized pro-tray, minisett, and micro-propagation methods, have emerged as promising climate-smart interventions (ICAR–Indian Institute of Spices Research 2021, Kumawat*et al.* 2020).

The concept of raising turmeric seedlings in nurseries prior to field planting has gained prominence in recent years, driven by the need to economize seed rhizome use, ensure early and uniform establishment, and enhance resilience against abiotic and biotic stresses (Tamil Nadu Agricultural University 2022). This review synthesizes existing research on standardized nursery protocols, highlighting their agronomic and climate-smart benefits, with emphasis on optimized media composition, pre-planting treatments, and transplanting schedules.

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1.1 Convectional Practices and limitations

Traditional turmeric establishment often involves direct planting of seed rhizomes into prepared fields. While this method is low input costs, it suffers from several limitations; high seed rate requirements (2,500-3,000 kg ha^{-1}), uneven sprouting due to soil moisture variability, greater exposure to soil-borne pathogens, and poor establishment under delayed or erratic rainfall (Nair, 2019). In addition, the lack of pre-plant treatment often increases the risk of rhizome rot caused by *Pythium* spp. and *Fusarium* spp. (ICAR–Indian Institute of Spices Research, 2021). These constraints are amplified under climate change scenarios, where early-season droughts or heavy pre-monsoon showers can cause significant seed losses.

1.2 Advances in standardized Nursery technology

Research over the past two decades has demonstrated the potential of nursery-based turmeric cultivation to address these constraints. In standardized nursery systems, pre-treated rhizomes or sprouted buds are raised in controlled environments, such as protrays, raised beds, or polyhouse structures, using optimized growing media. This approach enables early establishment, precise planting density, and better pest and disease management (Sharma *et al.*2018).

Multiple studies have evaluated and refined protocols for nursery raising, with particular emphasis on media composition, chemical and biological treatments, and transplant age. For example, coconut coir pith mixed with vermicompost in a 3:1 ratio has been shown to provide excellent aeration and water-holding capacity, promoting rapid sprouting and uniform growth (Kumawat*et al.*2020). Similarly, sand:soil:FYM (1:1:1) mixtures have been reported to support robust seedling vigor, especially when combined with *Trichoderma*-based bio-priming (Rani *et al.* 2019).

1.2 Media composition and seedling performance

Media selection is a cornerstone of standardized nursery protocols. Several studies have demonstrated the superiority of light, well-drained substrates enriched with organic matter. Coir pith-based media reduce bulk density, enhance root proliferation, and allow consistent moisture retention, critical for sprout development in warm climates (National Horticulture Board, 2020). Vermicompost additions contribute to microbial activity and nutrient availability, improving early rhizome sprouting rates (Tamil Nadu Agricultural University, 2022).Nursery trials at ICAR–Indian Institute of Spices Research (IISR) found that coir pith:vermicompost (3:1) produced transplants ready for field planting in 40–45 days with uniform growth and minimal mortality (ICAR–Indian Institute of Spices Research, 2021). In contrast, conventional soil-based beds often require 60–70 days to reach transplantablesize, with higher variability in plant height and root mass (Kumawat*et al*. 2020).

1.3 Chemical and Biological Pre-treatments

Seed rhizome health management is essential for disease-free nursery production. Rhizome treatment with fungicides such as mancozeb (0.3%) or carbendazim (0.1%) for 30 minutes has consistently reduced pre- and post-emergence damping-off (Sharma *et al.* 2018; Rani *et al.*2019). In parallel, integration of biological control agents such as *Trichoderma harzianum* or *Pseudomonas fluorescens*has been reported to enhance plant vigor and suppress soil-borne pathogens (Kumawat*et al.* 2020).

Moreover, climate-smart nursery strategies now increasingly emphasize bio-priming and integrated approaches. A combined treatment of hot water dipping (50°C for 30 min) followed by Trichoderma slurry coating has been shown to maintain high sprouting rates (>90%) while reducing chemical fungicide dependence (Rahman *et al.* 2018). These treatments align with CSA objectives by minimizing synthetic inputs and promoting biological soil health (Suma *et al.* 2017).

1.4 Transplant Age and Field Establishment

The optimal transplant age is another critical factor. Studies indicate that turmeric seedlings transplanted at 40–45 days after sprouting establish more quickly and uniformly than younger (<30 days) or older (>60 days) plants (Rani *et al.* 2019). Younger transplants often lack sufficient root mass for rapid establishment, while older seedlings may suffer transplant shock due to root binding in protrays (Sharma *et al.* 2018).

Trials conducted in Telangana and Kerala demonstrated that 45-day-old seedlings recorded higher plant height, leaf area index, and rhizome yield compared to direct planting, with yield gains ranging from 12–25% (Kumawat*et al.* 2020; Rani *et al.*2019). Early transplanting also enables better synchronization with monsoon onset, mitigating risks from late planting due to erratic rainfall patterns—a key climate resilience benefit (Sharma *et al.*2018).

2.Pro- Tray Nursery Systems

The pro-tray single-bud transplant system, pioneered at Tamil Nadu Agricultural University (TNAU), utilizes single-bud sprouts placed in cavity trays filled with a soilless medium of coir pith and vermicompost in a 75:25 v/v ratio (Tamil Nadu Agricultural University 2022). Before planting, rhizome buds are treated with carbendazim (0.2%) for 30 minutes and enriched with *Trichoderma harzianum* to prevent fungal pathogens (National Horticulture Board 2020). Seedlings are ready for transplanting at 30–35 days after sowing.Agronomically, this method achieves 60–70% savings in seed rhizome requirement, leading to reduced production costs and freeing up more rhizome for market sale (Sharma *et al.* 2018). Additionally, seedlings exhibit faster establishment, uniform growth, and reduced incidence of soil-borne diseases such as *Pythium* and *Fusarium* wilt (ICAR–Indian Institute of Spices Research 2021). From a climate adaptation perspective, early establishment enables seedlings to capitalize on the onset of monsoon, mitigating the effects of late or erratic rainfall (ICAR–Indian Institute of Spices Research 2021). Mitigation benefits include reduced transportation-related greenhouse gas emissions from decreased bulk seed movement and lower input use (Rahman *et al.* 2018).An enhanced variant of the pro-tray system involves PGPR-enriched nursery media. Here, the coir pith: FYM ratio (2:1) is supplemented with plant growth-promoting rhizobacteria consortia (Kumawat*et al.* 2020). Mancozeb (0.25%) is used for pre-plant dip, followed by PGPR inoculation. This approach has been shown to improve seedling vigour, yield by 10–15%, and disease resistance (Kumawat*et al.* 2020). PGPR treatment reduces dependency on chemicalfertilizers, thus contributing to emission reduction and improving soil health in the main field (ICAR–Indian Institute of Spices Research 2021).

Table 1. Comparative Cost Analysis of Different Technologies for 1 hectare

Technology	Seed rhizomes	Seed treatment	Additional cost	Total cost
Conventional Method	2500 kg per ha. (Mohan kumar *et al.* 2024) (Rs.50,000/-)	Carbendazim (50% WP)- Rs 320/Kg-Rs.2400/- Trichoderma (Rs.120/kg)-Rs.	Seed tuber planting (15 labourers- Rs.6099/-	Rs. 63,123/-

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		3000/- labour cost-Rs.1624.4/-		
Sand bed sprouting technique	900 kg per ha. (Rs.18, 000)	*Trichoderma viridae* (Rs. 120/kg)- Rs. 432/- Carbendazim (Rs. 320/ kg)-Rs.576/- 4 labourers cost= Rs. 1624.4/-	Polythene sheet cost (Rs.5200/-) and Spreading sand and placing pieces- 7 labours(Rs.2846.2/-)= (Rs.8046.2/-) Cutting tubers into pieces (15 labourers – Rs. 6099/-) Sprouted tuber pieces planting- Rs.6099 /-	Rs.40,877/-
Pro-tray Nursery systems	500 kg per ha.(Mohan kumar*et al.* 2024) (Rs.10,000/-)	*Trichoderma viridae* (Rs. 120/kg)- Rs.180/- Carbendazim (Rs. 320/ kg)-Rs. 480/- 4 labourers cost= Rs. 1624.4/-	Spacing: 45 cm x 20 cm =111,111 plants/ ha Single tray cost 40 cavities (Rs. 12.50/-) for 2777 trays per hectare= Rs. 34,713/- Soil less media cost- Rs. 30,250/- Pro-tray filling with soil less media – Rs.4066/- Single bud rhizomes cutting and planting = Rs. 6099/-	Rs.87,412/-

3. Minisett Technique

The minisett technique for turmeric, especially in cultivars like Kasturi has been standardized to enable rapid multiplication of planting material (Rani *et al.* 2019). The method involves cutting disease- free mother rhizomes into setts containing one or two viable buds, each weighing 8-10 g (Rani *et al.* 2019). These are planted in sterilized sand and compost (1:1) in raised nursery beds or pro-tray after carbendazim treatment (0.2% for 30 minutes) (National Horticulture board, 2020). Seedlings are transplanted at 35-40 days. This approach increases multiplication rates by two to three times compared to traditional clump planting (Rani *et al.* 2019). It also ensures uniform sprouting and healthy seedling development. In terms of climate adaptation, the minisett method facilitates rapid replanting in the event of crop loss due to floods, cyclones, or drought (ICAR- Indian institute of spices research, 2021). From a mitigation standpoint, reduced mother rhizome demand lowers resource extraction and associated energy costs in seed production (ICAR-Indian institute of spices research, 2021).

Table 2. Minisett Technique for Turmeric Propagation

Component	Key Point	Reference
Rhizome size	Use 3-node minisett (~7 g) for better sprouting than 2-node pieces	Aswathy *et al.*2015
Pre-sprouting treatment	Soak in benzyl adenine (BA) 100 ppm for 24 h for highest sprouting (~95 %)	
Nursery media	Vermicompost + coir pith + *Trichoderma* gives best seedling growth	
Transplanting age	Transplant seedlings at 60 days after sowing for best field performance	
Yield & economics	Yield ~15.98 t/ha; B:C ratio 3.29, with ~50 % seed rhizome saving	

4. Organic Soil less Media

In organic production systems, Nursery media composition plays a critical role in seedling survival under stress conditions. Studies have shown that a mix of coir pith, vermi compost, and sand in a 2:1:1 ratio with enriched with *Trichoderma viride* (10g/ kg media) can enhance transplant survival by up to 12% under high temperature stress (Sharma *et al.* 2018). This medium improves water-holding capacity, aeration and microbial diversity, all of which contribute to plant resilience in variable climates (Sharma *et al.* 2018). The use of compost and coir aligns with circular economy principles, recycling agro waste into productive substrates (Nair, 2019). This contributes to carbon sequestration and reduces dependence on synthetic inputs, thus aiding climate change mitigation (Inter-governmental Panel on climate change, 2019).

Table 3. Different organic nursery media on turmeric seedling performance and yield

Media Composition	Effect on Turmeric Seedlings	Reference
Vermicompost + Coir Pith + Trichoderma	Superior rooting, growth, yield, and highest B:C ratio	Aswathy*et al.*2015.
Soil + Sand + Manure (2:1:1)	Enhanced early bud/shoot growth, better water retention	Sari *et al.*2020.
Cocopeat (Coir) Alone	Best sprouting, seedling vigor, and field performance	Satav, 2018.
Cocopeat + Vermiculite + Perlite (Soilless)	Excellent aeration & moisture retention; healthy and vigorous seedling growth	Thomas *et al.* 2014.
FYM + Vermicompost + Neemcake	Improved plant growth, yield, and profitability	Sarma *et al.* 2015.
Soil + Husk (25:75)	Best growth parameters and rhizome yield	Alamsyah*et al.* 2022

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5. Micro propagation and Hardening

Micro propagation has been established as a reliable method for producing disease-free, true-to- type turmeric planting material (Rahman *et al.* 2018). Rhizome explants are cultured under aseptic conditions, followed by in-vitro multiplication and rooting. Plantlets are then hardened in sterilized cocopeat and sprayed with Bavistin (0.1%) before field transfer (Suma *et al.* 2017). The acclimatization phase lasts about 25-30 days. This technique ensures uniformity, high multiplication factor, and pathogen-free material, which is critical in disease-prone climates (Suma *et al.* 2017). Micro propagation also reduces the risk of yield losses from *Fusarium* and *Pythium* rot outbreaks (ICAR-Indian institute of spices research, 2021). Although more resource-intensive initially, it can significantly lower replanting frequency, reducing cumulative energy and input use over multiple cropping cycles (Rahman *et al.* 2018).

Table 4. In-Vitro Propagation Protocols for Turmeric

Stage	**Medium Composition**	**Observation**	**Reference**
Surface sterilization	30% Clorox, 20 min exposure	73.33% uncontaminated buds	Bandara*et al.* 2023
Shoot regeneration	MS + BAP 4.0 mg/l + NAA 0.5 mg/l	Highest shoot regeneration; vigorous growth	Bandara*et al.* 2023; Sinchana*et al.*2020
Root induction	½ MS + IBA 2.0 mg/l	Highest number of roots; roots in ~2 weeks	
Acclimatization	Progressive venting of culture vessels; transfer to cocopeat or coir dust mix under shade, then soil	58.33–72% survival after 4 weeks in field	

Table 5. Standardized nursery techniques for turmeric (*Curcuma longa* L.) and their climate-smart benefits

Nursery technique	**Key features**	**Agronomic benefits**	**Climate adaptation benefits**	**Climate mitigation benefits**	**References**
Pro-tray single-bud system	Single-bud sprouts in pro-trays (coir pith:vermi-compost 75:25); carbendazim + *Trichoderma* treatment	60–70% reduction in seed rhizome use; uniform growth; reduced disease incidence	Early monsoon utilization; less crop loss in erratic rainfall	Lower transport emissions; reduced bulk seed handling	Tamil Nadu Agricultural University 2022; National Horticulture Board 2020; Sharma *et al.* 2018

PGPR-enriched pro-tray system	Coir pith:FYM 2:1 with PGPR; Mancozeb dip + PGPR inoculation	10–15% yield increase; improved seedling vigour; better disease resistance	Enhanced stress tolerance	Reduced chemical fertilizer use; improved soil health	Kumawat*et al.* 2020; ICAR–Indian Institute of Spices Research 2021
Minisett technique	8–10 g rhizome setts (1–2 buds); sterilized sand:compost (1:1)	2–3× multiplication rate; uniform sprouting	Rapid replanting after floods/droughts	Reduced demand for mother rhizomes	Rani *et al.* 2019; National Horticulture Board 2020; ICAR–Indian Institute of Spices Research 2021
Organic soil-less media	Coir pith:vermicompost:sand (2:1:1) + *Trichoderma viride*	Up to 12% higher transplant survival	Greater resilience to temperature stress	Recycling of agro-waste; carbon sequestration	Sharma *et al.* 2018; Nair 2019; Intergovernmental Panel on Climate Change 2019
Micro-propagation & hardening	*In vitro* rhizome culture; hardening in cocopeat + Bavistin	Pathogen-free, true-to-type plants; high multiplication rate	Reduced losses in disease-prone climates	Lower replanting frequency; reduced input demand	Rahman *et al.* 2018; Suma *et al.* 2017; ICAR–Indian Institute of Spices Research 2021

Climate- Smart benefits of standardized Nursery Protocols

When integrated into turmeric cultivation, standardized nursery technologies provide multiple climate-smart benefits:

- **Reduced seed rate**: Nursery methods require 800–1,200 kg ha^{-1} of rhizomes, significantly lower than direct planting, reducing input costs and conserving planting material (Tamil Nadu Agricultural University, 2022).
- **Enhanced establishment:** Vigorous transplants tolerate early-season droughts and high temperatures better than direct-seeded rhizomes (Kumawat *et al.*2020).
- **Improved disease management**: Pre-plant treatments and controlled nursery conditions

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reduce soil-borne pathogen load in the field (Sharma *et al.*2018).

- **Water-use efficiency**: shorter field duration after transplanting reduces cumulative irrigation requirements (National Horticulture Board, 2020).
- **Higher and more stable yields**: yield improvements of 15–25% have been recorded across multi-location trials (Rani *et al.* 2019).
- **Green House Gas mitigation potential**: Reduced rhizome requirement and shorter field occupancy may lower GHG emissions per unit of yield (ICAR–Indian Institute of Spices Research, 2021).

Research gaps

While several nursery technologies have been standardized under experimental conditions, adoption at the farm level remains limited due to lack of awareness, training, and initial investment costs (National Horticulture Board 2020). There is also a need for region-specific protocols considering local soil types, climatic conditions, and cultivar preferences (ICAR–Indian Institute of Spices Research 2021). Additionally, lifecycle assessments quantifying the exact carbon footprint savings from these methods are sparse (Intergovernmental Panel on Climate Change 2019).Addressing these gaps through participatory on-farm trials, economic analyses, and capacity-building initiatives will be essential for scaling nursery-based climate-smart turmeric cultivation (Nair 2019).

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Social Media and Farmer Communication: A New Era of Agricultural Exchange

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Introduction

For many years, farmers relied mainly on traditional means of communication such as radio, newspapers, and extension officers to obtain agricultural information. These channels, though valuable, often lacked speed, reach, and interactivity. With the expansion of social media networks, communication in agriculture has taken a revolutionary turn. Today, digital platforms act as virtual meeting spaces where farmers, scientists, traders, and policymakers can interact instantly, share ideas, and solve problems together. This transformation has made information more accessible, affordable, and participatory than ever before.

Digital Connectivity in Rural Areas

India's countryside is experiencing a silent digital revolution. The increasing use of smartphones and low-cost internet services, supported by government initiatives like Digital India, has connected millions of rural users online. Platforms such as Facebook, WhatsApp, YouTube, Instagram, and X (Twitter) have become everyday tools for communication. Through these channels, farmers can receive updates about weather forecasts, pest management, crop practices, government schemes, and market prices in real time.

How Social Media Supports Farmer Communication

1. Instant Information Sharing

Social media has become a fast and efficient way to spread agricultural knowledge. Agricultural universities, Krishi Vigyan Kendras (KVKs), and research institutions now share expert advice, video demonstrations, and awareness campaigns online to help farmers make informed choices.

2. Learning from Fellow Farmers

Farmers learn best when knowledge comes from experience. Online communities and WhatsApp groups allow them to exchange practical tips, discuss local problems, and share success stories. This peer learning model enhances confidence and community bonding.

3. Market Access and Direct Selling

Many progressive farmers use social media to promote their produce directly to consumers and retailers. By posting photos, videos, or short product descriptions, they can eliminate middlemen and earn fairer prices. This digital exposure also encourages farm-based entrepreneurship.

4. Quick Communication During Emergencies

During floods, droughts, or pest outbreaks, farmers can use social media to send photos or videos for instant guidance from agricultural experts or government agencies. Such timely communication can reduce losses and enable quicker action.

5. Empowering Youth and Women in Agriculture

Rural youth are using social platforms to build careers as agri-influencers, sharing their farming experiences and innovative practices online. Women's groups, especially self-help groups (SHGs), are using WhatsApp and Facebook to coordinate production, microfinancing, and marketing activities effectively.

Barriers and Limitations

- Despite the progress, several challenges still exist:
- Limited digital literacy among rural users restricts full participation.

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- Spread of misinformation or unverified agricultural advice can mislead farmers.
- Language issues, as much of the online content remains in English.
- Poor internet infrastructure in remote villages.
- Lack of awareness about online privacy and data protection.

Government and Institutional Efforts

Recognizing the importance of social media in agriculture, the government and related institutions have launched various initiatives:

- **Kisan Call Centres (KCC):** Providing direct assistance to farmers in local languages.
- **mKisan Portal:** Integrating mobile messaging with social media outreach.
- **Digital Agriculture Mission (2021–2025)**: Building a national digital ecosystem for farmers.
- **Official YouTube Channels of ICAR and KVKs**: Disseminating video-based agricultural learning.

These programs reflect a blend of conventional extension methods and digital tools, ensuring that farmers receive timely and trustworthy information.

Future Prospects

To maximize the benefits of social media for farmers, the following measures are essential:

- Conducting digital literacy programs for farmers and extension workers.
- Developing content in regional languages with visual and audio support.
- Strengthening collaboration among government agencies, NGOs, and private tech firms.
- Promoting verified, expert-led channels to ensure accuracy of information.
- Encouraging youth-led digital entrepreneurship in agriculture.

Conclusion

Social media has reshaped how farmers connect, learn, and trade. It has evolved from being a mere social tool to becoming a powerful driver of agricultural innovation and empowerment. By facilitating faster communication, promoting knowledge sharing, and linking farmers directly to markets and institutions, it is helping build a more informed and resilient rural economy.

The next challenge lies in ensuring digital inclusiveness and information authenticity, so that every farmer—regardless of region or literacy level—can benefit from this digital transformation in agriculture

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Enhancing Crop Resilience to Moisture Stress Through Agronomic Interventions

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Moisture stress is a major limitation to crop growth and yield, especially in rainfed and semi-arid regions. It disrupts physiological processes like photosynthesis, leading to decreased productivity. Climate change has worsened water scarcity, making mitigation strategies essential. This review covers key agronomic practices to alleviate moisture stress, including drought-tolerant and early-maturing varieties, optimized planting time and density, mulching, conservation tillage, crop rotation, nutrient management, and use of anti-transpirants. These integrated approaches improve soil moisture retention, water-use efficiency, and crop resilience. Adopting them is crucial for sustaining agricultural productivity and food security under increasing environmental stresses.

Introduction

Moisture stress is one of the most critical abiotic constraints limiting agricultural productivity across rainfed and semi-arid regions of the world. It occurs when water availability in the soil falls below the optimum level required for normal plant growth and development, leading to disruptions in key physiological and biochemical processes such as photosynthesis, nutrient uptake, and assimilate translocation. The severity and duration of moisture stress significantly influence crop performance, often resulting in reduced plant height, chlorophyll content, leaf area index, and grain yield, as observed in crops like cotton and maize under water-deficit conditions. Frequent droughts, erratic rainfall patterns, and rising temperatures due to climate change have further intensified this challenge, threatening global food production and the sustainability of farming systems. To mitigate the adverse impacts of moisture stress, a range of agronomic practices have been developed and refined over time. These include the selection of drought-tolerant and early-maturing varieties, adjustment of sowing time and planting density, adoption of conservation tillage, mulching, crop rotation, and intercropping that improve soil moisture retention and enhance water-use efficiency. Integrated nutrient and soil management—such as the application of organic amendments and balanced fertilization—also strengthen root growth and improve soil structure, thereby facilitating better water infiltration and storage. In addition, the use of anti-transpirants, shelterbelts, and windbreaks has been shown to reduce transpiration losses and create favourable microclimatic conditions conducive to crop resilience under dryland environments.

Agronomic strategies to mitigate moisture stress

Crop selection and variety choice:

- ***Drought-tolerant varieties*** possess traits like deep, extensive root systems that enhance water uptake, thicker cuticles to reduce water loss, and efficient stomatal regulation. Genetic improvement has developed crops that maintain physiological functions even under low moisture. For example, in India, drought-tolerant maize hybrids developed under the DTMA (Drought Tolerant Maize for Africa) initiative or pearl millet varieties like 'Raj Bajra' are widely grown in Rajasthan and Gujarat to combat dry conditions.
- ***Early-maturing varieties*** complete their life cycle quickly, enabling harvest before severe

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drought periods, thus avoiding the most stressful conditions. Early-maturing wheat cultivars such as 'HD 2733' enable farmers in the Indo-Gangetic Plains to harvest before terminal drought phases.

Planting time and density adjustment:

- ***Optimizing planting time*** ensures crops' sensitive growth stages (such as flowering) coincide with periods of higher soil moisture, improving water availability during critical phases. In Maharashtra's rainfed regions, farmers plant sorghum early to align flowering with the monsoon peak.
- ***Adjusting plant spacing and density*** reduces intraspecific competition for limited water. Lower planting densities decrease canopy evapotranspiration demand and improve soil moisture conservation. Adjusting plant density, like reducing spacing in sorghum or pearl millet, minimizes water competition; this practice is common in parts of Karnataka and Telangana.

Mulching

- ***Organic mulches*** (straw, leaves, crop residues) create a protective cover on soil, significantly reducing surface evaporation, moderating soil temperature, and suppressing weed growth that would otherwise compete for water. *Example:* Applying paddy straw mulch in wheat fields reduces evaporation and suppresses weed growth, conserving soil moisture.
- ***Plastic mulches*** retain moisture, reflect sunlight, and inhibit evaporation, especially effective in high-value horticultural crops. Plastic mulch is widely used in vegetable cultivation (e.g., tomatoes, onions) in dry regions to conserve moisture and raise soil temperature for better growth.

Conservation Tillage

- Practices like zero or minimum tillage maintain crop residues on the soil surface, improving infiltration, reducing runoff, and minimizing evaporation. It also maintains soil structure which aids water retention. *Example:* Zero tillage wheat sowing after rice harvest in the Indo-Gangetic plains conserves soil moisture and improves water use efficiency compared to conventional tillage.

Crop rotation and inter cropping

- ***Crop rotation*** enhances soil fertility and structure by cycling deep-rooted and shallow-rooted crops, improving soil porosity and moisture availability. *Example:* Rotating legumes like chickpea or pigeon pea with cereals improves soil nitrogen and moisture retention.
- ***Intercropping*** enables more efficient use of available resources; certain crops with different root depths can utilize water from different soil layers, optimizing moisture use. Intercropping maize with cowpea helps maximize water use as maize roots explore deeper layers while cowpea uses topsoil moisture.

Wind break and shelter belts

- Establishing rows of trees or shrubs around fields lowers wind velocity, thereby reducing evapotranspiration and soil moisture loss, creating a more favorable microclimate. Agroforestry with Acacia and Eucalyptus as shelterbelts, practiced in dry regions of Rajasthan and Madhya Pradesh, reduces wind speed, thereby lowering soil moisture evaporation.

Nutrient management:

- Proper and balanced application of fertilizers enhances root development and overall plant vigor, allowing better water uptake and stress resilience. Balanced fertilization, combining nitrogen and potassium, in maize and sorghum is common in Andhra Pradesh and Karnataka to enhance root growth and water uptake, aiding resilience during drought.

Soil management:

- Incorporation of *organic amendments* such as compost and green manure increases soil organic matter, enhancing soil structure and water-holding capacity. Addition of farmyard manure or compost in degraded soils of dryland areas increases organic matter and soil water-holding capacity.

Application of *gypsum* in sodic or degraded soils improves soil permeability and promotes better water infiltration and retention.

Anti transpairants

In moisture-stressed areas, plants often face excessive water loss through transpiration, especially under high temperatures, low humidity, and strong winds. To mitigate this loss, farmers and agricultural scientists use anti-transpirants, which are substances applied to plant surfaces to reduce transpiration and conserve soil moisture. Anti-transpirants work primarily by forming a thin, protective film or coating on the leaf surface, which acts as a barrier to water vapor transfer. This coating can physically block the stomata or reduce their opening, thereby decreasing water loss. Some anti-transpirants also influence the internal physiology by temporarily closing stomata or altering leaf cuticle properties, thus decreasing transpiration rates during critical periods. Different types of anti transpirants used in agriculture are:

- **Stomatal closing type:**

These anti-transpirants induce closure or partial closure of stomata, the small pores on leaf surfaces through which most transpiration occurs. By reducing stomatal opening, they decrease water loss directly. Examples include chemicals like Phenyl Mercuric Acetate (PMA) and Abscisic Acid (ABA). Stomatal closers can significantly reduce transpiration but may also reduce photosynthesis if overused.

- **Film forming type:**

These substances create a thin, transparent, and often waxy or plastic-like film over the leaf surface, acting as a physical barrier to water vapor loss. The films allow gas exchange for photosynthesis but reduce water loss. Examples include latex, silicones, hexadecanol, and other wax emulsions.

- **Reflecting type:**

Reflectant anti-transpirants are typically fine particulate materials that coat the leaf surface and increase its reflectance or albedo, reducing the absorption of heat and light. This lowers leaf temperature and reduces transpiration rates. Common examples include kaolin clay, calcium bicarbonate, and China clay (kaolinite).

- **Growth retardants:**

These compounds slow down shoot growth and enhance root growth, indirectly reducing transpiration by limiting leaf area and water demand. Growth retardants may also influence stomatal behaviour. Examples include Cycocel (chlormequat chloride) and Paclobutrazol. These types of anti-transpirants are used in various combinations to reduce water loss, improve water use efficiency, and mitigate the adverse effects of moisture stress in crops.

Conclusion:

Moisture stress continues to be one of the most pressing abiotic challenges to sustainable agriculture, particularly in rainfed and semi-arid regions where water scarcity prevails. Its adverse effects on plant growth, physiology, and yield underscore the need for integrated, adaptive, and region-specific management strategies. Adopting drought-tolerant and early-maturing varieties, optimizing planting

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time and density, and implementing soil conservation measures such as mulching, minimum tillage, and organic amendments significantly improve soil moisture retention and crop performance. Similarly, integrated nutrient management and the use of anti-transpirants contribute to improved water-use efficiency, while shelterbelts and windbreaks create favourable microclimatic conditions that further minimize water loss. Collectively, these strategies represent a holistic framework for sustainable crop production in moisture-deficit environments.

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Good Agricultural Practices – The Key to Residue-Free Crop Production

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Introduction

Consumers in recent years have become more aware of the safety, quality and nutritional value of the food they consume. The growing concern over pesticide residues and their possible impact on human health has led to an increased demand for residue-free fruits, vegetables and grains. This trend has encouraged farmers and agricultural professionals to adopt more sustainable and responsible production methods. In this context, Good Agricultural Practices (GAPs) play a vital role as they form the foundation of safe and sustainable crop production. By following GAPs, farmers can produce food that meets safety standards, conserve natural resources and maintain soil and environmental health while ensuring better economic returns in the long run.

Why Residue-Free Farming Matters?

Pesticide residues in food have emerged as a serious global issue affecting both public health and agricultural sustainability. The excessive or indiscriminate use of plant protection chemicals can result in the buildup of toxic substances in edible crops and food products. Continuous consumption of such contaminated food may pose chronic health risks to humans and animals, while also disturbing soil and water ecosystems. Furthermore, residue contamination affects the reputation of exporting nations, as many importing countries maintain strict Maximum Residue Limits (MRLs) for pesticides in food commodities. Shipments that exceed these permissible limits are frequently rejected, causing significant economic losses to farmers and exporters. Adoption of Good Agricultural Practices (GAPs), including proper pesticide selection, correct dosage, and adherence to waiting periods, enables farmers to comply with these regulations and produce food that is both safe and environmentally sustainable.

Understanding Good Agricultural Practices

Good Agricultural Practices (GAPs) refer to a comprehensive framework of technical, environmental and social guidelines that help farmers produce crops in a safe and sustainable manner. These practices cover every stage of crop production beginning with seed selection, extending through cultivation, harvesting and continuing up to post-harvest handling and storage. The primary objective of GAPs is to minimize the potential risks arising from chemical, biological and physical contaminants that may affect both food quality and environmental health.

At their foundation, GAPs emphasize the importance of efficiency, balance and responsibility in farming operations. They encourage the judicious use of inputs such as fertilizers and pesticides, ensure proper water management and promote conservation of soil fertility and biodiversity. Farmers following GAPs are also trained to adopt hygienic handling practices and safe methods during harvest and post-harvest stages. Moreover, compliance with GAP standards not only improves the safety of agricultural produce but also opens up better market opportunities. Many national and international markets require GAP certification, which helps farmers gain consumer trust, achieve higher returns and participate more effectively in global trade.

Soil and Nutrient Management

Under Good Agricultural Practices (GAPs), nutrient management focuses on maintaining soil fertility through a combination of organic and inorganic sources. The use of organic manures, compost and

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green leaf manures improves soil organic matter, while scientifically recommended fertilizer doses ensure crops receive the right nutrients without causing chemical buildup. Balanced nutrition not only enhances plant growth but also promotes beneficial soil microorganisms that contribute to long-term soil health.

Practices such as crop residue retention, mulching and eco-friendly tillage methods help in improving soil structure, reducing erosion and conserving soil moisture. Farmers are also encouraged to follow crop rotation and intercropping with leguminous crops, which naturally enrich soil nitrogen and break pest and disease cycles. These methods reduce the dependency on synthetic fertilizers and pesticides, supporting a cleaner and more sustainable production system. Ultimately, maintaining healthy soil leads to improved productivity, better nutrient use efficiency and a resilient agro-ecosystem capable of withstanding environmental stress.

Smart Pest Management – The Heart of GAPs

Good Agricultural Practices (GAPs) incorporate the principles of Integrated Pest Management (IPM), which aims to reduce reliance on chemical pesticides by combining multiple eco-friendly approaches. IPM focuses primarily on prevention, maintaining field sanitation, destroying crop residues that harbour pests, using of pest and disease-resistant crop varieties and regularly monitoring pest populations through traps, light lures or field scouting. Early detection and correct identification of pests play a key role in selecting the most appropriate control strategy.

Biological control agents such as *Trichogramma* wasps, *Beauveria bassiana*, *Metarhizium anisopliae* and *Chrysoperla carnea* are effective natural enemies that help keep pest populations below economic thresholds. Cultural methods like crop rotation, timely sowing and removal of alternate host plants further strengthen pest suppression. When chemical control becomes unavoidable, GAPs recommend using only registered pesticides at the recommended doses, applying them with properly calibrated equipment and strictly observing pre-harvest intervals (PHIs). Following these practices ensures that pesticide residues degrade naturally before harvest, keeping the produce within safe residue limits and protecting both human health and the environment.

Water Management and Clean Irrigation Practices

Another important component of Good Agricultural Practices (GAPs) is the use and maintenance of clean irrigation water. Water quality plays a crucial role in determining both crop safety and yield. Using contaminated water for irrigation, pesticide spraying or fertilizer application can introduce harmful pesticide, heavy metals or disease-causing microorganisms onto crops. To avoid this, farmers following GAPs are advised to test the quality of irrigation water at regular intervals, especially in areas near industrial or urban regions.

Proper cleaning and maintenance of water tanks, sprayers, pipes and containers before each use are also essential to prevent cross-contamination. Efficient irrigation systems such as drip and sprinkler methods ensure uniform water distribution, reduce wastage and minimize surface runoff or leaching of chemicals into nearby water bodies. Clean water use, combined with efficient irrigation practices, ultimately contributes to producing safe, high-quality and residue-free agricultural produce.

Benefits Beyond Residue Reduction

Adoption of Good Agricultural Practices (GAPs) brings advantages to both farmers and consumers. For farmers, these practices lead to improved crop yields, enhanced soil fertility and efficient use of inputs such as fertilizers, pesticides and water. Over time, the adoption of GAPs lowers production costs and improves farm profitability through better resource management. Environmentally, GAPs contribute to conserving biodiversity, reducing contamination of soil and groundwater and maintaining ecological balance. The use of eco-friendly approaches also promotes the health of beneficial organisms like pollinators and natural enemies of pests, creating a more stable and resilient farming system.

From the consumer perspective, GAP-certified produce assures higher safety standards, minimal pesticide residues and better nutritional quality. This strengthens consumer confidence in locally produced food and enhances the market reputation of farmers who follow sustainable practices. Overall, GAPs serve as a bridge between safe food production, environmental conservation, and economic sustainability in modern agriculture.

Residue-free farming is more than a production goal. It is a responsibility shared by all stakeholders in the agricultural chain. Extension workers, input suppliers and market regulators must work together to educate and support farmers in adopting GAP-based systems. With collective commitment, achieving residue-free production in major crops like vegetables, fruits and cereals is within a reach.

Conclusion

Good Agricultural Practices (GAPs) represent a vital step toward achieving truly sustainable farming systems. By combining scientific knowledge with field-level management, GAPs help farmers produce crops that are safe for consumption, economically viable and environmentally responsible. These practices encourage the efficient use of resources, promote soil and water conservation and reduce dependence on harmful agrochemicals. As the global demand for safe and traceable food continues to rise, the adoption of GAPs offers a practical pathway for farmers to meet both market and regulatory expectations. Widespread implementation of these practices not only supports residue-free crop production but also strengthens consumer confidence in agricultural produce. In the long term, embracing GAPs will play a key role in building a cleaner environment, healthier communities and a more resilient agricultural future

Advisory Takeaway

Farm Advisory Note:

- Always follow manufacturer instructions and pre-harvest intervals when applying crop protection products.
- Maintain field records, water testing, and hygiene for certification readiness.
- Reduce input dependence through soil fertility management and biological pest control.
- Drip irrigation and clean storage practices significantly cut chemical residue risks.

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Advancing Smart Farming through Thermal Imaging: The Next Phase of Precision Agriculture

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Introduction

Farmers in the modern era face several pressing challenges, including rising input costs, unpredictable weather patterns, and increasing demands for sustainable agricultural practices. Among these concerns, agricultural water use remains a major contributor to global water scarcity, with irrigation accounting for nearly 70% of total freshwater withdrawals worldwide (UNESCO, 2022). On the other hand, Crop Water Productivity (CWP) is closely linked to the efficiency of water use and crop production, making the monitoring of crops crucial at various growth stages for applications such as assessing water stress, managing inputs like fertilizers and pesticides, and estimating yields (Biswal et al., 2025).

In this context, thermal sensors have emerged as transformative tools in precision agriculture, offering the capability to detect subtle physiological and environmental variations that are imperceptible to the naked eye. By capturing invisible infrared radiation emitted from plant canopies, soil surfaces, and even livestock, these sensors translate thermal patterns into actionable data. This information enables early detection of crop diseases, water stress, and pest infestations, facilitating timely interventions that optimize input use, enhance productivity, and promote sustainable farming practices (Manickavasagan et al., 2005).

The origins of thermal sensing can be traced back to 1800, when Sir William Herschel discovered infrared radiation while studying sunlight. What began as a scientific discovery has since evolved into a practical agricultural technology widely used for detecting crop stress, managing irrigation, monitoring livestock health, and optimizing yields (NASA, 2023).

In recent years, thermal imaging has evolved from a specialized innovation into a vital technology within precision agriculture. Global market analyses indicate that the agricultural thermal imaging sector, valued at approximately USD 1.25 billion in 2024, is projected to nearly triple by 2033, reflecting its rapidly expanding adoption and integration into modern farming practices. The widespread accessibility and affordability of thermal cameras; ranging from handheld and drone-integrated units to smartphone attachments, have enabled farmers across scales to proactively assess crop stress, detect pest infestations, and optimize irrigation long before visual indicators become apparent.

1. Working Principles of Thermal Sensors for Agricultural Applications

Thermal sensors detect heat patterns by measuring infrared radiation that all objects emit based on their temperature. In agricultural applications, these sensors work because plants, soil, and animals have unique thermal signatures that change when conditions aren't optimal (Ahmad et al., 2021) (Figure 1).

For instance, during periods of water stress, crops close their stomata—microscopic pores on the leaf surface to reduce water loss through transpiration. This physiological response diminishes evaporative cooling, leading to an increase in leaf temperature by approximately 2–5 °C, a subtle change imperceptible to the human eye but readily detectable through thermal imaging technology (GTGUARD, 2025).

Most agricultural thermal sensors use microbolometer technology, which creates detailed temperature maps without requiring expensive cooling systems. These devices can detect temperature differences as small as 0.1°C, making them sensitive enough to identify problems before they become serious (Renkeer, 2024). The technology works best during stable weather conditions, typically in early morning or late evening hours when solar heating effects are minimized.

Zhang et al. (2010), highlighted that thermal sensors serve as an efficient tool for detecting crop water stress by capturing changes in leaf surface temperature. Water stress in plants occurs when there is an imbalance between the rate of water lost through transpiration and the water absorbed by the roots. When sufficient water is available, transpiration increases, leading to evaporative cooling of the leaves, which lowers their temperature. Conversely, under water deficit conditions, the stomata close to reduce water loss, causing a reduction in transpiration and a subsequent rise in leaf temperature. Thermal sensors detect this temperature difference and translate it into thermal imagery or temperature indices, allowing the identification of stressed and non-stressed plants.

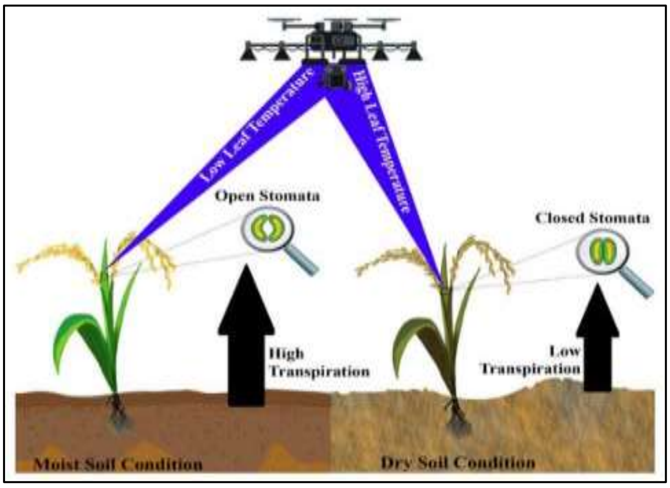

Figure 1. Working of thermal sensor in agriculture *(Ahmad et al., 2021)*

2. Agricultural Applications of Thermal Imaging Sensors

Thermal sensing technology has become an essential tool in precision agriculture for assessing crop water stress and improving irrigation management (Figure 2). Conventional approaches such as soil moisture measurement or visual crop inspection are often time consuming, localized, and destructive, thereby limiting their usefulness for real-time decision-making (Khose and Mailapalli, 2024). In contrast, thermal sensors capture the infrared radiation naturally emitted by plant canopies or leaves, which directly corresponds to their surface temperature. Due to the evaporative cooling effect of transpiration, well-hydrated plants typically exhibit lower leaf temperatures, whereas water-stressed plants experience stomatal closure that limits transpiration and consequently leads to higher leaf temperatures.

Thermal sensors, deployed as handheld devices, fixed ground-based systems, or UAV-mounted platforms, enable monitoring of crop conditions across spatial and temporal scales. By interpreting thermal imagery and indices such as the Crop Water Stress Index (CWSI), Water Deficit Index (WDI), farmers can distinguish stressed from non-stressed areas, allowing precise irrigation scheduling and enhanced water use efficiency (Biswal et al., 2022). However, external environmental factors such as solar radiation, wind speed, and air humidity can significantly affect canopy temperature measurements, necessitating proper calibration and atmospheric correction to ensure data accuracy.

Beyond irrigation management, thermal sensors have shown immense potential in various other agricultural domains. They are increasingly applied for disease and pest detection (Biswal et al., 2023), monitoring plant growth dynamics, estimating yield, assessing fruit maturity, and managing frost and heat stress. Additionally, integration with UAV and satellite systems (Khose et al., 2025) enables large scale field monitoring and precision input management. The subsequent sections will delve into these diverse applications of thermal sensors, emphasizing their role in advancing sustainable and data driven agricultural practices.

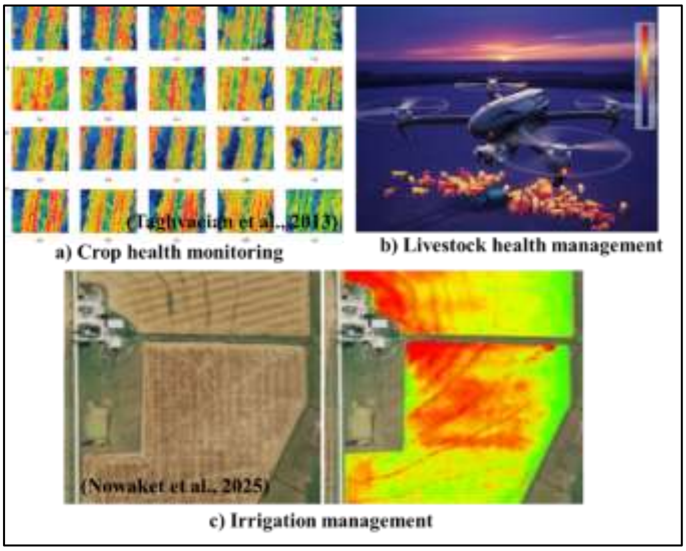

Figure 2. Application of thermal sensors in various sectors of agriculture.

2.1.Crop Health Monitoring

Thermal imaging has emerged as a powerful tool for monitoring crop health by enabling early detection of physiological stress long before visible symptoms appear. Plants under stress exhibit subtle temperature variations that thermal cameras can detect, providing farmers with crucial lead time for intervention. This technology allows for rapid, non-invasive assessment of plant conditions, supporting more precise and proactive management decisions.

Water stress is among the primary indicators detected through thermal sensing, as plants facing moisture deficiency exhibit increased leaf surface temperatures resulting from reduced transpiration. Likewise, nutrient deficiencies and pest or disease infestations produce characteristic thermal anomalies associated with alterations in plant metabolism and canopy temperature. Interpreting these thermal patterns enables farmers to detect early signs of stress, focus interventions on affected zones, and optimize the application of irrigation, fertilizers, and pesticides.

Recent research in Israel highlighted the effectiveness of this approach using avocado orchards, where thermal cameras accurately measured crop water stress and showed strong potential as an alternative to traditional pressure chamber methods (IsraeliAgri, 2025). Unlike conventional labor-intensive and destructive methods, thermal imaging enables rapid, large-scale, and repeatable monitoring of crops throughout the growing season. Its non-destructive nature enhances efficiency while supporting sustainable crop management through timely interventions and optimized resource use.

2.2. Irrigation Management

Irrigation is the life-blood of many farming systems, yet traditional methods often depend on fixed schedules or infrequent soil sampling (Khose and Mailapalli, 2023) that can lead to overwatering or water stress. Thermal sensors have transformed this practice by providing a real-time, field-wide view of moisture distribution. Because wet soil and well-watered plants release less thermal radiation than dry areas, irrigated zones appear cooler in thermographic images, while under-irrigated patches glow as warmer "hot spots" (Dslrpros, 2024).

While thermal imaging excels at showing surface temperature differences, it works best when integrated into a broader soil moisture monitoring strategy. Gravimetric sampling, the traditional laboratory method of measuring soil water content by weighing samples before and after oven drying, remains the standard calibration method. By correlating thermal signatures with gravimetric measurements taken at representative locations, farmers develop accurate thermal to moisture models tailored to their soil types and crop canopies. Such combined use ensures that thermal readings reliably reflect actual root zone moisture rather than surface anomalies or soil texture variations. In some cases, multispectral cameras complement thermal sensors by capturing reflectance in visible and near-infrared bands. Multispectral data help distinguish plant-

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based temperature changes from bare soil effects, detect canopy cover density, and identify early signs of stress before water deficits become severe (Khose and Mailapalli, 2024). When thermal and multispectral datasets are fused, actionable irrigation maps can be generated that factor in both water availability and crop vigor, enabling truly precision-guided water applications.

Beyond simply saving water, thermal drone surveys also improve operational efficiency. Leak detection shifts from slow, labour-intensive visual and trench investigations to rapid thermal sweeps. For example, drone-mounted thermal imaging has been used on commercial farms and irrigation networks to reveal subsurface and drip line malfunctions quickly. After repairs guided by thermal surveys, operators have reported substantial reductions in unaccounted water loss by 20% and prevented crop stress that would otherwise reduce marketable yields by an estimated 10%. By integrating thermal sensing with gravimetric calibration and multispectral data, irrigation can be managed dynamically in response to both soil moisture and crop physiological status. This multi-sensor approach optimizes water use efficiency, enhances drought resilience, reduces energy consumption for pumping, and promotes higher profitability through healthier and more uniform crop growth.

2.3. Soil and Environmental Assessment

Thermal sensors help farmers understand their growing environment better. Soil temperature mapping guides planting decisions and reveals compaction issues or drainage problems. In greenhouses, thermal monitoring ensures optimal growing conditions by tracking temperature distribution and identifying hot or cold spots that could stress plants (Chen et al., 2024). The technology also supports precision agriculture by identifying management zones within fields. Areas with different thermal characteristics often require different treatment approaches for fertilizer application, planting dates, or variety selection (Renkeer, 2024).

2.4. Livestock Health Monitoring

Dairy farms have embraced thermal imaging for automated health screening. Thermal cameras can detect mastitis by identifying elevated udder temperatures during milking, allowing farmers to catch infections early before they spread or affect milk quality. The technology also monitors heat stress in horses and helps identify lame animals through thermal patterns in their hooves (FLIR, 2015). One significant advantage is continuous monitoring; thermal cameras work 24/7 without disturbing animals, providing constant health surveillance that would be impossible with manual methods. This automated approach improves animal welfare while reducing labor costs and treatment expenses. Thermal imaging has become an increasingly valuable technology in livestock management, offering farmers a non-invasive and efficient method to monitor animal health and welfare. Thermal sensors detect the infrared radiation naturally emitted by animals, converting it into temperature maps that reveal abnormal physiological conditions. This technology enables early diagnosis of infections, injuries, and metabolic disorders, ensuring timely intervention and improved overall herd health.

In dairy farming, thermal imaging is particularly effective for detecting mastitis, a common and costly udder infection. Elevated udder surface temperatures captured by thermal cameras during milking can indicate inflammation before visible symptoms appear, allowing farmers to isolate and treat affected cows promptly. Similarly, thermal monitoring is used to identify heat stress in livestock and detect lameness in horses and cattle by analyzing thermal asymmetries in hooves and legs (FLIR, 2015). Such early detection helps prevent productivity loss, reduce antibiotic usage, and enhance animal welfare.

A major advantage of thermal sensors is their ability to provide continuous, automated monitoring without disturbing animals. This automated system not only improves diagnostic accuracy but also reduces labor costs and veterinary expenses. As the technology becomes more affordable and integrated with artificial intelligence, thermal imaging is poised to become a cornerstone of precision livestock farming, enabling data-driven decisions for healthier and more sustainable animal production.

3. Types of Thermal Sensors Employed in Agricultural Monitoring and Analysis

I. **Handheld thermal cameras** offer the most flexibility for farmers wanting to investigate specific problems (Figure 3a). These portable devices provide immediate results for spot checks on crops, equipment, or animals. They are perfect for diagnostic work and training farmers to recognize thermal patterns (Tester UK, 2025).

II. **Fixed thermal cameras** work well for continuous monitoring in greenhouses, dairy barns, or high-value crops (Figure 3b). These systems integrate with automated controls to maintain optimal conditions and alert farmers to problems. While more expensive initially, they provide 24/7 monitoring that can prevent major losses (Chen et al., 2024).

III. **Drone mounted thermal cameras** excel at field-scale monitoring (Figure 3c). A single flight can survey hundreds of acres, creating detailed thermal maps that guide precision farming decisions. These systems offer unmatched coverage and data quality for large operations (Flyeye, 2025).

IV. **Satellite thermal imaging** provides regional monitoring for very large farms or agricultural research (Figure 3d). While less detailed than drone systems, satellite data helps track weather patterns, drought conditions, and regional crop performance trends (Farmonaut, 2025).

Figure 3. Types of thermal cameras used in agriculture.

4. Key Challenges and Limitations Encountered in the Research

Despite their considerable advantages, the application of thermal sensors in agriculture faces several challenges. Environmental factors such as wind, humidity, and solar radiation can influence measurement accuracy, necessitating careful calibration and strategic timing of data collection. Additionally, while initial costs remain substantial for some farmers, they are gradually decreasing as the technology improves. Training requirements represent another hurdle for farmers who need to learn how to interpret thermal data and integrate it with other management information. Many thermal sensor companies now provide training programs and simplified software to address this challenge (Renkeer, 2024). Data management can overwhelm farmers with information. Successful thermal monitoring requires systems that convert raw temperature data into actionable recommendations. Cloud-based platforms and artificial intelligence increasingly help farmers process thermal data into practical decisions (Farmonaut, 2025).

5. Prospective Directions for Future Research

The future of agricultural thermal sensors looks bright, with several exciting developments on the horizon. Artificial intelligence integration will automate thermal data interpretation, making the technology accessible to farmers without specialized training. Artificial intelligence systems will recognize crop stress patterns, predict problems, and recommend specific actions based on thermal signatures (GTGUARD, 2025). As manufacturing scales expand and market competition intensifies, the cost of thermal cameras is expected to decline. Industry projections indicate that within five years, thermal cameras suitable for agricultural applications could be priced below $100, potentially becoming as ubiquitous as conventional farm tools (Noyafa, 2025). Integration with other technologies will create comprehensive farm monitoring systems. Thermal sensors combined with soil moisture monitors, weather stations, and satellite data will provide complete environmental awareness for precision agriculture. Blockchain technology may also track thermal data for food safety and quality assurance throughout supply chains (Islam et al., 2023). Autonomous systems represent the ultimate goal, robots and drones that continuously monitor crops using thermal sensors, automatically adjusting irrigation, applying treatments, or harvesting based on thermal data without human intervention. This technology will help address labor shortages while optimizing farm productivity (Chen et al., 2024).

6. Conclusion: Key Findings and Implications

Thermal sensing technology is revolutionizing modern agriculture by providing farmers with advanced diagnostic capabilities that extend beyond the limits of human vision. These sensors enable the early identification of crop stress, optimization of irrigation scheduling, and continuous monitoring of livestock health; addressing key operational and environmental challenges in farming systems. Although the adoption of thermal technologies requires initial financial investment and technical adaptation, their rapid return on investment and measurable improvements in productivity and resource efficiency make them an increasingly valuable tool for data-driven farm management.

With ongoing reductions in cost and continual advancements in resolution, integration, and analytical capabilities, thermal imaging is poised to become a standard component of precision agriculture, comparable in importance to tractors or combines. By offering quantitative insights into plant physiology and microclimatic variations, thermal sensors empower farmers to enhance sustainability, maximize yield quality, and improve decision-making processes. Ultimately, the integration of thermal sensing represents a crucial step toward achieving resilient, resource-efficient, and high-performance agricultural systems for a growing global population.

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Tiny Allies: How Beneficial Insects Are Becoming the New Warriors of Indian Farms

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Picture this: you're standing in a field, and all around you, an invisible war is being fought. But here's the twist: the soldiers defending your crops aren't manufactured in labs. They're buzzing overhead, crawling beneath leaves, and quietly doing what they've done for millennia. They're insects. Yes, insects. For generations, Indian farmers have reached for chemical sprays whenever pests showed up. It made sense, right? Spray the problem away. But something remarkable is happening now across farms from Punjab's sugarcane belt to Maharashtra's cotton fields. Farmers are discovering that nature has already equipped them with an army that doesn't cost a fortune and doesn't poison the soil. These beneficial insects are staging a comeback; honestly, it's about time we paid attention.

Meet Your Farm's Secret Defense Team

Here's a fact that might surprise you: of all the millions of insect species crawling around Earth, fewer than 2% actually harm crops (FAO, 2025). The rest? They're either minding their own business or actively helping you grow food.

Let's talk about the good guys. There are four main groups worth knowing:

The hunters. Ladybird beetles with their cheerful spotted backs can polish off 50 aphids before lunch, and over their lifetime, they'll munch through around 5,000 of these pests (UCANR, 2025). Green lacewings, delicate as lace curtains, are equally ruthless when it comes to pest control. Their larvae are eating machines.

The assassins. These are the parasitoids, tiny wasps you've probably never noticed. Species like *Trichogramma chilonis* and *Bracon hebetor* operate like something from a thriller movie. They lay eggs inside pest insects, and their larvae consume the host from within. Brutal? Maybe. Effective? Absolutely (Mao et al., 2024).

The matchmakers. Bees, butterflies, and flies, these pollinators do far more than make your garden look pretty. They're responsible for the reproduction of over 80% of flowering crops. In India alone, their work contributes roughly ₹112,615 crores to agriculture annually, which accounts for nearly 9% of our agricultural GDP (ICAR, 2017; FAO, 2025). Without them, many of our favorite foods would simply vanish.

The recyclers. Beetles, ants, and termites, these decomposers might work underground, out of sight, but their contribution is massive. They break down organic matter, enrich soil, and keep nutrients cycling through the ecosystem (Saha et al., 2025).

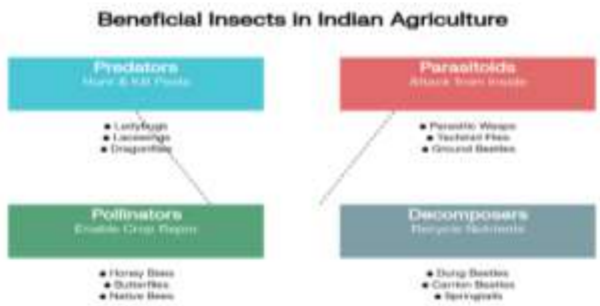

Fig 1. Illustration showing the diversity and ecological roles of beneficial insects in Indian agriculture.

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Real Stories from Real Farms

Let me share what's actually working out there in the fields.

Sugarcane Fields in Punjab

Up north in Punjab, sugarcane growers were battling stalk borers, nasty pests that tunnel through stems and wreck entire crops. Enter *Trichogramma chilonis*, a parasitoid wasp so small you'd need good eyesight to spot it. These wasps attack borer eggs before they even hatch. ICAR and Punjab Agricultural University ran trials and found that farmers using these tiny warriors saw borer damage drop by 54-58%. Better yet, they saved serious money on pesticides (Sharma et al., 2023; ICAR-NBAIR, 2019). Now, farmers release tricho-cards, little strips with wasp eggs, every couple of weeks across thousands of hectares.

Cotton Farms and the Green Lacewing

Down in the cotton belt, *Chrysoperla carnea,* the green lacewing, has become something of a celebrity. Its larvae are voracious predators of aphids, thrips, and whiteflies. Research published in crop science journals confirms that lacewing larvae can demolish hundreds of pests during their development without harming other beneficial insects (Kaur & Singh, 2024). Cotton farmers across central and southern India now consider lacewings essential partners.

Pigeonpea Protection

The wasp *Bracon hebetor* might not look intimidating, but tell that to caterpillar pests. This parasitoid specializes in attacking caterpillars that damage pigeonpea and stored grains. Recent field trials showed it could control over 80% of *Helicoverpa armigera* larvae, one of agriculture's most destructive pests (Mao et al., 2024). NIPHM has been promoting this approach through demonstrations across Telangana and Maharashtra (NIPHM, 2016).

The Coconut Crisis Solution

When the rugose spiralling whitefly invaded southern coconut plantations a few years back, panic set in. This invasive pest was decimating trees. ICAR-NBAIR scientists identified a fungal pathogen called *Isaria fumosorosea* that specifically targets this whitefly. Two applications, spaced 15 days apart, killed 70-80% of the pests in field conditions (ICAR-NBAIR, 2021). Combined with another parasitoid called *Encarsia guadeloupae*, this biological approach saved farmers about ₹9,500 per hectare and eliminated the need for chemical pesticides.

The Pollinator Bonus

Here's something most people don't realize: a single hectare of mustard visited by bees can produce an extra 180–200 kg of seed compared to fields relying only on wind pollination (FAO, 2025). That's not marginal, that's significant income. Many agricultural extension centers now encourage farmers to keep beehives on their land. It's a win-win: better pollination and honey income on the side.

Why This Works So Well

Chemical pesticides are like dropping a bomb; everything in the blast radius dies, good and bad alike. Beneficial insects work differently. They're precision instruments. Take those *Trichogramma* wasps. They detect pest eggs using chemical signatures invisible to us, inject a paralyzing venom, and then lay their eggs. It's targeted warfare (Sharma et al., 2023). Predators like lacewings respond to pest density naturally when aphid populations spike, predator numbers rise to match, creating a natural balance (Kaur & Singh, 2024). Pollinators boost yields not just by moving pollen around, but by improving genetic diversity in plants. Studies show crops like cotton and oilseeds can see yield improvements up to 34% through effective insect pollination (ICAR, 2017). Underground, decomposer insects maintain soil structure, improve aeration, and support the microbial communities that plants depend on (Saha et al., 2025).

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The Next Wave: Biology Meets Technology

India isn't just sticking with traditional biocontrol. We're getting creative. AI-powered drones now survey fields, identify pest hotspots, and release beneficial insects exactly where they're needed most, reducing labor costs and improving coverage (IndiaAI, 2024). Digital pheromone traps monitor pest populations in real-time, helping farmers time their interventions perfectly (Reddy et al., 2024). Microbial biocontrol agents, fungi like *Beauveria bassiana* and *Metarhizium anisopliae,* are being commercialized through ICAR networks, offering farmers eco-friendly pest solutions you can spray (ICAR-NBAIR, 2023a). Meanwhile, ecological engineering approaches promoted by NIPHM and FAO encourage farmers to plant flowering borders and practice intercropping, providing food and shelter for beneficial insects year-round (NIPHM, 2016; FAO, 2018). We're witnessing a biological revolution powered by data, drones, and biodiversity.

What You Can Actually Do

If you're farming or know someone who is, here's practical advice:

* **Learn to identify the helpers.** Not every insect in your field is an enemy. Farmer field schools teach identification skills; knowing a ladybug from a leaf beetle matters (NIPHM, 2016).
* **Be selective with sprays.** If you must spray, use selective products that target specific pests. Broad-spectrum pesticides kill everything, including your allies. Spray only when pest numbers cross economic thresholds.
* **Plant borders strategically.** Marigolds, sunflowers, and coriander these flowering plants that provide nectar and habitat for parasitoids and pollinators. Think of them as recruitment stations for your insect army (FAO, 2018).
* **Try biocontrol products.** ICAR-NBAIR and local agricultural extension centers supply beneficial insects like *Trichogramma* and *Chrysoperla*, plus fungal biopesticides. They're increasingly affordable and accessible.
* **Join forces.** When farmer groups coordinate biocontrol efforts, the impact multiplies. Farmer-Producer Organizations have shown that collective action against pests works better than individual attempts (ICAR-NBAIR, 2022b).

ICAR-NBAIR has developed and licensed 53 biocontrol technologies to 126 companies. These innovations have helped reduce India's pesticide consumption by hundreds of metric tons each year (ICAR-NBAIR, 2022a).

Looking Forward

Not every agricultural hero wears boots and carries equipment. Some have wings. Some are smaller than a grain of rice. Beneficial insects aren't replacements for modern farming; they're partners in it. Their presence signals something important: ecological health, system resilience, genuine sustainability. By protecting and promoting pollinators, predators, and parasitoids, India accomplishes more than pest control. We're rebuilding soil life, cutting farmer costs, and securing our food future. As these tiny warriors reclaim their rightful place in our fields, they teach us something fundamental: when we work with nature instead of against it, everybody wins. The future of Indian farming might just depend on creatures most of us never notice. Maybe it's time we started paying attention.

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DNA- 70th Anniversary: Discovery to Present

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Deoxyribonucleic acid, also known as DNA, is a molecule that contains the genetic instructions for all known living things, including many viruses, in order to grow, develop, function, and reproduce. It is frequently referred to as the "genetic code" or the "blueprint of life" since it holds the data required for the development and functioning of an organism. DNA is a long, double-stranded molecule made up of repeating units called nucleotides. DNA is composed of organic bases, phosphoric acid, and 2'-deoxy-D-ribose sugar, or pentose sugar. The sugar-phosphate backbone is made up of the molecules of sugar and phosphate joined together by phosphodiester bonds. A 5'C-O-P-O-C3' linkage is created when the 3°C of one sugar molecule is coupled to P, which is then attached to the 5'C of the following sugar molecule. The sugar phosphate backbone (-P-S-P-S-P-S-) is produced by identical phosphodiester connections formed by the free 5' and 3' carbons of the two sugar molecules. Pyrimidines and purines are the two different kinds of organic bases, or nitrogenous bases, found in DNA. Thymine (T) and cytosine (C) are the pyrimidine bases, whereas adenine (A) and guanine (G) are the purine bases. The pyrimidines are linked to the 1'C of the pentose by their N at position 3, whereas the purines are attached by their N at position 9. The nucleosides are created when pentose molecules and organic bases combine, whereas nucleotides are created when phosphoric acid links with the 5' or 3C residues of pentose molecules in nucleosides. The phosphate groups at 5'C, which are triphosphates that compose nucleosides, are contained in the nucleotides that play a role in the formation of DNA.

DNA is a crucial genetic material that stores instructions for building, maintaining, and regulating an organism. It encodes information for protein synthesis, essential for all cellular processes. The journey towards identifying DNA as the genetic material began with Frederick Griffith's experiments in 1928. He was studying *Streptococcus pneumonia*, a bacterium that causes pneumonia. Griffith observed that a "transforming principle" from one strain of the bacterium could transfer genetic information to another strain, changing its characteristics. Oswald Avery, Colin MacLeod, and Maclyn McCarty continued Griffith's work and, in 1944, conclusively demonstrated that DNA was the substance responsible for the transformation observed in experiments of Griffith. They isolated DNA from the virulent strain of bacteria and showed that it could transform the non-virulent strain when added to it. Frankel-Conrat and Singer's TMV (tobacco mosaic virus) experiment from 1957 proved that some viruses employ RNA as their genetic material. However, Meischer identified the nucleic acids themselves much earlier, in 1871, and gave them the name nuclein. In eukaryotic cells, genes are located on chromosomes, which are composed of chromatin, a complex of DNA and proteins. This further supported the idea that DNA was the genetic material because it was intimately associated with genes and their inheritance.

The 70th anniversary of the discovery of the DNA double helix structure was celebrated in 2023. This ground-breaking discovery is one of the most significant milestones in the history of science and genetics. On April 25, 1953, Watson and Crick published their famous paper in the journal Nature, describing the double helix structure of DNA. This discovery revealed how genetic information is stored and replicated, with the famous double-stranded

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ladder-like structure of DNA composed of four nucleotide bases (adenine, thymine, cytosine, and guanine) that pair up in a complementary manner. A key turning point in the history of genetics and molecular biology will occur in 2023, the 70th anniversary of the discovery of the DNA structure. A summary of significant advancements and improvements in DNA study from its discovery to the present is given below:

Classical (from 1869s to 1970s)

S. No.	Years	Name of Scientists	Work done
1.	1869	Friedrich Miescher	Discover "nuclein" in the nuclei of human white blood cell, which is today known as DNA
2.	1881	Albrecht Kossel	Identified that nuclein is nucleic acid and gave name DNA
3.	1889	Richard Altman	Purified DNA from protein
4.	1928	Frederick Griffith	Gave "transformation principle"
5.	1944	Oswald Avery- Colin MacLeod-Maclyn McCarty	Proved that DNA is genetic material
6.	1950	Erwin Chargaff	Discovered that DNA composition is species specific
7.	1952	Alfred Hershey and Martha Chase	They said that DNA is hereditary material
8.	1952	Rosalind Franklin	Take 'Photo 51' a highly detailed image of the 'B' or hydrated form of DNA
9.	1953	Watson and Crick	Proposed the "double helix" structure of DNA
10.	1958	Meselson and Stahl	Demonstrated that DNA is semi-conservatively replicated

Modern Era (1970s to till now)

11.	1970	Hamilton O. Smith and Daniel Nathans	Discovered restriction enzyme
12.	1972	Stanley Norman Cohen and Herbert Boyer	Constructed Recombinant DNA
13.	1977	Fred Sanger	Developed method of DNA sequencing
14.	1983	Kary B. Mullis	Invent Polymerase chain reaction
15.	1985	Alec Jaffery	Developed DNA fingerprinting method
16.	1996	Alexander Rich	Discovered Z-DNA
17.	2003	Paul Hebert	Coined the term DNA barcoding

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18.	2012	Emmanuelle Charpentier and Jennifer Doudna	The pioneers of CRISPR

Achievements of DNA techniques:

Since its discovery, this unravelling process occurred during DNA replication, where the two strands are separated and new complementary strands are synthesized. The unravelling and replication of DNA play a crucial role in cell division and the transmission of genetic information from one generation to the next. This realization opened up a whole new field of research known as DNA nanotechnology. Scientists began to explore how DNA can be manipulated and engineered to create intricate structures and devices at the nanoscale. This was demonstrated by the invention of DNA sequencing methods, by Sanger and Coulson, which allowed for the deciphering of the genetic code and provided a pathway for the study of genetic disorders and personalized medicine. Another milestone was the development of polymerase chain reaction by Kary B. Mullis in 1985. Over the years, various techniques for analyzing and manipulating DNA have been developed. These include methods like DNA fingerprinting, DNA cloning, and DNA hybridization. These advancements have broadened the applications of DNA research in diverse fields.

Furthermore, the advancements in DNA analysis and manipulation techniques have paved the way for breakthroughs in fields such as forensics, agriculture, and biotechnology. One of the most significant recent milestones in DNA research is the advent of genome editing technologies, such as CRISPR-Cas9. CRISPR-Cas9, discovered in 2012, is a revolutionary genome editing tool that allows precise modification of DNA in living organisms. It has opened up new possibilities for targeted gene editing, gene therapy, and the study of gene function. CRISPR-Cas9 has the potential to treat genetic disorders, create genetically modified organisms, and advance our understanding of biology.

Importance of Milestones works:

DNA technology has significantly impacted communities and scientific resources through medical advances, agriculture improvements, and forensic science. It allows for genetically modified organisms (GMOs) with improved crop yields, pest resistance, and nutritional content, contributing to food security. DNA profiling is crucial in forensic science for crime solving and identifying suspects accurately. DNA technology also helps monitor and protect endangered species by analyzing their genetic diversity. DNA sequencing aids in conservation and resource management. It has sparked interest in genetics and biotechnology, increasing science literacy and community engagement. Advances in DNA technology provide educational resources for schools and universities. DNA technology has not only advanced scientific understanding but also significantly impacted community health, agriculture, conservation efforts, and other aspects of society, offering opportunities and challenges that must be carefully considered.

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Impact of Climatic Factors on Disease Incidence in Rice and Implications for Breeding

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Introduction

Rice is one of the most important crops in the world. It feeds billions of people, mainly in Asia. However, pathogens like *Magnaporthe oryzae* (which causes rice blast) and Rhizoctonia solani (which causes sheath blight) are always putting its productivity at risk. These infections don't work alone. Climate conditions, especially temperature and humidity, have a big effect on how often, how bad, and how quickly they spread. As climates change (due to global warming, changes in rainfall patterns, higher humidity or dew periods, etc.), it is important to understand how these conditions affect disease dynamics. This is important not only for managing diseases but also for guiding breeding programs to create rice varieties that can withstand them. This essay looks at how temperature and humidity affect outbreaks of blast and sheath blight, looks at data from field and lab investigations, and talks about how breeding tactics might change to keep rice production going and even improve it.

Effects of Temperature on Blast and Sheath Blight

Temperature has a complex effect on the growth of both rice blast and sheath blight. For M. oryzae, the best temperature for sporulation, infection, and lesion growth is usually in the middle range. Studies show that daytime/nighttime combinations around 25–28 °C (and often slightly lower night temperatures, like 17–23 °C) are good for spore germination, infection structure (appressorium) formation, and disease progression. When temperatures get too high, some of the body's defenses against disease don't work as well. However, in some cases, very high temperatures can make disease cycles less effective. For instance, *M. oryzae* infection effectiveness may diminish when diurnal or nocturnal temperatures surpass specific thresholds (30–33 °C).

Sheath blight, which is caused by *Rhizoctonia solani*, also reacts strongly to temperature. Field and experimental data show that sheath blight can grow and spread best when the temperature is between 30 and 34 °C and the low temperature is between 16 and 25 °C. When temperatures are too low, pathogens proliferate, spread, and get worse; when they are too high, other things like drying out or stress may stop the disease from spreading. Temperature also affects disease risk by interacting with humidity, dew duration, and the microclimate of the canopy (which may be cooler at the base or lower in the plant canopy).

Effects of Humidity on Disease Initiation and Progression

In many circumstances, humidity may be even more important than temperature. High relative humidity (RH), particularly exceeding 90%, frequently accompanied by leaf wetness or dew, facilitates critical phases in the pathogen life cycles: spore germination, the development of infective structures, lesion formation, and sporulation. For *M. oryzae*, conidial germination and appressorium production necessitate moisture; elevated relative humidity conditions lead to increased frequency of infection cycles. In models for forecasting blast disease and studying how diseases spread, RH (typically morning RH or night RH), rainfall, how long leaves stay wet, and dew are often the best predictors.

For sheath blight, the same is true: high relative humidity in the morning and evening (above 90%) and warm temperatures, and even mild rains, make the disease worse and spread faster. In numerous field investigations, disease severity has a

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positive correlation with elevated relative humidity (RH), particularly in lower canopies and near the soil surface or beneath dense canopies where dampness persists for extended durations. In Odisha, India, for instance, the best conditions for sheath blight to start and grow were temperatures between 31 and 34 °C during the day and between 17 and 23 °C at night, with relative humidity levels of 70 to 83% (and often over 90%).

The length of time that leaves stay wet, whether from dew, fog, drizzle, or rain splash, is also very important. Even if the relative humidity (RH) is high, pathogens may not be able to get through or may grow too slowly if there isn't enough moisture on the leaf surfaces. It is conceivable for numerous disease cycles to happen in one season when it is moist for a long time and the temperatures are warm and moderate.

Evidence and Observations: Modes of Disease Under Varying Climatic Regimes

Numerous studies indicate that the incidence of both blast and sheath blight increases during wet or humid seasons, in densely planted fields that sustain a humid microclimate, and with extended durations of dew or leaf wetness. Recent research on sheath blight across several seasons and genotypes revealed that the percent disease index (PDI) has a positive correlation with relative humidity and a negative correlation with excessively high maximum temperatures. In a six-season trial, relative humidity consistently exhibited a positive link with disease spread, while maximum and minimum temperatures shown more intricate relationships, occasionally negative, contingent upon other interacting variables.

In the case of rice blast, research in Tamil Nadu, India, and other places have revealed that when the maximum temperature increases beyond the optimal level, it is typically inversely correlated with the severity of the disease. On the other hand, rainfall, wind speed, and high relative humidity are positively correlated with the severity of the disease. Minimum air temperature, average relative humidity, and rainfall are common inputs for forecasting models.

Also, lab studies show that M. oryzae pathogenicity is higher in high humidity because the pathogen is more active and because plant basal defenses (such specific hormonal pathways and communication, including ethylene and jasmonic acid) are weaker. For instance, at approximately 90% relative humidity (RH), inhibition of ethylene signaling has been documented, leading to diminished baseline resistance in rice. Warm temperatures may also weaken JA-mediated or other defense responses, making genotypes that were once resistant or only partially resistant more vulnerable.

Implications of Climate Change

As the world gets warmer, rainfall patterns change, relative humidity changes, and the number of days with dew or wet leaves changes. This means that areas that used to be safe from blast or sheath blight may now be more likely to get sick. The changing agro-ecological zones could change where some types do well. Resistance genes that were effective in previous climatic conditions may be less effective in new temperature and humidity interactions, particularly if pathogen populations adapt or if host defense mechanisms are sensitive to temperature and humidity variations. For instance, some R genes may not work well at high temperatures, or their defense may not work as well when the humidity is too high. Because of these facts, breeders and pathologists need to plan resistance breeding programs with these changes in mind.

Breeding Implications: Strategies to Develop Climate-Resilient, Disease-Resistant Rice

1. Testing lines in different and changing weather conditions: Breeding trials should test lines in different places and times of year, especially in places that are humid, warm, or likely to have very wet or dewy periods, so that resistance under the "worst-case" conditions is known.

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2. Concentrate on quantitative, enduring resistance: Single major "R" genes may provide robust resistance; nevertheless, they are frequently circumvented when environmental conditions favor pathogen virulence or when there are transitions in pathogen races. Polygenic resistance (quantitative trait loci, or QTLs) is usually more stable as the environment changes.
3. Incorporation of knowledge of defense-pathway sensitivities: Breeders may select genotypes that maintain certain defense pathways (ethylene, jasmonic acid, etc.) under stress, or for compensatory mechanisms, such as enhanced structural defenses, increased leaf waxiness, cuticle traits, or canopy architecture that reduces humidity in the lower canopy or traits that reduce dew retention.
4. Using contemporary molecular tools: Marker-assisted selection and genomic selection can help combine several resistance loci with modest effects, speed up selection, and maybe even find alleles that work well in hot or humid conditions. Also, genome editing tools like CRISPR/Cas may be able to change susceptibility genes or regulatory elements so that they are less sensitive to damaging environmental conditions.
5. Integration with agronomic and managerial practices: Breeding cannot function in isolation. For instance, planting dates could be changed to avoid times when there is a lot of dew or high humidity. Canopy management (plant spacing and density), nutrient management (too much nitrogen makes the canopy more humid), and water management (drainage and levee management) can all help make microclimates less favorable for disease. These practices will help resistant cultivars perform better.
6. Making predictions, making models, and giving early warnings: Weather data (temperature, RH, rainfall, dew) can benefit both breeders and farmers with disease predicting systems. For breeders, they can assist figure out where to test new cultivars and what environmental stressors are most important. For farmers, they can tell them when to use fungicides or take other preventative steps. This lowers the selection pressure on infections and makes resistance last longer.

Conclusion

Temperature and humidity are the most important weather conditions that affect how often and how bad rice blast and sheath blight infections are. Moderate temperatures often help pathogens grow, while excessive temperatures, especially high ones, can either stop or change how diseases spread. High humidity, wet leaves or dew, and favorable microclimates (such a dense canopy and moist soil surface) all help many infection cycles and a high disease burden. Climate change is expected to disrupt the patterns of temperature, rainfall, and humidity. This could make the risk of catastrophic disease outbreaks worse, especially in places where disease control is already difficult. In response, rice breeding programs need to use methods that choose for stable, quantitative resistance in different weather conditions; include tests for environmental resilience (including defense mechanisms that work in high humidity and warmth); and work with agronomic practices, prediction tools, and pathogen monitoring. Only by using these kinds of integrated, forward-thinking methods can rice varieties stay productive and disease-resistant in a changing climate, which will protect food security for millions of people.

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AI and IoT in Entomology: A Smart Revolution in Studying and Managing Insects

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Introduction

Insects have ruled the planet for over 400 million years, shaping ecosystems, pollinating plants, recycling nutrients and sometimes ravaging crops. As the human population grows and the demand for sustainable agriculture intensifies, managing insects has become both more urgent and more complex. Traditional entomological methods hand collection, manual identification, and field scouting are time-consuming and often imprecise.

The twenty-first century, however, has witnessed a technological revolution where Artificial Intelligence (AI) and the Internet of Things (IoT) have started transforming agriculture and environmental sciences. Entomology, the study of insects, is rapidly evolving under their influence. Together AI and IoT are turning insect study and pest management from a reactive activity into a proactive, data-driven science. These technologies not only automate data collection but also enable real-time monitoring, predictive modeling, and decision support systems that make pest control more efficient, eco-friendly, and sustainable. This article explores how AI and IoT are reshaping the field of entomology from research labs to farmers' fields and what the future may hold for this fascinating merger of biology and technology.

Understanding AI and IoT: The Smart Duo

Artificial Intelligence (AI)

AI refers to the ability of machines to mimic human intelligence learning from data, recognizing patterns, and making decisions. In entomology, AI is widely used for:

- Image recognition of insects using computer vision.
- Predictive modeling of pest outbreaks.

Data analytics for understanding insect behavior, distribution, and diversity. Machine learning (ML) algorithms, particularly deep learning networks like convolutional neural networks (CNNs), have achieved remarkable accuracy in identifying insect species based on photographs or videos.

Internet of Things (IoT)

IoT is a network of interconnected sensors, devices, and tools that collect and exchange data in real time. In entomology, IoT devices—such as smart traps, environmental sensors, and camera modules—monitor temperature, humidity, light intensity, and insect activity continuously. The data is transmitted wirelessly to cloud platforms where AI analyzes it for trends and anomalies.

When combined, AI interprets what IoT senses, resulting in a powerful system for automated insect surveillance and management.

Applications of AI and IoT in Entomology

a. Smart Pest Monitoring Systems

One of the most promising applications of AI and IoT is in automated pest detection and monitoring. Traditional pheromone traps or light traps require manual inspection, but AI-enabled smart traps capture images of trapped insects and identify species instantly.

For example, in cotton fields, IoT-based traps equipped with micro-cameras and sensors capture images of pink bollworm moths. AI algorithms

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process these images to distinguish them from non-target insects with over 90% accuracy. This helps farmers take timely actions and minimizes pesticide misuse.

b. Predictive Pest Outbreak Modeling

AI systems can process data from weather sensors, soil moisture devices, and satellite imagery to predict pest emergence and migration. By combining historical pest data with current climate conditions, AI can forecast potential outbreaks days or even weeks in advance.Such predictive analytics allow farmers to adopt Integrated Pest Management (IPM) strategies, such as adjusting sowing dates, introducing natural enemies, or using biopesticides, thereby reducing reliance on synthetic chemicals.

c. IoT-Enabled Traps and Surveillance

IoT-based insect traps collect and transmit field data continuously. They may include:

- Optical sensors for detecting wing movement.
- Acoustic sensors for identifying wing-beat frequencies.
- Environmental sensors for temperature and humidity.

These smart traps are solar-powered and connected to mobile applications, allowing real-time remote access. Researchers and farmers receive instant alerts when pest thresholds are reached, optimizing crop protection measures.

d. AI in Insect Identification and Taxonomy

Taxonomists often face difficulties identifying morphologically similar insect species. AI-driven image recognition has simplified this task. Platforms like iNaturalist and BugGuide use AI to assist users in recognizing species from uploaded photos, making insect identification accessible to non-experts and enriching biodiversity databases.

Deep learning models are also helping museums digitize insect collections, enabling global access to taxonomic information.

e. Smart Beekeeping and Pollinator Monitoring

The global decline in pollinators, especially honeybees, has raised alarms. IoT devices are being deployed inside beehives to monitor parameters such as hive temperature, humidity, and bee activity. AI algorithms analyze sound and vibration data to detect colony stress, swarming behavior, or disease outbreaks early.

Such "smart hives" are revolutionizing apiculture by improving colony health management and enhancing pollination services in agriculture.

f. Vector Surveillance and Public Health

AI and IoT are instrumental in controlling insect vectors of diseases such as malaria, dengue, and chikungunya. IoT-based mosquito traps equipped with sensors and cameras can detect the presence of Aedes aegypti or Anopheles species and map their distribution. Machine learning models then analyze the data to predict vector population surges, aiding public health authorities in early intervention.

Achievements and Real-World Case Studies

Several successful projects worldwide demonstrate the integration of AI and IoT in entomological research:

1. Mosquito IoT System (MosquIoT) – Developed to monitor mosquito populations using low-cost sensors and AI-driven recognition models. It uses "TinyML" technology for on-device learning, reducing power consumption and internet dependency.

2. AI-Based Cotton Pest Detection in India – Smart pheromone traps with embedded cameras and neural networks have been tested in Gujarat and Maharashtra to detect pink bollworm moths with up to 95% accuracy, helping in timely pest control decisions.

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3. Smart Hive Technology in Europe – Beekeepers in Italy and Finland use IoT-based hives equipped with microphones and AI analysis tools to predict colony collapse well before visible symptoms appear.

4. Drone-Based Insect Monitoring – Researchers in Japan and Australia are using drones equipped with high-resolution cameras to detect locust swarms. AI models analyze aerial images to estimate swarm density and direction.

These examples showcase how AI and IoT are transitioning from experimental technologies to field-ready tools for scientists and farmers alike.

Advantages and Impact

1. The convergence of AI and IoT brings numerous benefits to entomology and agriculture:
2. Real-Time Data Collection: Continuous monitoring helps in early detection of pest invasions.
3. Precision Pest Management: Enables targeted control measures and reduces pesticide use.
4. Cost and Labor Efficiency: Automated systems reduce dependence on manual scouting.
5. Environmental Safety: Promotes eco-friendly practices and conserves beneficial insects.
6. Enhanced Decision Making: Predictive analytics improve planning and intervention timing.
7. Data-Driven Research: Provides large datasets for studying insect ecology, climate response, and behavior.

Collectively, these benefits contribute to sustainable agriculture, improved food security, and better ecosystem management.

Challenges and Limitations

Despite their promise, AI and IoT technologies face several constraints in their widespread adoption:

- High Initial Cost: Sensors, drones, and AI systems can be expensive for small farmers.
- Connectivity Issues: Poor internet access in rural areas limits IoT performance.
- Data Privacy and Security: Continuous monitoring raises concerns about data ownership and misuse.
- Technical Expertise: Farmers and field workers need training to operate and maintain devices.
- Species Complexity: Many insects have similar morphologies, making AI identification challenging.
- Environmental Constraints: Sensors must withstand harsh field conditions and power fluctuations.
- Addressing these challenges requires collaboration among engineers, entomologists, policymakers, and extension agencies.

The Road Ahead: Future Prospects

The future of entomology will be more digital, data-driven, and interconnected. Emerging trends include:

- Edge Computing and TinyML: On-device processing reduces the need for continuous internet access and ensures faster decision making.
- Multimodal Sensing: Integration of visual, acoustic, and environmental data enhances species identification accuracy.
- Blockchain Integration: Ensures data security and traceability in agricultural monitoring networks.
- AI-Driven Pest Forecast Apps: Farmers will receive mobile alerts and advisories generated by AI models linked to IoT traps.
- Citizen Science Platforms: Public participation in insect data collection will expand datasets for AI training.

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- Climate-Adaptive AI Models: Predict pest behavior under changing climatic conditions to support resilient agriculture.

These advancements will empower entomologists with smarter tools and provide farmers with actionable intelligence to manage pests sustainably.

Conclusion

The fusion of Artificial Intelligence and the Internet of Things represents a technological leap in entomology. Together, they are making the invisible visible—transforming minute observations of insect life into actionable insights. Whether it is identifying pests in real time, predicting outbreaks, safeguarding pollinators, or improving human health through vector control, the AI-IoT alliance is redefining how we understand and manage the insect world.

However, technology is only as effective as its accessibility and ethical use. To fully harness its potential, investment in rural digital infrastructure, data sharing frameworks, and farmer education is crucial. Collaboration among scientists, technologists, and policymakers will ensure that these innovations promote sustainability and biodiversity conservation.

In the coming decade, entomology will no longer be confined to microscopes and notebooks—it will thrive in the cloud, driven by sensors, algorithms, and data. As AI and IoT continue to evolve, they promise not only smarter pest control but also a deeper understanding of the delicate balance between humans and insects—one of nature's most intricate relationships.

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Sustainable Production and Resource Use Efficiency in Vegetable Farming

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Farming for the Future

Vegetables are vital for nutrition, income and employment across India. Yet, growing them sustainably has become increasingly challenging. Rising input costs, shrinking land holdings, soil degradation, and erratic rainfall all threaten the long-term productivity of our vegetable systems.

Sustainability in vegetable farming doesn't mean reducing productivity-it means producing more with fewer resources, while caring for soil, water and biodiversity. Across India, Scientists and farmers are now working together to make vegetable cultivation resource-efficient, climate-smart, and eco-friendly.

Efficient use of water: Every Drop Counts

Water is one of the most limiting resources in vegetable cultivation. Crops like tomato, okra, and cucumber demand frequent irrigation, but overwatering wastes both water and nutrients.

Modern technologies like drip irrigation, sprinkler systems, and fertigation have revolutionized water management in vegetables

- Drip irrigation delivers water directly to the root zone, reducing losses by evaporation and runoff.
- Mulching with organic or biodegradable materials helps retain soil moisture and suppress weeds
- Scheduling irrigation based on soil moisture sensors or weather data ensure water is applied only when the crop truly needs it.

Studies show that drip irrigation can save up to 50 % of water and increase yield by 20-40 % compared to traditional flood irrigation in vegetable crops.

Nutrient Management: Feeding the Crop, Not the Soil

Vegetables are nutrient-hungry crops, but excessive fertilizer use leads to nutrient leaching, soil pollution, and economic loss.

- Integrated Nutrient Management (INM) combines organic sources (compost, farmyard manure, vermicompost) with judicious use of inorganic fertilizers. This approach maintains soil health while meeting crop nutrient needs.
- Biofertilizers like *Azospirillum, Azotobacter, and Phosphate-Solubilizing Bacteria (PSB)* further improve a nutrient availability naturally.
- Fertigation (supplying fertilizer through drip irrigation) enhances nutrient-use efficiency by 30-40 % and reduces wastage.

Energy and Input Efficiency: Doing more with Less

- Energy inputs-from tillage, irrigation pumps, fertilizers, and pesticides-contribute to both production cost and environmental footprint
- Adopting low-input technologies, renewable energy (solar pumps), and minimum tillage can significantly cut energy consumption in vegetable farms.
- Use of biopesticides, trap crops, and natural enemies under Integrated Pest Management (IPM) helps minimize chemical pesticide use while keeping pest populations under control.

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Sustainability resources: Conventional vs sustainable approach

Resources	Conventional system	Sustainable Approach	Efficiency Gain
Water	Flood irrigation	Drip/mulch based irrigation	40-50%
Nutrients	Blanket fertilizer use	INM+fertigation	30-40%
Energy	Diesel Pumps	Solar powered drop	25-30%
Pest Control	Broad pesticides	IPM+biocontrol	Safer, 20% cost cut

Soil Health and Carbon Stewardship

Healthy soil is the foundation of sustainable vegetable production. Continuous cultivation and heavy fertilizer use often reduce soil organic matter.

Practices such as crop rotation, green manuring, and cover cropping improve soil structure, add organic carbon, and prevent erosion. Incorporating crop residues instead of burning them enriches the soil and enhances microbial activity.

Inclusion of legumes like cowpea or beans in vegetable rotations adds natural nitrogen to the soil, reducing fertilizer need in the next crop.

Technology and Knowledge Integrations

Modern sustainability also relies on digital agriculture-tools like soil sensors, mobile apps, and remote monitoring systems enable farmers to make data-driven decisions on irrigation, fertilization, and pest management

- Farmer training and participatory research plays a vital role. When farmers understand the "why" behind sustainable practices, adoption rates rise dramatically.
- The Road to Sustainable Vegetable Farming
- The shift toward sustainability isn't a single step but a continuous journey. It involves combining scientific innovation, local knowledge and policy support.
- Government programs like the National Mission on Sustainable Agriculture (NMSA) and Paramparagat Krish Vikas Yojana (PKVY) encourage resource-efficient and organic vegetable farming.

If adopted widely, sustainable practices can lead to

- Higher water and nutrient efficiency
- Reduced environmental impact
- Improved soil fertility and biodiversity
- Better returns for farmers

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Alternative Proteins: The Future of Sustainable Food

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Alternative proteins spanning plant-based meats, insect proteins, and cellular agriculture, are reshaping the landscape of food production and consumption globally. Driven by urgent concerns over environmental sustainability, resource constraints, and population growth, these innovative protein sources promise to transform how nutritious foods are produced while reducing the ecological footprint of agriculture. Plant-based meats leverage the functionality of crops like soy, pea, and wheat to replicate the flavour and texture of conventional meat, offering a sustainable and accessible substitute. Insect proteins, with their efficient conversion of waste into high-quality nutrients, stand out as a resource-light option with significant ecological benefits. Cutting-edge cellular agriculture pioneers the cultivation of real animal meat from cells, eliminating the need for livestock rearing and presenting vast potential for animal welfare, food security, and environmental impact. As alternative proteins move into the mainstream, they are set to play a critical role in meeting the nutritional and sustainability needs of a growing global population.

Introduction

The global food system is experiencing a revolution, with alternative proteins emerging as a central solution to some of the world's most pressing challenges. Driven by population growth, resource constraints, sustainability concerns, and shifting consumer preferences, alternative proteins encompassing plant-based meats, insect proteins, and cellular agriculture offer promising ways to produce nutritious, eco-friendly food. This article explores these groundbreaking protein sources, inspecting their science, benefits, difficulties and potential to transform agriculture and human diets.

Plant Based Meat

Insect Based Protein

Cultured Meat

The Rise of Plant Based Meats

Plant-based meats are perhaps the most familiar face of the alternative protein movement, flooding supermarket shelves and fast-food chains worldwide. Using proteins extracted from soy, pea, lentil, wheat, chickpea and other crops, food technologists mimic the appearance, flavour and texture of animal meat through advanced processes such as extrusion, emulsification, and flavour encapsulation. The plant-based meat sector is booming due to its sustainability advantages. Compared to animal agriculture, these products require far less land and water, and emit fewer greenhouse gases. These foods appeal to vegetarians, vegans, and growing numbers of flexitarian consumers looking to cut animal products for health or environmental reasons.

Nutritionally, plant-based meats can be excellent protein sources and are often fortified with nutrients like iron and vitamin B12. Ongoing research continues to improve taste and nutritional

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profiles while addressing critics concerns over high processing levels and sodium content.

Insect Proteins: An Eco-Friendly Protein Solution

For billions worldwide, insects have long been a trusted protein source and they are now gaining momentum as a sustainable superfood in global markets. Edible species like crickets, mealworms and black soldier fly larvae are remarkably efficient. They need minimal land, water and feed, and emit a fraction of the greenhouse gases of cattle or poultry farms.

Insects are rich in essential amino acids, healthy fats, and micronutrients, making them a complete protein source. The sector is supported for its ability to upcycle food waste into protein, supporting circular economy models. While insect protein has found niche popularity in snacks, protein bars, and animal feeds, key challenges include consumer acceptance in Western markets and the need for robust food safety standards.

Still, with the global push for sustainable foods and innovative processing methods, insect proteins are expected to become a critical part of future food systems particularly in regions facing resource constraints and rising protein demand.

Cellular Agriculture: Cultured Meat on the Horizon

At the cutting edge of protein innovation lies cellular agriculture by growing real meat directly from animal cells in bioreactors. Using techniques developed in biotechnology and tissue engineering, cellular agriculture produces beef, chicken and seafood that are molecularly identical to conventional meat without raising or slaughtering animals. This technology can massively reduce greenhouse gas emissions, land and water use, and antibiotic reliance associated with factory farming. Cultured meat addresses ethical concerns and can be customized for enhanced nutrition, texture, or flavour by controlling the cell-culture environment.

Despite its promise, challenges remain: high production costs, regulatory barriers, and scaling difficulties have so far delayed mass-market entry, and cultured meats are still several times more expensive than conventional products.

Key Aspects of Alternative Proteins

Protein Type	Main Source	Sustainability	Nutritional Value	Acceptance	Market Share
Plant-Based Meat	Soy, pea, wheat	High	Moderate-high	High	62%
Insect Protein	Crickets, larvae	Very High	High	Low-medium	~5%
Cultured/cultivated	Animal cells	Very High	High (customizable)	Low	Emerging

Barriers and Opportunities

Common challenges for all segments include production cost, taste/texture optimization, regulation, and consumer acceptance. For instance, plant-based and insect protein products must continually improve culinary appeal; cultured meats require major scale-up and regulatory approvals.

Opportunities abound as global food and agri-tech leaders invest in research, biotech, and food science to make alternative proteins delicious, affordable and widely available. Partnerships between startups, large corporations and governments globally aim to accelerate innovation and bring these novel proteins mainstream.

Conclusion

Alternative proteins will play an essential role in meeting the nutrition, environmental and ethical challenges of the 21st century. Continued innovation in plant-based meats, insect proteins, and cellular agriculture stands to redefine food systems and empower healthier, more sustainable diets for the world's growing population. By embracing these technologies, society can ensure secure, climate-resilient and responsible protein production for generations to come.

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Vertical Farming Systems: A New Paradigm for Resource-Efficient Food Production

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Vertical farming represents a transformative approach to urban agriculture, offering a sustainable solution to food production challenges amid rapid urbanization and environmental stress. This article assesses the sustainability of vertical farming systems (VFS) through environmental, economic, and social dimensions. By integrating hydroponics, aeroponics, and aquaponics with controlled environment agriculture, VFS enables optimized resource utilization and year-round production. Environmentally, it minimizes land and water requirements and can reduce greenhouse gas emissions relative to conventional agriculture. Technological advances in LED lighting and climate control have further enhanced system efficiency. Economically, VFS offers prospects for improving urban food security and shortening supply chains, yet high initial capital investment and energy costs constrain profitability. Socially, vertical farming can enhance access to nutritious food, promote urban resilience, and stimulate community participation in food systems. Nevertheless, barriers such as high technological demands, limited crop diversity, and dependence on non-renewable energy impede widespread adoption. The article concludes that realizing the full potential of vertical farming requires targeted policy support, research innovation, and integration with renewable energy sources to ensure long-term sustainability and scalability of VFS within the global food system.

Introduction

As global population growth and urbanization intensify, the demand for sustainable food production systems has become more urgent. This burgeoning global population growth is placing unprecedented pressure on traditional agricultural systems to meet the growing food demands while minimizing environmental degradation (Sarkar et al.,2023). Vertical farming, a technology-driven agricultural practice where crops are grown in stacked layers within controlled environments, has emerged as a promising solution to address this challenge (Sarkar and Sarkar, 2024a). Unlike conventional agriculture, vertical farming optimizes space usage, reduces water consumption, and minimizes the reliance on pesticides, making it an innovative alternative to traditional farming systems (Despommier, 2010). The core advantage of vertical farming lies in its ability to grow crops year-round in urban areas, closer to consumers, thereby reducing transportation emissions and providing fresh produce even in regions where arable land is scarce (Banerjee & Adenaeuer, 2014). Furthermore, the integration of advanced technologies-such as LED lighting, hydroponic and aeroponic systems, and automated monitoring has the potential to significantly enhance the efficiency of resource use (Al-Chalabi, 2015). Despite these promising opportunities, several challenges remain. High energy consumption, the initial capital investment required, and the technical expertise needed for system maintenance are notable barriers to its widespread adoption (Kalantari et al., 2018). This article aims to review the sustainability of vertical farming systems (VFS) by analyzing both the opportunities and challenges associated with their implementation. Through a multidisciplinary lens, this article will explore the environmental, economic, and social impacts of vertical farming, assess the technological innovations driving its development, and examine the policy frameworks that could

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facilitate its integration into future urban food systems. By identifying key gaps and opportunities, this study provides a comprehensive understanding of how vertical farming can contribute to a more sustainable food production paradigm in the 21st century.

1. Overview of Vertical Farming Systems (VFS)

Vertical farming systems (VFS) (Fig.1) are an innovative approach to agricultural production that aims to optimize resource use while increasing crop yield, particularly in urban settings (Sarkar and Sarkar, 2024a). This method involves the cultivation of crops in vertically stacked layers, often integrated within controlled-environment agriculture (CEA) systems. The key advantage of VFS is its ability to produce food in spaces that would otherwise be unsuitable for traditional agriculture, such as urban buildings, reducing the need for arable land and minimizing transportation distances to consumers (Kalantari et al., 2018; Sarkar and Sarkar, 2024b).

Fig 1: Vertical Farming

1.1. Types of Vertical Farming

Vertical farming can be broadly categorized into three main types based on the cultivation method: hydroponics, aeroponics, and aquaponics. Hydroponics is the most common form of vertical farming, where plants are grown in a nutrient-rich water solution without soil. This method allows for precise control over nutrient levels and water use, leading to significant water savings compared to conventional agriculture (Al-Kodmany, 2018). Aeroponics takes this a step further by suspending plant roots in the air and periodically misting them with nutrient-laden water. Aeroponics is highly efficient in water use, often reducing consumption by up to 98% compared to traditional soil-based agriculture. Aquaponics integrates hydroponic farming with aquaculture, creating a symbiotic system where waste produced by fish is converted into nutrients for plant growth, while the plants help purify the water for the fish.

1.2. Key Components of Vertical Farming Systems

Vertical farming systems rely on several critical components to maintain optimal growing conditions. These include (Fig 2):

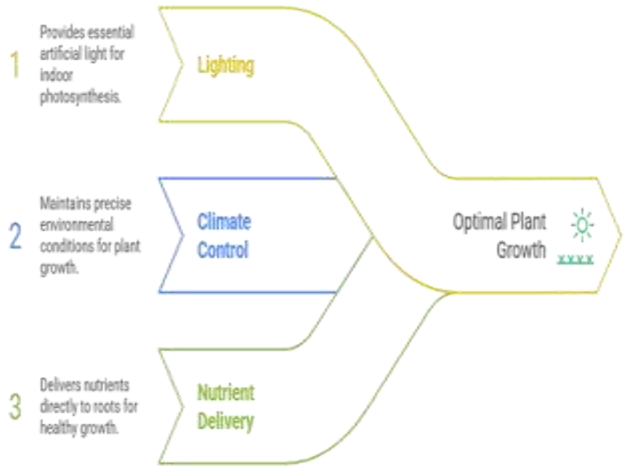

Fig.2 Components of Vertical Farming Systems

Lighting:

Since most vertical farms operate indoors or in controlled environments, artificial lighting, typically LED, is essential for photosynthesis. LED technology has advanced significantly, allowing for energy-efficient light sources that can be tailored to the specific needs of plants.

Climate Control:

VFS requires precise control of temperature, humidity, and CO_2 levels. Sophisticated sensors and automation systems ensure that environmental conditions are maintained for optimal plant growth, regardless of external climate factors.

Nutrient Delivery Systems:

In hydroponic and aeroponic systems, nutrients are delivered directly to plant roots through a liquid solution. Automated systems monitor nutrient levels and adjust them as necessary to promote healthy growth and maximize efficiency.

2. Environmental Sustainability of Vertical Farming

Vertical farming systems (VFS) present both opportunities and challenges in terms of environmental sustainability, primarily through their potential to optimize resource use and reduce environmental impacts when compared to traditional agriculture. However, realizing these benefits requires addressing key sustainability metrics: energy consumption, water efficiency, carbon footprint, and waste management.

2.1. Energy Consumption and Efficiency

One of the primary environmental challenges of vertical farming is the significant energy demand, particularly from artificial lighting and climate control systems. Most vertical farms rely on LED lighting to replicate sunlight and provide the necessary light spectrum for plant growth. While modern LED technology is highly energy-efficient compared to traditional lighting methods, vertical farming still consumes significantly more energy than field-based agriculture, where crops rely on natural sunlight. To mitigate this, advancements in LED efficiency, along with the integration of renewable energy sources such as solar or wind, are critical for improving the environmental sustainability of these systems.

2.2. Water Use Efficiency

A key advantage of vertical farming is its capacity for high water-use efficiency. Unlike conventional agriculture, which is responsible for over 70% of global freshwater withdrawals, vertical farming can dramatically reduce water consumption through closed-loop systems. Hydroponic and aeroponic systems, which are commonly used in vertical farms, typically require up to 90% less water than soil-based farming (Despommier, 2010). These systems recirculate water, allowing for precise control of water usage and minimizing loss through evaporation or runoff. However, water use in vertical farms is not entirely impact-free, as there are challenges related to the disposal and treatment of nutrient-rich wastewater.

2.3. Carbon Footprint and Emissions

Vertical farming's carbon footprint is another critical aspect of its environmental sustainability. While vertical farms reduce land-use pressures, their reliance on energy-intensive systems, particularly in urban settings, can lead to higher greenhouse gas (GHG) emissions if powered by non-renewable energy sources. However, when coupled with renewable energy, vertical farming systems can significantly reduce their carbon footprint, presenting a pathway toward carbon-neutral food production.

2.4. Waste Management and Resource Recycling

Effective waste management is another area where vertical farming can improve environmental sustainability. Vertical farming offers the potential for closed-loop systems where waste, such as plant residues, can be composted or repurposed as bioenergy (Sarkar et al., 2023a, Sarkar et al., 2023b). Moreover, the controlled nature of vertical farms means that pesticide and herbicide use is typically much lower or entirely absent, reducing the environmental pollution often associated with conventional farming practices (Maurya et al, 2023). Additionally, innovations in nutrient recycling, such as using organic waste as a fertilizer source, are increasingly being integrated into vertical farming systems to further reduce waste and increase circularity.

3. Economic Sustainability of Vertical Farming

Economic sustainability is a critical factor determining the long-term viability of vertical farming systems (VFS). The financial dynamics of vertical farming involve considerations such as capital investment, operating expenses, profitability, and market scalability. While vertical farming presents promising economic opportunities, several challenges must be addressed to ensure sustainable economic growth.

3.1. Capital and Operating Costs

One of the primary economic barriers to vertical farming is the high initial capital investment. Establishing a vertical farm requires significant upfront costs for infrastructure, technology, and equipment, such as LED lighting, hydroponic or aeroponic systems, climate control mechanisms, and automation technologies. The dependence on consistent energy sources not only increases costs but also raises concerns about the economic sustainability of vertical farming unless renewable energy sources are integrated into the system.

3.2. Profitability and Market Potential

Despite the high initial and operating costs, vertical farms have the potential to become profitable, especially in urban areas where land prices are high, and fresh produce is in demand. The ability of vertical farming systems to produce crops year-round, independent of seasonal variation, adds to their economic appeal. Additionally, the reduced transportation costs due to proximity to urban centers can lower logistics expenses and improve the overall profit margins (Despommier, 2010). However, profitability is highly dependent on local market conditions, the type of crops grown, and the efficiency of the technology utilized. Nevertheless, achieving consistent profitability requires optimizing energy efficiency and scaling up operations to leverage economies of scale.

3.3. Economic Scalability

One of the central challenges in the economic sustainability of vertical farming is scalability. While small-scale vertical farms can be economically viable in niche markets, such as local restaurants or direct-to-consumer sales, scaling these operations to meet broader market demand requires significant investment and technological advancements. Economies of scale are difficult to achieve due to the complex and costly technology involved. Studies show that without substantial cost reductions in key areas like energy, vertical farming will struggle to compete with traditional agriculture on a large scale.

3.4. Job Creation and Local

Economies Vertical farming also has the potential to contribute to local economies by creating new job opportunities in agriculture, technology, and logistics. This is particularly significant in urban areas, where traditional farming jobs are scarce. The demand for skilled labour in fields such as plant science, data analysis, and farm management could stimulate economic growth and innovation in urban centers. Moreover, vertical farms can boost local economies by reducing dependency on food imports, keeping more food production within the community (Touliatos et al., 2016). However, the highly automated nature of many vertical farms could reduce the need for manual labour, leading to fewer job opportunities compared to traditional farming. Therefore, while vertical farming offers new economic opportunities, its potential impact on job creation is complex and requires further investigation to ensure that it supports local economies in a balanced and equitable way.

4. Social Sustainability of Vertical Farming

Social sustainability, a critical component of sustainable development, focuses on the impacts of agricultural practices on society, including food security, health benefits, urbanization, and community resilience. Vertical farming (VF) offers

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significant potential to address many of these social challenges, particularly in the context of growing urban populations and increasing demand for locally sourced, fresh produce.

4.1.Food Security and Access to Fresh Produce

One of the most compelling arguments for the social sustainability of vertical farming is its potential to enhance food security, particularly in urban areas where access to fresh and nutritious food is often limited. Vertical farms can be located within or near cities, reducing the distance food must travel from farm to table. This proximity not only lowers transportation emissions but also increases the availability of fresh produce in urban food deserts areas where access to affordable and healthy food is scarce. As cities continue to grow, ensuring a stable supply of locally produced food becomes essential for maintaining food security, and vertical farming can play a pivotal role in this process.

4.2. Health and Nutrition Benefits

Vertical farming systems can significantly impact public health by providing communities with a steady supply of nutrient-rich vegetables and fruits. Unlike conventional farming, which is often dependent on seasonal cycles, vertical farms can produce crops year-round, ensuring a consistent supply of fresh produce. Moreover, the controlled environment of vertical farms minimizes the use of pesticides, thereby providing cleaner, safer food to consumers.

4.3.Urbanization and its Role in Sustainable Farming

Urbanization is both a challenge and an opportunity for social sustainability in agriculture. As more people move to cities, the demand for sustainable urban agriculture grows. Vertical farming, integrated into urban landscapes, can mitigate the adverse effects of urban sprawl by utilizing limited space more efficiently. By producing food in high-density areas, vertical farming reduces the need for large-scale rural farms and minimizes land degradation and deforestation (Sarkar and Sarkar, 2025a). Additionally, urban vertical farms can revitalize underutilized spaces, such as abandoned buildings, contributing to urban regeneration and community development.

4.4.Consumer Perception and Acceptance

The success of vertical farming hinges not only on its technical and environmental benefits but also on consumer acceptance. Widespread adoption requires continued education and transparent communication about the safety, sustainability, and advantages of vertical farming. Building this trust is crucial for ensuring the long-term social sustainability of these systems.

4.5.Equity and Access

While vertical farming holds promise, questions of equity remain. Many vertical farming operations require significant capital investment and technical expertise, which can limit access for small-scale farmers and underserved communities. To truly achieve social sustainability, it is essential to develop models that make vertical farming accessible to diverse socioeconomic groups. This might include community-driven projects, public-private partnerships, or government incentives aimed at supporting smaller-scale, local initiatives (Banerjee & Adenaeuer, 2014). Such efforts can help bridge the gap between high-tech agricultural solutions and the needs of marginalized communities.

5. Technological Opportunities in Vertical Farming

Technological innovation plays a crucial role in advancing the sustainability and efficiency of vertical farming systems (VFS). Recent developments in LED lighting, automation, artificial intelligence (AI), and biotechnology have significantly transformed vertical farming, offering opportunities to address the environmental and economic challenges associated with traditional agriculture.

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5.1. Innovations in LED Lighting and Energy Efficiency

Energy consumption remains one of the most significant operational costs in vertical farming. Advances in light-emitting diode (LED) technology have enabled more energy-efficient lighting systems that can be fine-tuned to deliver optimal light spectra for plant growth. The ability to control light intensity and wavelength offers opportunities to optimize growth conditions for different crop types, making LED lighting a critical component of sustainable vertical farming.

5.2. Automation and Artificial Intelligence in Farming

Automation is transforming vertical farming by reducing labour costs and increasing precision in plant management. The integration of AI and machine learning algorithms allows for real-time monitoring of plant health, environmental conditions, and resource use (Sarkar and Sarkar, 2025b). Automated systems equipped with AI can optimize irrigation, nutrient delivery, and climate control, resulting in higher yields and reduced resource waste. Moreover, robotics are being increasingly used for planting, harvesting, and packaging, further reducing the reliance on human labour and improving operational efficiency.

5.3. Data-Driven Farming

IoT and Big Data The use of the Internet of Things (IoT) and big data analytics is transforming the way vertical farms are managed. Sensors distributed throughout farms can monitor environmental conditions, water usage, and plant health in real time, feeding data into advanced analytics platforms that predict plant needs and optimize resource allocation. This data-driven approach allows for more precise control over farm conditions, leading to increased yields, resource efficiency, and reduced environmental impact. The application of IoT in vertical farming also supports predictive maintenance of equipment, minimizing downtime and ensuring optimal operational efficiency.

6. Challenges to Sustainability in Vertical Farming

Vertical farming presents a promising approach to sustainable agriculture, but several challenges hinder its widespread adoption and long-term sustainability. Addressing these challenges requires a nuanced understanding of the current limitations and potential solutions.

6.1. High Initial Costs and Financial Barriers

The capital investment required for setting up vertical farming systems remains one of the most significant barriers. Initial costs encompass the infrastructure, technology, and ongoing maintenance, which can be prohibitively expensive for small-scale operators. The financial feasibility of vertical farms is further complicated by the need for specialized equipment and controlled environment systems, which adds to the financial burden.

6.2. Energy Dependency and Renewable Energy

Integration Energy consumption is a major concern for vertical farming, as these systems require significant amounts of electricity to power artificial lighting, climate control systems, and other technologies. Integrating renewable energy sources, such as solar or wind power, into vertical farming operations could mitigate some of these issues, but it also involves additional costs and technological hurdles. The intermittent nature of renewable energy sources further complicates their integration, necessitating effective energy storage solutions.

6.3. Technical Knowledge and Expertise Gaps

The successful operation of vertical farms requires a high level of technical expertise in areas such as plant biology, engineering, and data analytics. The complexity of managing controlled environments and optimizing growth conditions presents a steep learning curve for new entrants.

6.4. Limited Crop Variety and Biodiversity

Vertical farming systems are often optimized for specific crops, particularly leafy greens and herbs, due to their lower light and space requirements. However, growing a diverse range of crops in vertical farms poses significant challenges, including the need for varied light spectra and growth conditions. This limitation impacts the overall biodiversity of vertical farms and constrains their ability to contribute to food system resilience.

7. Conclusion

Vertical farming represents a transformative approach to modern agriculture, offering significant opportunities to enhance sustainability in food production systems. As this review has highlighted, vertical farming systems provide a promising solution to address critical issues such as urban food security, resource efficiency, and the environmental impacts of traditional agriculture. By utilizing controlled environments and advanced technologies, vertical farms can potentially reduce water and land use, lower greenhouse gas emissions, and enable year-round production of fresh produce. However, realizing the full potential of vertical farming requires overcoming several substantial challenges. High initial capital investments and operational costs continue to be major barriers to widespread adoption. The reliance on energy-intensive technologies necessitates the integration of renewable energy sources and innovative energy management solutions to ensure the environmental benefits of vertical farming are not undermined by its energy footprint. Furthermore, the technical expertise required to manage these systems poses a significant hurdle, underscoring the need for specialized training and interdisciplinary collaboration. The limited variety of crops that can be economically grown in vertical farms also highlights a gap in current practices, suggesting that further research and technological development are needed to expand crop diversity and optimize growth conditions for a broader range of species. Additionally, policy and regulatory frameworks must evolve to support the growth of vertical farming by providing incentives, standards, and infrastructure that align with sustainable practices. Looking ahead, the future of vertical farming lies in its ability to adapt and innovate. Emerging technologies, such as artificial intelligence, robotics, and advanced data analytics, hold the potential to address many of the current limitations and enhance the efficiency and sustainability of vertical farming systems. As research continues to advance, it will be crucial to balance technological developments with practical, scalable solutions that align with broader sustainability goals. In conclusion, while vertical farming presents a viable pathway to a more sustainable agricultural future, its success will depend on overcoming financial, technical, and operational challenges. By fostering innovation, enhancing education and training, and implementing supportive policies, stakeholders can harness the full potential of vertical farming to contribute to a resilient and sustainable food system. Future research should focus on addressing these challenges and exploring new opportunities to ensure that vertical farming can play a pivotal role in the global effort to create a more sustainable and secure food supply.

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CRISPR–Cas Revolution in Agriculture: Precision Genome Editing for Sustainable Crop Improvement and Food Security

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CRISPR–Cas genome editing has revolutionized modern biology and is rapidly transforming agricultural research and crop improvement. This powerful, precise and cost-effective technology enables targeted modification of genes to enhance yield, disease resistance, stress tolerance and nutritional quality in crops. The system, derived from a natural bacterial defense mechanism, has been refined through tools such as base and prime editing, making complex plant genomes more accessible. India has emerged as a key participant in CRISPR-based agricultural research, with efforts focusing on major food and horticultural crops. As policies evolve and precision tools advance, CRISPR–Cas stands poised to drive a new era of sustainable, resilient and high-quality crop production globally and in India.

Introduction

CRISPR–Cas systems (Clustered Regularly Interspaced Short Palindromic Repeats and CRISPR-associated proteins) have transformed biology in the past decade. What began as a bacterial immune memory has become a precise, efficient toolkit for editing genomes across plants, animals and microbes. In agriculture, CRISPR offers faster, targeted improvements from disease resistance and stress tolerance to nutritional enhancement potentially accelerating breeding and reducing reliance on chemical inputs. This article traces CRISPR's history, explains key methodologies, surveys agricultural applications and case studies in major crops, considers the Indian context and looks ahead to future trends.

A brief history:

CRISPR sequences were first noticed as odd, repeating DNA segments in bacteria and archaea during the late 1980s and 1990s, but their purpose remained mysterious until the 2000s when researchers recognized them as part of an adaptive immune system that stores viral DNA snippets and uses them to fight repeat infections. The breakthrough that made CRISPR a gene-editing tool occurred in 2012: Emmanuelle Charpentier and Jennifer Doudna (and contemporaneous foundational work by others) showed that the CRISPR–Cas9 enzyme could be programmed with an RNA guide to cut DNA at precise sites and that the system could be simplified into a single-guide RNA to target new sequences opening the door to routine genome engineering. Over the following years the toolbox expanded (Cas variants, base editors, prime editors), increasing precision, reducing off-targets and broadening the types of edits possible.

Core principles and how CRISPR–Cas works

At its core, CRISPR–Cas editing relies on two parts:

1. **Guide RNA (gRNA)**: a short RNA molecule that pairs with the DNA target sequence through base complementarity.
2. **A nuclease (Cas protein)**: an enzyme (most commonly Cas9) that creates a double-strand break (DSB) at the targeted site.

After the break, a cell repairs the DNA either by non-homologous end joining (NHEJ), often introducing small insertions/deletions (useful for knocking out

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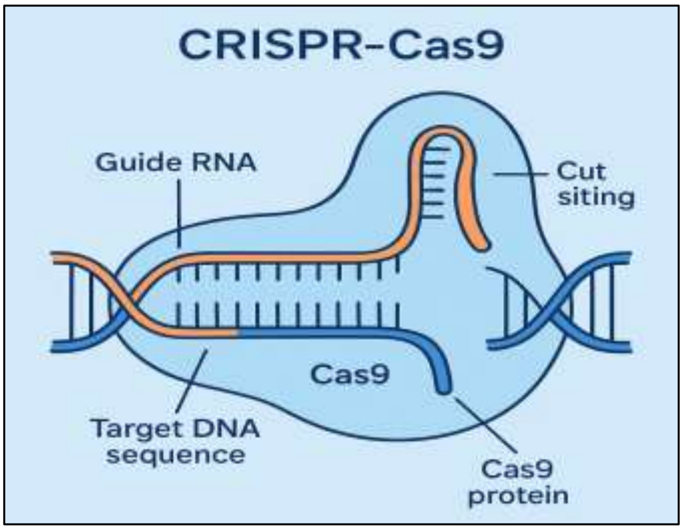
genes), or by homology-directed repair (HDR) if a repair template is provided (used to insert or replace sequences). Improvements on the basic platform include **base editors** (which chemically convert one nucleotide to another without making DSBs) and **prime editors** (which can write small sequences directly at a target using a reverse transcriptase fused to Cas9 nickase), allowing precise point mutations and small insertions with lower risk of large unintended changes. These advances have greatly increased CRISPR's utility for plant breeding.



Methodology and procedural overview:

Applying CRISPR in crop plants follows a set of broadly similar steps, though specifics vary by species and lab:

1. **Target selection and guide design**
   - Identify gene(s) or regulatory elements tied to the desired trait (disease susceptibility genes, negative regulators of stress tolerance, quality traits).
   - Design gRNAs that uniquely bind target DNA with minimal predicted off-targets.
2. **Construct assembly**
   - Build DNA constructs expressing the Cas protein (or base/prime editor) and gRNA(s). Plant-specific promoters drive expression. Multiplexing (editing several targets simultaneously) is common.
3. **Delivery into plant cells**
   - Methods include Agrobacterium-mediated transformation (common for many dicots and some monocots), biolistic particle bombardment, or protoplast transfection. Newer approaches explore RNP (ribonucleoprotein) delivery so no foreign DNA integrates.
4. **Regeneration and selection**
   - Edited cells are regenerated into whole plants via tissue culture. Selection markers or PCR/genotyping identify edited events.
5. **Molecular characterization**
   - Sequence the target locus to confirm edits and check for off-target changes. Cytogenetic and copy-number analyses may be performed.
6. **Phenotyping and field evaluation**
   - Edited lines are tested in greenhouse and multi-location field trials for trait performance and agronomic stability.
7. **Regulatory and safety testing**
   - Depending on jurisdiction and the nature of the edit (whether novel DNA was inserted or only small edits without foreign DNA), different regulatory pathways apply.

This workflow is being refined constantly: for example, DNA-free editing (delivering Cas protein and gRNA directly as RNPs) can produce edited plants indistinguishable from those generated by conventional breeding and may simplify regulatory pathways in some countries.

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Applications in agriculture:

CRISPR's strengths lie in precision, speed and the ability to target endogenous genes directly. Key application areas:

- **Disease resistance**: Knockout of susceptibility genes or editing of resistance-related genes has produced plants resistant to viruses, bacteria and fungi (e.g., citrus, rice, tomato).
- **Abiotic stress tolerance**: Altering regulators of drought, salinity and temperature responses can improve resilience to climate extremes.
- **Yield and resource use efficiency**: Edits that improve grain filling, plant architecture or nitrogen use can increase productivity or input efficiency.
- **Quality and nutrition**: Biofortification (e.g., increasing provitamin A, modifying oil composition) and reducing anti-nutritional factors.
- **Herbicide tolerance and domestication traits**: Creating point mutations to confer herbicide resistance or rapidly domesticating wild relatives by editing key domestication loci.
- **Post-harvest traits**: Slowing browning, altering ripening to reduce waste.

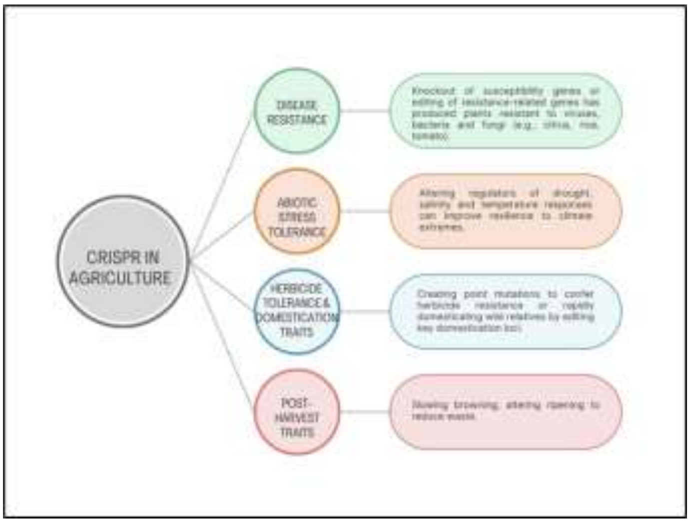
Published reviews and reports show active work across staple crops (rice, wheat, maize), horticultural crops (tomato, banana, potato) and even in livestock and aquaculture (disease resistance, productivity traits). The breadth is growing with improved delivery and editing accuracy.

Case studies in major crops

Rice

Rice has been one of the most intensively edited crops. Examples include edits to:

- **OsSWEET promoter regions** to confer resistance to bacterial blight by disrupting pathogen transcriptional activation sites.
- **Genes controlling yield and grain size** (e.g., OsGS3, OsGn1a) to improve grain yield and architecture.
- **Stress tolerance genes** for drought and salinity; and base editing to create herbicide resistance alleles. Rice case studies demonstrate both single-gene knockouts and subtle allelic modifications improving resilience and yield.



Wheat

Wheat is more complex because of hexaploid genomes. CRISPR has been used to simultaneously edit homeologous copies of genes to produce visible phenotypes — for example, editing **TaMLO** homologs provided broad powdery mildew resistance. Multiplex editing across subgenomes is now routine in wheat research.

Tomato and potato

Tomato has been a testbed for fruit quality and shelf-life edits (e.g., ripening regulators, firmness genes). In potato and other clonally propagated crops, CRISPR can introduce desired changes without sexual crossing, which simplifies maintenance of elite varieties. Potato researchers have used CRISPR to reduce enzymatic browning and to alter tuber composition.

Maize and other cereals

In maize, edits target stress responses, flowering time and yield components; in many cereals, base editing and prime editing are being trialed to create precise SNPs associated with desirable agronomic traits.

The Indian perspective — research, deployment and regulation

India has a large scientific base working on genome editing in crops that matter to Indian agriculture (rice, wheat, pulses, millets, potato, banana, cotton and horticultural crops). Several public research institutions and universities are actively developing genome-edited lines for traits such as disease resistance, drought tolerance and improved nutritional content. Reviews published in recent years summarize India's research initiatives and call for clear, proportionate, science-based regulatory pathways to realize agricultural benefits.

On regulation, India's approach has evolved: draft and interim guidelines have suggested differential regulation — lighter oversight for edits that do not introduce foreign DNA and align with conventional breeding changes and more scrutiny for edits that introduce novel sequences or transgenes. This "product-based" or risk-proportionate stance is similar to policies adopted by some other countries and is intended to enable research and commercialization of gene-edited crops that are essentially indistinguishable from conventionally bred varieties while ensuring safety for more complex modifications. However, detailed implementation, transparency and capacity building for risk assessment remain active policy discussions in India.

Notably, recent developments (through 2024–2025) include reports of advanced genome-edited rice varieties under field evaluation and discussion about translating such research to smallholder agriculture. Public engagement, seed system integration, intellectual property considerations and clear regulatory timelines will be critical to equitable adoption in India.

Challenges and safety considerations

While CRISPR is powerful, it is not a silver bullet. Key challenges include:

- **Off-target edits and unintended effects**: although greatly reduced with better design and improved editors, they require careful molecular screening.
- **Delivery and regeneration bottlenecks**: many crops or elite varieties are difficult to transform or regenerate from tissue culture.
- **Trait complexity**: many important traits (yield, drought tolerance) are polygenic and influenced by environment; editing single genes may not be sufficient.
- **Regulatory and public acceptance**: policies differ widely between countries and public trust hinges on transparent science, risk assessment and benefits to farmers and consumers.
- **Access and equity**: ensuring smallholder farmers can benefit, rather than only large agribusiness, requires public sector involvement, sensible intellectual property approaches and seed system linkages.

Future trends

Several technological and translational trends are shaping the near future:

1. **Precision editors (base and prime editors)** will make single-nucleotide improvements more routine, enabling allele tailoring for adaptive traits.
2. **DNA-free editing and RNP delivery** promise edited plants without transgene footprints, easing regulatory and public concerns.

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3. **Multiplex and regulatory network editing** — simultaneous edits to multiple genes and regulatory elements will help tackle polygenic traits.
4. **De-novo domestication** — editing wild relatives to rapidly create new crops with resilience traits.
5. **Integration with speed breeding and genomic selection** — combining CRISPR edits with accelerated breeding cycles and predictive genomics will shorten the time from discovery to farmer fields.
6. **Trait pipelines targeting climate adaptation and nutrition** — many projects now prioritize drought, heat, salinity tolerance and biofortification to meet global food security goals.
7. **Ethical, social and policy dimensions-** Responsible deployment of CRISPR in agriculture means attention to biosafety, transparent regulatory review, farmer choice, benefit sharing and engagement with consumers and civil society. Public-sector research, participatory breeding models and public–private partnerships can help align gene-editing outcomes with smallholder needs. Clear labelling policies, where needed and education campaigns can improve public understanding of the differences between gene editing and older transgenic techniques.

Conclusion

CRISPR–Cas technologies have moved from a molecular curiosity to a practical force reshaping plant breeding. Their precision, flexibility and expanding toolkit (Cas variants, base editors, prime editors) make it possible to tackle many agricultural challenges faster than traditional methods. For countries like India where smallholders predominate and climate stresses threaten yields genome editing offers real opportunities, provided regulatory frameworks are science-based and inclusive. The coming decade will likely see more genome-edited crops reaching trials and, where permitted, fields — transforming crop resilience, nutrition and sustainability if technological promise is coupled with sound governance and equitable access.

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Rupohi Thekera (*Garcinia lanceifolia* Roxb.): A Medicinal Treasure of Assam

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Garcinia lanceifolia Roxb.,locally known as *Rupohi Thekera*, is an underutilized medicinal fruit native to Assam and Northeast India. Traditionally used for treating digestive issues, infections, and inflammation, it is now gaining scientific attention for its antibacterial, antidiabetic, antioxidant, anti-obesity and liver-protective properties. Rich in compounds like hydroxycitric acid and garcinol, it shows promise in natural health care. However, further research, especially in humans is needed to confirm its benefits and ensure safe, effective use. Promoting awareness, sustainable use, and conservation of this endemic plant is essential for preserving both its medicinal value and cultural heritage.

Introduction

In the lush landscapes of Assam and the broader North-eastern region of India, nature harbours many under-appreciated fruit crops possessing potential health benefits. Among these is *Garcinia lanceifolia* Roxb., locally known as ***Rupohi Thekera*** (ৰূপহী থেকেৰা). In local culture, it is not only valued for its unique sour taste but also for its multifarious medicinal properties. This article explores its botany, traditional uses, phyto-chemistry, and what modern science tells us about its health benefits, along with challenges and recommendations for its use and conservation.

BOTANICAL DESCRIPTION AND ECOLOGY

- **Taxonomy:** *Garcinia lanceifolia* Roxb., belongs to the family Clusiaceae. It is related to other Garcinia species that are known for medicinal and dietary uses.
- **Morphology:** It is an evergreen small tree (or large shrub), glabrous, growing up to about 3-4 meters (around 10-12 feet) under shaded or semi-shaded conditions. The leaves are simple, glossy, the bark, fruit, and seeds have characteristic features. The fruit is roughly ovoid, with 6-8 seeds, and turn into a yellowish-orange hue when ripe.
- **Phenology:** Flowering occurs approximately in February-March and fruits mature around June-July.
- **Geographical Distribution:** It is endemic to Assam and parts of North-eastern India, also reported in neighbouring regions (Bangladesh, Myanmar). It grows in evergreen or semi-evergreen forest patches, sometimes in homesteads under cultivation or semi-wild conditions. However, there are concerns of reduction in its natural population.

ETHNO-BOTANICAL AND TRADITIONAL USES

Many indigenous communities in Assam (tribal and non-tribal) have used *Rupohi Thekera* for food, medicine and other domestic purposes:

- **Culinary use:** The ripe fruit is eaten raw or dried. The fruit is acidic, imparts a sour flavour. Young

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- leaves and shoots (slightly acidic) are cooked as vegetables. The fruits are also made into pickles ann juices.

Fig.1: ***Garcinia lanceifolia*** **Roxb. shrub**

Fig.2: ***Garcinia lanceifolia*** **Roxb. Bearing fruits**

Fig.2: ***Garcinia lanceifolia*** **Roxb. Bearing fruits**

- **Traditional medicinal uses:**
  1. To treat diarrhoea, dysentery, and dyspepsia (indigestion) among local people.
  2. For biliousness (i.e. issues related to bile secretion / digestive upsets) and "bilious complaints".
  3. Leaves are used as stomachic (supporting digestion) and diuretic (promoting urine production).
  4. Also used in folk remedies for fever, jaundice, urinary problems, etc.
- **Other uses:** The resin ("gum resin") sometimes termed "gamboge" is used in some traditional medicine. Also, as a part of cultural and local value, the plant is grown in gardens, used in home remedies.

Phytochemical Composition

To understand how *Rupohi Thekera* exerts medicinal effects, it's necessary to see what chemicals are present in different parts of the plants:

- **Major classes of compounds:** xanthones, biflavonoids, benzophenones, benzoquinones, triterpenes. E.g., Garcinol, Iso-Garcinol, xanthochymol and guttiferone isoforms etc. These compounds also impart antioxidant properties that help modulate oxidative stress.
- **Hydroxycitric acid (HCA) and its derivatives:** HCA is a key compound, mostly present in the rind of the fruit, which inhibits fat synthesis by blocking ATP-citrate lyase and may aid in weight loss and appetite suppression. It also shows potential benefits for lipid regulation, blood sugar control, and liver protection. Dutta *et al.* (2020) estimated around 539.13mg/g of HCA in *Garcinia lanceifolia* Roxb.

MODERN SCIENTIFIC STUDIES CONFIRMING MEDICINAL PROPERTIES

A number of in-vitro, in-vivo (animal) studies have begun to validate traditional claims. Below is a summary of key research findings.

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Study / Effect	What was done / tested	Findings / Outcome	Citation
Antibacterial activity of bark	Methanolic bark extract tested against bacteria such as *Bacillus subtilis*, *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *E. coli*, etc.	Showed credible antibacterial activity, especially against organisms that cause diarrhoea and dysentery. Supports traditional use in diarrhoeal diseases.	Bora *et al.,* 2014
Antidiabetic & Antiulcer activity	Hydroalcoholic bark extract (250 mg/kg and 500 mg/kg) tested on Wistar albino rats; parameters studied included blood glucose, lipid profile, ulcer indices in alcohol and acetic acid-induced models.	Extracts significantly reduced blood glucose levels, improved lipid profile, and showed protective effects against gastric ulcers.	Deka *et al.,* 2020
Analgesic & Anti-inflamm atory properties	Methanolic stem bark extract tested in rat models using hot plate, tail flick (for pain), and carrageenan-induced paw oedema (for inflammation) at doses of 250 mg/kg and 500 mg/kg.	Significant analgesic and anti-inflammatory activity was observed, confirming traditional ethnomedicinal uses for pain and swelling relief.	Hussain *et al.,* 2020
Hepato-protective (liver protection)	Fruit rind extracts administered to rats with CCl_4-induced liver damage; markers such as ALT, AST, ALP, bilirubin, and total protein were assessed, along with liver histopathology.	Extracts reversed liver damage: reduced enzyme and bilirubin levels, improved protein concentration, and histological signs of healing. Demonstrates hepatoprotective effects.	Rahman *et al.,* 2023

GAPS IN KNOWLEDGE

- **Lack of human clinical trials:** Almost all evidence comes from animal studies or in vitro experiments. Translating doses, metabolism, and effects to humans is not straight forward.
- **Dose standardization:** The exact doses that have effect in animals may not scale simply to human dosing, and often the preparations used (extracts, pure compounds) are not same as traditional preparations.
- **Long-term safety data missing:** Acute toxicity looks good in some studies, but effects of long-term use, possible adverse reactions, interactions with other drugs are not well studied.
- **Variability of quality:** The phytochemical content can vary depending on region, growing conditions, harvest time, preparation method (e.g. bark vs fruit rind vs leaves), which affects potency and safety.
- **Conservation concerns:** Some studies suggest that *G. lanceifolia* populations are under pressure in the wild, possibly threatened by habitat loss, overharvesting.

POTENTIAL APPLICATIONS AND WAYS OF USING *Rupohi Thekera*

Given its traditional uses and scientific backing, here are potential ways in which Rupohi Thekera can be used (with caution), and possible forms of products / preparations.

- **Food and culinary uses**- ripe fruit is eaten raw, used in making juices, pickles, fresh or dried fruit rind is used as a souring agents in local cooking.

- **Herbal teas / decoctions**- Bark or fruit rind decoction may be used, especially for gastrointestinal discomfort, mild fevers.
- **Extracts / supplements**- In principle, the bark or fruit rind extracts and its powder could be developed into standardized herbal remedies or nutraceuticals.
- **Topical preparations**- Although not much data exists, antibacterial effects suggest potential in topical use for skin infections, wounds etc.
- **Combination herbs**- Could be combined with other known medicinal plants to complement effects (e.g. for liver protection, digestive support).

DOSAGE AND SAFETY CONSIDERATIONS

Preclinical studies have shown that *Garcinia lanceifolia* Roxb., exhibits low acute toxicity, with an LD_{50} exceeding 5000 mg/kg in animal models, indicating a favourable short-term safety profile (Sharma *et al.,* 2020). Commonly tested doses in rats range from 250 to 500 mg/kg, which translate to significantly lower human-equivalent doses when adjusted using standard body surface area conversion methods (Deka *et al.,* 2020; Hussain *et al.,* 2020; Reagan-Shaw *et al.,* 2008). Despite these promising findings, there is limited data on long-term human safety, including potential chronic toxicity, reproductive effects, and interactions with other drugs. Therefore, individuals with pre-existing health conditions such as diabetes, liver disorders, or those who are pregnant should use it cautiously under medical supervision. Initiating treatment at low doses is advisable due to the potential for allergic responses or herb-drug interactions (Sharma *et al.,* 2020).

RECOMMENDATIONS FOR USE AND FURTHER RESEARCH

1. **Human Clinical Trials**- There is a strong need for well-designed clinical studies in humans, randomized, controlled trials to assess efficacy for specific conditions (e.g. mild dyspepsia, ulcer, blood sugar control, liver protection).
2. **Standardization of Extracts**- Identification and isolation of major bioactive compounds, ensuring consistent extraction methods so that potency and safety are reproducible.
3. **Safety Profiling**- Study long-term safety, possible toxicity with chronic use, interaction with pharmaceutical drugs (especially antidiabetics, liver metabolites, etc.).
4. **Dose Optimization**- Determination of effective dose ranges in humans, considering weight, age, underlying conditions.
5. **Sustainable Harvesting / Cultivation**- Promotion of cultivation, good harvesting practices, to prevent depletion of wild populations, possibly domestication, selective breeding for high bioactive content.
6. **Public Education**- Educating local communities about benefits and risks, encourage usage in food and home remedies under safe guidance, avoiding over-use or use in vulnerable populations (pregnant women, children, etc.) without evidence.

CONSERVATION AND SUSTAINABILITY

Given its status as an endemic plant with valued medicinal and food uses, conserving *Garcinia lanceifolia* Roxb., is important. This should be done through proper habitat protection, ensuring that forests and semi-forests where it grows are protected, avoiding deforestation and land conversion. Home garden cultivation, agroforestry, should be promoted, so that pressure is eased on wild populations. Research into best propagation methods (seed, cuttings), growth conditions to improve yields of bioactive compounds should be conducted. In addition, ethnobotanical surveys, local knowledge transfer should be actively done so that knowledge of use and cultivation is maintained.

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CONCLUSION

Garcinia lanceifolia Roxb., (*Rupohi Thekera*) is a valuable local plant with deep roots in Assam's food and healing traditions. Modern studies now support many of its traditional uses, such as, helping with digestion, blood sugar, inflammation, weight management and liver health. With more research and sustainable cultivation, this underappreciated fruit could become a powerful natural remedy for generations to come.

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Okra: The Slimy Superfood with a Smart Future

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Few vegetables divide opinion quite like okra. Some love its mild flavour and soft texture, while others wrinkle their noses at its characteristic "slime." Yet, what many call slime is, in fact, a treasure trove of natural compounds that could redefine the future of food, health, and sustainable industries. This "slimy" vegetable okra (*Abelmoschus esculentus* L. Moench) is not just a staple in Indian kitchens but a rising global superfood with smart scientific potential.

1. The Humble Green Pod with a Grand Legacy

Okra has travelled a remarkable journey from its African cradle to becoming one of India's favourite vegetables. Believed to have originated in Ethiopia and later spread to Asia through Arab traders, okra has adapted well to tropical and subtropical climates worldwide (Gemede *et al*., 2015). Today, India is the world's leading producer, contributing nearly 70% of global output, with over 6 million tonnes annually. For farmers, okra is a gift it matures quickly, provides a steady cash flow due to continuous fruiting, and thrives in varied soils and seasons. For consumers, it is a nutritional powerhouse. And for scientists, it is a biological marvel whose mucilage and seeds promise to revolutionize industries from food to pharmaceuticals.

2. Inside the Pod: A Treasure of Nutrition

Fresh okra pods contain around 90% water, 2% protein, 7% carbohydrates, and about 3% dietary fibre. They are rich in vitamins A, C, K, and B-complex (especially folate), as well as essential minerals like calcium, magnesium, and potassium (Adetuyi & Ibrahim, 2014). But the magic lies in okra's mucilage a thick, gel-like substance that forms when pods are cut or cooked. Far from being just a kitchen nuisance, this mucilage is a natural source of soluble fibre and complex polysaccharides such as galactose, rhamnose, and glucuronic acid (Adelakun *et al*., 2021). These components make okra an excellent functional food for maintaining gut health, reducing cholesterol, and moderating blood glucose levels. Studies show that okra mucilage slows glucose absorption, making it particularly beneficial for people with diabetes (Agarwal *et al*., 2022). Moreover, the mucilage acts as a prebiotic, supporting the growth of beneficial gut bacteria. When consumed regularly, okra contributes to improved digestion, better lipid metabolism, and enhanced immunity (Gemede *et al*., 2015).

3. Mucilage: The Science Behind the Slime

What gives okra its characteristic sliminess? The answer lies in mucilage a complex matrix of polysaccharides and glycoproteins that serve several biological roles. In plants, mucilage helps retain water, protect seeds, and aid germination. In humans, it behaves as a natural thickener and emulsifier.

Chemically, okra mucilage is composed of acidic polysaccharides that form viscous solutions in water. This viscosity is what gives cooked okra its slippery feel but it also gives it incredible functional properties:

- **Water-binding capacity** – helps maintain hydration and digestion.
- **Emulsification** – stabilizes mixtures like salad dressings or soups.
- **Film-forming ability** – useful in biodegradable packaging materials.
- **Viscosity modulation** – ideal for pharmaceutical and cosmetic formulations (Adelakun *et al*., 2021).

In the food industry, okra mucilage is now being studied as a natural alternative to synthetic additives such as xanthan gum and gelatin. It improves texture, mouthfeel, and shelf stability while being plant-based and biodegradable. In pharmaceuticals, mucilage serves as a binder, suspending agent, and drug-release modifier, making it a sustainable substitute for synthetic polymers (Dantas *et al*., 2021).

4. Okra Oil and Seeds: Hidden Nutritional Wealth

Beyond the pod and its mucilage, okra seeds are equally valuable. Containing 20–40% oil and 20% protein, they are rich in unsaturated fatty acids especially linoleic acid, which supports cardiovascular health (Dantas et al., 2021). Okra seed oil compares favourably with cottonseed and soybean oil in quality and stability. Its mild flavour and light texture make it suitable for cooking and cosmetic applications. The defatted seed meal is an excellent protein supplement, and its flour is used to fortify baked goods and snacks, enhancing nutritional content without compromising taste. Recent studies also show that okra seed proteins possess antioxidant and antihyperglycemic properties, adding to the crop's growing nutraceutical importance (Agarwal *et al.,* 2022).

5. Cultivation and Agronomic Significance

Okra thrives best in warm conditions, between 25–35°C, and grows well in well-drained loam soils. It can be cultivated throughout the year under irrigated conditions, making it one of the few vegetables that ensures consistent farmer income (Choudhary *et al*., 2022). High-yielding varieties such as Arka Anamika, Parbhani Kranti, and Kashi Kranti have been developed in India with tolerance to major diseases like yellow vein mosaic virus (YVMV) and okra enation leaf curl virus (OELCV) (ICAR-IIVR, 2023). Integrated nutrient management combining farmyard manure, compost, and balanced fertilizers has proven effective in improving soil health and yield. Meanwhile, integrated pest management (IPM) strategies that use neem-based pesticides, pheromone traps, and resistant varieties help reduce chemical dependence and preserve ecological balance (Pandey & Lal, 2022).

6. Beyond the Kitchen: Industrial Applications of Mucilage

The commercial applications of okra mucilage are rapidly expanding across sectors:

***a. Food industry*:** Mucilage serves as a natural thickener, emulsifier, and stabilizer in soups, ice creams, and sauces. Unlike synthetic gums, it is biodegradable and safe for consumption. It can also reduce fat in low-calorie formulations while improving mouthfeel (Adelakun *et al*., 2021).

***b. Pharmaceutical and biomedical uses*:** In medicine, okra mucilage acts as a drug carrier, tablet binder, and controlled-release agent. It can be used to encapsulate sensitive compounds, such as probiotics and vitamins, ensuring targeted and sustained release. Research also indicates its potential in wound-healing gels and biodegradable capsules (Dantas *et al.,* 2021).

c. Cosmetic and biopolymer applications: Okra's slimy extract is finding a place in the cosmetic industry as a natural moisturizer and hair-conditioning agent. Moreover, researchers are experimenting with okra mucilage in bioplastics and eco-friendly films that could replace conventional plastics, aligning with global sustainability goals (Choudhary et al., 2022).

d. Environmental applications: Recent innovations show that okra mucilage can adsorb heavy metals and organic pollutants, making it a green solution for wastewater treatment (Nath et al., 2020). This opens a new frontier where a simple vegetable becomes part of environmental remediation efforts.

7. Okra and Health: From Folk Medicine to Functional Food

In traditional medicine, okra has been used to treat gastritis, ulcers, and inflammation. Modern science now validates many of these claims. Okra extracts have demonstrated antioxidant, antimicrobial, and anti-inflammatory activities, largely attributed to

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polyphenols, flavonoids, and polysaccharides (Gemede et al., 2015). Regular consumption of okra has been linked with improved lipid profiles, reduced oxidative stress, and lower risk of metabolic disorders (Agarwal et al., 2022). Its mucilage helps coat the digestive tract, soothing irritation and aiding nutrient absorption. As a low-calorie vegetable rich in fibre, okra is ideal for weight management. Moreover, its potential as a functional ingredient is now being explored in developing diabetic-friendly foods, nutraceutical supplements, and fermented beverages.

8. Value Addition: Turning Green Pods into Gold

Post-harvest losses in okra are high due to its perishability. Hence, value addition plays a vital role in ensuring profitability. Products such as dehydrated okra flakes, frozen pods, pickles, powders, and snack mixes are gaining popularity in domestic and export markets. Processing okra not only increases its shelf life but also preserves its bioactive compounds. Okra mucilage can be dried and powdered for use as a natural stabilizer, while seed flour adds functional properties to food products. These ventures create employment opportunities, especially for rural women and self-help groups, contributing to inclusive growth.

9. Challenges and the Road Ahead

Despite its potential, okra cultivation faces several challenges. The yellow vein mosaic virus (YVMV) continues to cause significant yield losses, while climatic fluctuations affect flowering and fruit quality. Inadequate post-harvest infrastructure and market linkages limit farmer income.

Future strategies must focus on:

- Developing climate-resilient and pest-tolerant hybrids.
- Expanding organic okra production for premium markets.
- Promoting biotechnological innovations for high-mucilage and nutrient-rich varieties.
- Strengthening value chains and cold storage networks.

With growing demand for plant-based, natural, and sustainable materials, okra mucilage and seed oil industries hold immense potential for India's bioeconomy.

10. The Smart Future of a Slimy Superfood

The story of okra is the story of innovation emerging from simplicity. What was once dismissed as "too slimy" is now being celebrated as a source of bioactive compounds, eco-friendly materials, and health-promoting food. As we step into an era of smart agriculture and green technology, okra embodies the fusion of nutrition, science, and sustainability. With its mucilage acting as a bridge between health and industry, okra stands poised to become one of the smart superfoods of the 21st century an emblem of how traditional crops can find new relevance in a changing world. Indeed, the next time you see a slimy okra pod, remember: that slime might just hold the key to a smarter, healthier future.

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Understanding Tassel blast and leaf firing in maize

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Introduction

Maize stands as one of the top three cereal crops globally, often earning the title "queen of cereals" for its remarkable yield potential and adaptability to diverse agro-climatic zones. In recent decades, rising global temperatures—primarily driven by human activities—pose severe challenges to crop production, affecting growth, metabolism, and yield across key staple crops like maize. Forecasts indicate that average global temperatures could rise by up to 1.5°C above pre-industrial levels by 2050. The impact of high heat, particularly when temperatures exceed 35°C, combined with drought stress during the critical reproductive and grain-filling phases, can drastically depress maize productivity. Notably, even a moderate temperature increase above 30°C has been linked to yield reductions of approximately 13%, far surpassing losses attributed to within-season rainfall variability. Khodarahmpur *et al.*, 2010 also predicted that maize yield may reduce upto 70% under high temperature stress conditions. One of the most critical physiological disorders exacerbated by rising temperatures is the development of tassel blast and leaf firing symptoms, both of which directly compromise productivity and grain quality in maize. Tassel blast is the desiccation of the tassel, which prevents pollen release and can lead to male sterility. Leaf firing is the drying and death of leaf tissue, which reduces the plant's ability to photosynthesize and leads to smaller ears and reduced grain yield. Tassel blast and leaf firing donot directly effect the yield production but indirectly *via* secondary traits such as number of grain per ear, silk receptivity, shelling percentage etc.

Tassel Blast: Tassel blast refers to the condition where the tassel becomes desiccated, leading to poor or absent pollen release and, ultimately, male sterility. This event most frequently occurs when elevated temperatures coincide with tassel emergence, often causing a delay in anthesis and significant tassel damage. The sensitive V6 (six visible leaf collar) stage, corresponding to early reproductive development, is particularly vulnerable, with heat stress at this phase often resulting in malformed, desiccated tassels. Affected tassels become dry, brittle, and pale—effectively "blasted"—with no viable pollen. This leads to reduced pollination and a sharp decline in yield. Recent research has also identified specific genetic loci (e.g., QTL~LVS_TSBL~ on chromosome 5) associated with tolerance to tassel blast.

Leaf Firing: Leaf firing, on the other hand, manifests as scorching and premature death of leaf tissues. These symptoms commonly appear after periods of heat waves, particularly when leaves are developing near tassel emergence. The relationship between tassel blast and leaf firing is well-established, as stress-induced injury increases reactive oxygen species and causes electrolyte leakage, leading to chlorosis, tissue death, and impaired photosynthesis. When the photosynthetic

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apparatus is compromised, the plant's capacity for grain production declines, resulting in smaller ears, reduced kernel sets, and lower overall yield. Genetic studies have identified loci associated with leaf firing tolerance, such as Zm00001d043634 and Zm00001d025343 on chromosome 3, with expression highest at the vegetative stage.

Key Management Strategies

- Irrigation: Maintain consistent soil moisture, particularly from the V12 to R2 stages, to reduce drought stress during reproduction and early grain fill.
- Nutrient Management: Conduct regular soil testing and address deficiencies, especially in nitrogen, potassium, magnesium, boron, and zinc. Split fertilizer applications to optimize nutrient uptake.
- Use drought-tolerant and disease-resistant maize hybrids, especially in regions prone to high temperatures. Moreover, different traits sensitive to high day, high night temperature and the interaction of temperature with other environmental factors (e.g., VPD and photoperiod) and edaphic factors (e.g., salt and nutrient stress) need to be explored in order to understand the physiological, biochemical, and molecular basis of heat tolerance in maize.
- Pollen viability and other characteristics of pollen growth are severely affected by heat stress in many crops. While male reproductive organs particularly are more susceptible to heat stress as compared to the female counterparts in some crop species such as sorghum (Djanaguiraman *et al.*, 2018), pearl millet pistil was reported to be relatively more sensitive to heat stress (Djanaguiraman *et al.*, 2018). Therefore, a better understanding of the relative tolerance levels of pollen and ovule in maize and associated metabolic and biochemical changes would need further studies to determine mechanistic understanding of reproductive stage heat stress tolerance in maize.
- Disease and Pest Prevention: Regularly monitor for pests and diseases, and intervene promptly with appropriate chemical or biological agents to prevent secondary stress that could worsen tassel or leaf damage.
- Chemical Use Precautions: Avoid applying herbicides or other chemicals during tasseling and peak heat periods, as this can aggravate stress symptoms.
- Agronomic Practices: Adopt mulching, conservation tillage, and appropriate plant spacing to improve soil moisture retention and minimize competition for water and nutrients.
- Research Directions: A deeper understanding of how maize reproductive organs respond to heat is needed, as male organs (pollen, tassels) are generally more sensitive, but some female structures (such as the pistil in pearl millet) may also be vulnerable in other crop species.

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Why Young India Must Reimagine Farming as Entrepreneurship

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India's agriculture sector, long perceived as a subsistence-based and traditional occupation, is now poised for transformation. With nearly 65% of the population under the age of 35, the country's youth are uniquely positioned to lead this shift by reimagining farming as a science-driven and entrepreneurial pursuit. Research underscores the rising importance of technology, value chain efficiency, and farmer-led innovation in boosting agricultural productivity. Emerging tools such as AI, IoT, drone technology, and blockchain are redefining what is possible in modern farming—making it more precise, resilient, and economically viable. Supported by government initiatives like Startup India and PM Kisan Sampada Yojana, a robust ecosystem for agri-entrepreneurship is taking shape. This article explores how young Indians can leverage these developments to redefine agriculture as a profession of innovation, creativity, and sustainable impact—one that not only secures livelihoods but also strengthens India's food security and global agricultural standing.

Introduction

Agriculture in India has traditionally been treated as a subsistence activity, but the sector is now at a turning point. With nearly 65% of the population under 35, young Indians hold the key to transforming farming into a scientifically informed and entrepreneurial venture. Research shows that productivity gains in agriculture are increasingly driven by technology adoption, efficient value chains, and farmer-led innovations.

Viewing farming through an entrepreneurial lens can help tackle pressing challenges like climate change, land fragmentation, and water stress. Emerging tools such as AI-based yield prediction, IoT-enabled irrigation, drone-assisted monitoring, and blockchain for supply chain traceability provide practical solutions that make agriculture more precise, profitable, and sustainable. Government initiatives like Startup India and PM Kisan

Sampada Yojana further create a favorable ecosystem for agri-innovationFor India's youth, this is more than an economic opportunity—it is a chance to reimagine farming as a profession of creativity, risk-taking, and scientific problem-solving. By merging traditional knowledge with modern science and entrepreneurial spirit, agriculture can evolve into a sector that ensures food security, creates employment, and strengthens India's role in global food systems.

The Case for Agri-Entrepreneurship

Research shows that productivity gains in agriculture are increasingly driven by the adoption of technology, the creation of efficient value chains, and farmer-led innovations (Pingali, 2012; Gulati & Juneja, 2019). Viewing farming as a business — rather than a livelihood of last resort- -opens new avenues for income, innovation, and impact.

Young Indians can drive this transformation by applying their **scientific knowledge, digital skills, and entrepreneurial energy**. Entrepreneurship in agriculture isn't limited to growing crops — it includes building tech platforms, managing agri-logistics, innovating with bio-inputs, and creating food brands that reach global markets.

Technological Transformation in the Field

We are entering an age of **data-driven agriculture**, where the focus is shifting from quantity to quality, and from guesswork to precision. Tools and techniques emerging in the sector include:

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- **AI and machine learning**: For predicting crop yields and disease outbreaks.
- **IoT sensors**: For monitoring soil moisture and optimizing irrigation.
- **Drones**: For aerial monitoring, spraying fertilizers, and surveying large farms.
- **Blockchain**: For building transparent and tamper-proof supply chains.

These technologies allow farmers to make **evidence-based decisions**, reducing input costs and increasing productivity. Importantly, many of these tools are being developed and deployed by young Indian startups.

Government Support and Policy Framework

The Indian government has taken crucial steps to encourage innovation and entrepreneurship in agriculture.

- **PM Kisan Sampada** Yojana supports food processing, infrastructure, and cold storage chains.
- **Startup India** offers tax breaks, mentorship, and seed funding for agri-tech ventures.
- **eNAM (National Agriculture Market)** helps farmers get better prices through nationwide digital trading.

These schemes create a **supportive policy environment** that empowers young entrepreneurs to step into agriculture with confidence and creativity.

Tackling Agricultural Challenges Through Innovation

Indian agriculture today faces multifaceted challenges:

- **Climate Change** is reducing rainfall predictability and increasing heat stress on crop.
- **Land Fragmentation** limits mechanization and scale efficiency.
- **Post-Harvest Losses** cost India ₹92,000 crore annually (as per Ministry of Food Processing Industries).
- **Water Scarcity** demands more efficient irrigation techniques.

Agri-entrepreneurship offers scalable solutions. For instance, climate-resilient seed varieties, solar-powered cold storage units, mobile-based agri-advisory apps, and direct-to-consumer models can **make agriculture resilient and responsive** to 21st-century problems.

The Role of Education and Startup Culture

India's growing network of agri-business schools, FPO incubators, and rural innovation hubs is nurturing a **new class of farmer-entrepreneurs**. Institutions like MANAGE, IRMA, and IIM-A's Centre for Innovation Incubation and Entrepreneurship are playing a key role in this movement.

Meanwhile, startups like **DeHaat, Ninjacart, Bijak**, and **AgNext** are not just business success stories — they are proof that agriculture can be **high-tech, high-impact, and highly aspirational** for young Indians.

Conclusion

Agriculture is no longer just about tilling the soil — it's about solving problems, building systems, and feeding the future. For India's youth, this is more than an opportunity — it is a responsibility.

By reimagining farming as a platform for entrepreneurship, we can:

- Create dignified rural jobs.
- Strengthen food security.
- Promote sustainable development.
- Lead India's transition to a climate-resilient economy.

It's time to move from the plough to the platform — and let India's young innovators cultivate not just crops, but change.

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Strategic Optimisation of Organic Amendments toward Soil Fertility and C.S.A Goals

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Organic amendments, such as compost, biofertilizers, and biochar play a pivotal role in enhancing soil fertility and advancing the objectives of climate-smart agriculture (CSA). These amendments not only improve soil physical, chemical, and biological properties but also contribute to carbon sequestration, greenhouse gas (GHG) mitigation, and resilience against climate variability. This article reviews current research and practices in optimizing organic amendments for sustainable soil fertility management and achieving CSA goals. The combined use of composts, bio-based amendments, and recycled crop residues can significantly boost nutrient availability, enrich soil organic carbon, and ensure long-term productivity in the face of climate change.

Introduction

Ensuring global food security requires farmers to maintain healthy soil, but this is complicated by the need to address climate change. A key problem is that chemical fertilizers, despite boosting crop growth in the short term, cause long-term soil degradation, kill off essential soil microbes, and lead to environmental contamination. In contrast, organic amendments—such as compost, manure, green manure, biochar, and microbial inoculants—offer a more sustainable approach that aligns with the three pillars of Climate-Smart Agriculture (CSA):

- Increased productivity
- Enhanced resilience (adaptation)
- Reduced greenhouse gas emissions (mitigation).

Optimizing the use of organic amendments involves improving their nutrient composition, application strategies, and synergistic integration with other soil management practices. Recent studies emphasize that properly managed organic inputs can simultaneously improve soil structure, water retention, and microbial health while reducing the carbon footprint of farming systems.

2. Role of Organic Amendments in Soil Fertility

2.1 Improvement of Soil Physical and Chemical Properties

Organic amendments enhance soil structure by increasing aggregation, porosity, and water-holding capacity. Composts and farmyard manure (FYM) add humic substances that promote stable soil aggregates, reducing erosion and compaction. Chemically, they supply macro- and micronutrients (N, P, K, Ca, Mg, Zn, Fe) and increase cation exchange capacity (CEC), thereby improving nutrient retention and reducing leaching losses.

2.2 Enhancement of Soil Biological Activity

Bio-amendments such as vermicompost, biofertilizers, and microbial inoculants enhance soil microbial diversity and enzyme activities. Beneficial microorganisms, including nitrogen-fixing bacteria (*Rhizobium*, *Azotobacter*), phosphate-solubilizing bacteria (PSB), and mycorrhizal fungi, improve nutrient cycling and availability. These biological processes foster a dynamic and self-sustaining soil ecosystem.

2.3 Nutrient Release Dynamics

Unlike synthetic fertilizers that provide immediate nutrient surges, organic amendments release nutrients slowly and synchronously with crop demand. This minimizes nutrient losses and ensures steady plant growth. Moreover, the addition of organic matter enhances the mineralization–immobilization balance, improving overall nutrient use efficiency (NUE).

3. Organic Amendments and Climate-Smart Agriculture (CSA)

3.1 Carbon Sequestration and Greenhouse Gas Mitigation

Organic amendments contribute significantly to carbon sequestration by increasing soil organic carbon (SOC) pools. Biochar, in particular, has a high carbon stability and can sequester carbon for hundreds of years. Compost application promotes the formation of stable humic substances, further improving carbon storage. Research shows that soils under long-term organic management emit less nitrous oxide (N_2O) and methane (CH_4) compared to those under intensive chemical fertilization.

3.2 Building Climate Resilience

By improving soil structure and water-holding capacity, organic amendments make cropping systems more resilient to drought, flooding, and temperature extremes. The enhanced soil buffering capacity supports plant tolerance to abiotic stress. For instance, biochar-amended soils exhibit improved aeration and moisture retention, crucial for sustaining crops during dry spells.

3.3 Sustainable Productivity

CSA emphasizes maintaining productivity under variable climates. Integrated use of compost and microbial inoculants improves root growth, nutrient uptake, and crop yields. Long-term trials indicate that organic amendments sustain yield stability better than inorganic fertilizer-only systems, especially in degraded soils.

4. Optimisation Strategies for Organic Amendments

4.1 Quality Assessment and Standardization

Optimizing organic amendments starts with ensuring consistent quality. Parameters such as C:N ratio, nutrient content, maturity, pH, and microbial load should be evaluated before field application. Composts with a C:N ratio between 15:1 and 25:1 are ideal for balanced nutrient release.

4.2 Integration with Inorganic Fertilizers

Integrated Nutrient Management (INM) combines the benefits of organic and inorganic inputs. Applying 50–75% of the recommended chemical fertilizer dose along with compost or biofertilizer has shown to enhance yield, improve soil fertility, and reduce fertilizer dependency.

4.3 Site-Specific Management

Soil type, climate, and cropping system dictate the type and rate of organic amendment. For sandy soils, compost and biochar enhance water retention, whereas for clay soils, vermicompost and microbial inoculants improve aeration and nutrient availability. Climate-specific management ensures efficient nutrient use and adaptation benefits.

4.4 Use of Biochar and Advanced Bio-Amendments

Biochar and microbial-enriched composts represent next-generation organic amendments. Biochar improves carbon sequestration and nutrient retention, while microbial enrichment (e.g., *Trichoderma*, *Pseudomonas*) accelerates organic matter decomposition and disease suppression.

5. Challenges and Future Prospects

Despite their benefits, organic amendments face challenges such as variable quality, limited availability, high transport costs, and lack of farmer awareness. Future research should focus on developing region-specific composting technologies, microbial consortium formulations, and decision-

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support tools for optimized use. The adoption of digital soil health monitoring and carbon accounting systems can further enhance the effectiveness of organic amendments in CSA frameworks. Emerging innovations—such as biochar-compost blends, nano-biofertilizers, and precision organic nutrient management—offer promising avenues for scaling up sustainable soil fertility management.

6. Conclusion

Organic amendments, when optimized through quality management, integration, and site-specific strategies, can play a transformative role in achieving both soil fertility and climate-smart agriculture goals. Their multifaceted benefits—enhancing soil health, supporting productivity, and mitigating climate impacts—position them as critical tools in sustainable agricultural development. Integrating scientific knowledge with traditional composting practices can ensure that farming systems remain both productive and resilient in the face of climate challenges.

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Meta analysis of yield in integrated nutrient management on maize cultivation

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Maize were grown at four different combinations comprising four levels of enriched FYM with fertilizers viz., conventional (FYM @ 10 t/ha+100% RDF), enriched FYM+50% RDF, enriched FYM+100% RDF and enriched FYM+150% RDF and four biofertilizer levels viz., control, *Azotobacter,* PSB and *Azotobacter*+PSB were laid out factorial concept in randomized block design with three replications. The application of FYM @ 10 t/ha enriched with 150% RDF recorded significantly increased grain yield (4449.52 kg/ha), stover yield (8026.52 kg/ha), The experimental soil was clay loam, slightly alkaline in reaction (pH 7.8), medium in available nitrogen (260.40 kg/ ha) and available phosphorus (18.26 kg/ha) (Gajendra singh *et al* .,2012).Among fertilizer levels, application of 100 per cent RDF recorded significantly higher maize equivalent yield (10986kg/ha) compared to 75 per cent (10416kg/ha) and 50 per cent RDF (9720kg/ha), this is due to nutrient exhaustive nature of maize crop. Chandrashekara *et al.* (2000) conducted the field experiment in Arabhavi, Karnataka during the *kharif* season of 1996 and reported that the application of poultry manure (10 t/ha) with recommended rate of fertilizers(RRF 150 kg N/ha in three split doses) produced longer cobs (14.35 cm) with bigger diameter (15.6 cm) and heavier cob weight (170.5 g/cob) than application with control. The per cent increase in cob length, cob girth, and grain weight per plant with the application of poultry manures was 13.1, 23.8 and 53.2 %, respectively, compared with control. Nanjappa *et al.* (2001) conducted an experiment on maize to study effect of integrated nutrient management at Bangalore, Karnataka. The grains per row were recorded maximum with 75% RDF + FYM 6 t/ha, which was at par with RDF (150 : 75 : 40 kg NPK/ha) alone and significantly superior over 50% RDF + 12 t FYM/ha and FYM 24 t/ha treatments. The grain weight per plant was recorded maximum with 75% RDF + FYM 6 t/ha, which was at par with RDF alone and both these treatments were significantly superior over rest of the treatments.

Introduction

Maize is the queen of cereals, occupies a pride place among cereal crops in India. It has emerged as third most important food crop after rice and wheat as it represents 24% of total cereal production. It is a staple food for vast rural population of our country. The integrated plant nutrient supply envisages conjunctive use of inorganic and organic sources of plant nutrients and use of biofertilizers for crop productivity besides sustaining soil health. FYM is traditional source of organic manure. Out of total utilizable nutrient content of FYM, only one third N and two-third P are available in the current season crop and rest in the succeeding crop in the recent years (Gajendra singh *et al.,* 2012).The productivity of the system mainly depends on proper nutrient and moisture management practices. Low organic matter content in vertisols coupled with low and imbalanced application of macro and micro nutrients to the crop limits the full potential of yield and is the main yield barrier for crops (Ghosh *et al.* 2003). Integrating chemical fertilizers with organic manures was quite promising, not only in maintaining higher productivity but also in providing greater stability in crop production (Nambiar and Abrol 1992). Among fertilizer levels, application of 100 per cent RDF recorded significantly higher maize equivalent yield (10986kg/ha) compared to 75 per cent (10416kg/ha) and per cent RDF (9720kg/ha), this is due to nutrient

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exhaustive nature of maize crop (UK Shanwad 2010). Whereas judicious uses of organic manures and inorganic fertilizers are essential to safeguard soil health and augment productivity and input use efficiency which can sustain a highly intensive production system. The positive effect of judicious use of FYM and inorganic fertilizers on productivity of crops has been reported by many workers (Bandyopadhyay *et al*., 2003; Hati *et al*., 2006; Bhattacharyya *et al*., 2008). Today, for the country of India's dimension, with no scope for horizontal expansion and complexity of problems and challenges, there is no alternative but continue to improve productivity without further degrading its natural resources that too in a sustainable manner (Narayanswamy *et al*., 1994). In this contest we will have to adopt a rationalist organic farming approach to have an 'Evergreen Revolution'. This has led to the concept of integrated nutrient management (INM) gain momentum in recent years to improve and maintain the soil health. Besides this, with escalating cost of energy based fertilizer material, limited fossil fuels, INM approach combines the use of organic sources along with fertilizers, which would be remunerative for getting higher yields with considerable fertilizer economy (Subbian and Palaniappan, 1992)

Discussion:

The productivity of the crop in terms of grain and stover yield tended to increase with application of FYM integrated with chemical fertilizers.(Fig.1.) Application of FYM @ 10 t/ ha enriched with 150% RDF recorded significantly the highest grain yield (4449.52 kg/ha) which represented increase of 363.75, 383.25 and 570 kg/ha over application of FYM 10 t/ha enriched with 100% RDF, conventional practice and FYM 10 t/ha enriched with 50% RDF, respectively. The highest stover yield (8026.52 kg/ha) was recorded when the crop was supplied with FYM @ 10 t/ha enriched with 150% RDF, which represented significant increase of 705 kg/ha over FYM @ 10 t/ha enriched with 50% RDF but was found at par with conventional practice and FYM @ 10 t/ha enriched with 100% RDF. Similar trend was also observed in harvest index. Application of FYM @ 10 t/ha enriched with 150% RDF recorded significantly highest protein content in grain (Gajendra singh *et al.,* 2012). Uptake of nitrogen and phosphorus by grain, stover and the total uptake by the crop were significantly the highest with application of FYM enriched with 150% RDF. Application of FYM @ 10 t/ha enriched with 150% RDF significantly increased available nitrogen and phosphorus in soil over control and FYM @ 10 t/ha enriched with 50% RDF. However, it remained at par with FYM @ 10 t/ ha enriched with 100% RDF. Nutrient uptake is product key of yield and nutrient content, considerable increase in either nutrient content or in yield may increase the uptake. The results are in confirmation with the findings of Dadarwal *et al*. (2009) and Balai *et al*. (2011). Application of 100 per cent RDF produced significantly higher yield of maize (5578kg/ha) and bengal gram (1495kg/ha) thereby maize equivalent yield (10986kg/ha). Increase in the levels of NPK from 50 to 100% resulted in significant increase in the yield of both the crops. Similar results have been reported by Channabasavanna *et al*. (2007). Application of 100 per cent NPK recorded 13.0 and 5.4 per cent higher maize equivalent yield over 50 and 75 per cent NPK, respectively, This might be due to higher supply of plant nutrients by application of organic and/or chemical fertilizers to both the crops where initial soil was low in available nutrients and organic C content (Ramachandran & Biswas., 2020).

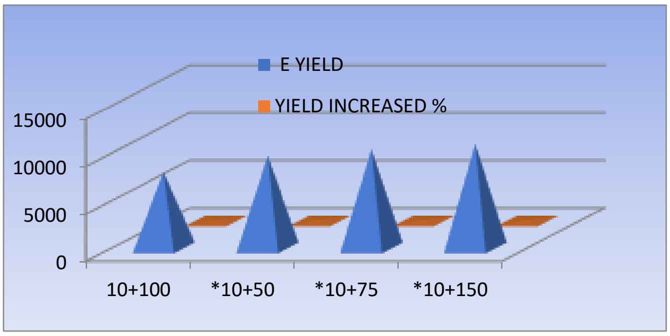

Fig.1.Yield in integrated nutrient management on maize

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Conclusion:

From the Meta analysis yield is influenced by Integrated nutrient methods and quantity, manures, enriched manures and recommended dose of fertilizers. Here 36% of yield increase through 150 percentage of recommended dose of fertilizers with INM . 75 percentage of recommended dose of fertilizers with INM involved then yield factors 29% influenced and compared to these two with enriched FYM, 50 percentage of recommended dose of fertilizers with INM of Agronomic practices increased yield 21% increased through INM involved for yield and yield parameters impact development.

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Virus-Free Planting Material: Ensuring Healthy Crops

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Plant viruses are one of the most imposing limitations to global agricultural productivity. Viruses result in serious yield and quality losses in numerous horticultural and field crops such as banana, citrus, potato, sugarcane, cassava, and tomato. In contrast to fungal or bacterial diseases, viruses cannot be cured once a plant is already infected. Therefore, preventing the entry and transmission of viruses through virus-free planting material is one of the most important measures toward attaining sustainable crop production and maintaining food security.

Concept of Virus-Free Planting Material

Virus-free or virus-indexed planting material is defined as vegetatively propagated plants that are tested and certified as free from known plant viruses, viroids, and other pathogens related to them. As a number of horticultural crops like banana, potato, sugarcane, citrus, and cassava are clonally propagated, if the mother plant contains any viral infection, it can easily be transferred to subsequent generations. Hence, ensuring virus-free planting material is essential to ensure crop health, productivity, and quality.

Virus-free planting material production is a sophisticated process that combines plant tissue culture, diagnostic testing, and certification procedures. The goal is not only to rid the material of prevailing viral infections but also to avoid reinfection when multiplying, storing, and distributing it. Some of the important methods and techniques employed for virus-free planting material production are:

1. Meristem Tip Culture

Meristem tip culture is the most common and dependable method for virus-free plant production. The apical meristem, which is usually 0.1–0.3 mm long and consists of cells that are actively dividing, tends to be free from viruses since viral spread is slower than cell division at the growing point. An excised meristem is cultured on a nutrient medium in aseptic and controlled environmental conditions for regeneration of a whole plant. This technique has been applied effectively in crops such as banana, potato, sugarcane, and sweet potato.

2. Thermotherapy and Chemotherapy

Thermotherapy is the technique of subjecting infected plant tissues or plantlets to high temperature (usually ranging from 35°C to 55°C) for some period of time in order to suppress or prevent viral replication. Chemotherapy also uses antiviral compounds like ribavirin or acyclovir to inhibit viral replication. Meristem tip culture is usually combined with such treatments to enhance the possibility of getting totally virus-free plantlets.

3. Micropropagation

After virus-free plantlets are recued, these are propagated by micropropagation a tissue culture technology that allows for the mass and quick propagation of genetically homogeneous and virus-free plants in sterile laboratory conditions. Micropropagation provides a clean planting material constant supply to nurserymen and farmers. It also diminishes the reliance on mother plants raised in the field, thus lessening the risk of reinfestation by insect or mechanical vectors.

4. Indexing and Molecular Diagnosis

To verify the lack of viruses, indexing a procedure for testing plants for certain pathogens is carried out using biological, serological, or molecular methods. Classic biological indexing includes grafting suspected material onto indicator plants to look for symptoms, whereas contemporary molecular methods provide high sensitivity and accuracy.

- ✓ Serological tests like Enzyme-Linked Immunosorbent Assay (ELISA) are commonly employed for the detection of certain viral antigens.
- ✓ Molecular assays such as Reverse Transcription Polymerase Chain Reaction (RT-PCR), Real-Time PCR (qPCR), and Next-Generation Sequencing (NGS) enable the rapid detection of known and new viruses with high accuracy.
- ✓ Such diagnostic tests are a part of virus-indexing and certification programs globally.

5. Maintenance and Certification

Once virus-free stock plants have been procured, their health status is of paramount importance. This is maintained by cultivating them in insect-proof screen houses or greenhouses under rigorous quarantine conditions. Testing and inspection at regular intervals are made to verify the plants' freedom from viral infection. Certification agencies or national seed certification authorities then approve the release of such planting material as "virus-free" or "certified clean stock" for commercial propagation and marketing.

Significance of Virus-Free Planting Material

The application of virus-free planting material is a pillar of contemporary, eco-friendly plant production systems. Because viral infection is impossible to cure once the virus is established, prevention is the most effective management option—obtained through the initiation with clean, pathogen-free planting stock. The utilization of virus-free materials has several agronomic, economic, and environmental benefits:

1. Improved Yield and Quality

Virus-free plants grow vigorously, are more physiologically efficient, and developed uniformly. This is reflected in increased yields, better tuber or fruit size, and higher quality produce that can compete with domestic and export market requirements. Potatoes and bananas, for instance, display high yield benefits of up to 30–50% over infected plantings.

2. Increased Disease Incidence

Employing virus-free propagation material prevents the introduction of major sources of infection, thereby avoiding the initial introduction and subsequent transfer of viruses in the field. This mitigates disease pressure and the reliance on chemical control strategies against insect vectors like aphids, whiteflies, and mealybugs that disperse viral pathogens.

3. Enhanced Economic Returns

The farmers are directly benefited from using virus-free planting material by enhanced productivity, fewer losses, and better marketability of their produce. The net cost-benefit ratio is good because it saves on pesticide consumption, lowers the requirement for replanting, and improves the quality of the harvest, resulting in increased profitability.

4. Facilitates Export and Certification

In global trade, the export of planting materials is controlled by strict phytosanitary regulations. Most importing nations mandate certification that guarantees the material is free of certain viruses and other diseases. The application of virus-indexed, certified planting stock thus accelerates smoother exportation, conformity with quarantine regulations, and involvement in high-value international markets.

5. Facilitates Sustainable Agriculture

Virus-free planting materials make a contribution to sustainability by minimizing chemical interventions, lowering environmental contamination, and

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maintaining biodiversity. Cleaner plants also use nutrients and water more effectively, sustaining robust farm systems despite the specter of climate change and resource shortages.

Crops That Have Been Impacted by Virus-Free Material

There are various economically valuable crops that have performed exceptionally well in terms of yield, quality, and lifespan since adopting virus-free planting technologies. Some examples are:

1. Potato (*Solanum tuberosum* L.)

Potato is very susceptible to a variety of viruses like Potato Virus X (PVX), Potato Virus Y (PVY), and Potato Leafroll Virus (PLRV). Virus-free seed tubers obtained by meristem tip culture and thermotherapy, kept under controlled conditions, have transformed seed potato production. In sophisticated systems, aeroponic and hydroponic techniques are applied for the mass multiplication of virus-free mini-tubers for continuous supply to farmers.

2. Banana (*Musa* spp.)

Banana propagation via conventional suckers tends to pass on viral diseases such as Banana Bunchy Top Virus (BBTV) and Banana Mosaic Virus (BMV). Micropropagation via tissue culture method guarantees homogenous, disease-free planting material, resulting in improved productivity and homogenous quality bunches. Virus-free sucker use has significantly lowered disease incidence in prominent banana-growing belts of India and Southeast Asia.

3. Citrus (*Citrus* spp.)

Citrus orchards all over the globe have been ravaged by Citrus Tristeza Virus (CTV) and Citrus Greening (HLB). The development of Citrus Certification and Budwood Programs that concentrate on generating virus-free budwood using shoot tip grafting and indexing has played a crucial role in reviving lagging citrus industries. The programs make sure that nurseries sell only certified clean material.

4. Sugarcane (*Saccharum officinarum* L.)

Sugarcane viruses like Sugarcane Mosaic Virus (SCMV) and Sugarcane Yellow Leaf Virus (SCYLV) profoundly impact yield and sugar recovery. Tissue culture-based propagation systems and the utilization of virus-free setts have helped enhance cane productivity and ratoon performance. These programs also improve the shelf life of varieties and check the spread of vector-borne diseases.

5. Cassava and Sweet Potato

Sweet potato and cassava in tropical and subtropical areas are frequently ravaged by Cassava Mosaic Virus (CMV), Cassava Brown Streak Virus (CBSV), and Sweet Potato Feathery Mottle Virus (SPFMV). Clean planting stock development using meristem culture, combined with molecular indexing and community-based multiplication systems, has significantly minimized yield losses and increased food security in Africa and Asia.

Production and Certification System

A strong and transparent production and certification system is crucial to guaranteeing the authenticity, purity, and traceability of virus-free planting material. Certification is a mechanism for quality assurance, ensuring that the supplied planting material is phytosanitary and genetically suitable for the required standards. The process generally goes through three key stages:

1. Foundation Source

It entails the identification and support of elite mother plants that have been certified as virus-free by thorough molecular (RT-PCR, NGS) and serological (ELISA) tests. Such plants are used as the basis for all subsequent propagation. The material source is typically held in quarantine or insect-proof conditions to avoid reinfection.

2. Multiplication Stage

During this stage, the certified virus-free plantlets are reproduced under highly controlled in vitro or screen-

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house conditions. Micropropagation, node culture, or somatic embryogenesis methodologies are applied based on the crop. The multiplication environment is carefully monitored to eliminate the presence of insect vectors and other sources of contamination. Regular indexing and inspection at every sub-culturing interval guarantee that the plantlets remain free from viruses throughout the propagation process.

3. Distribution Stage

Upon successful certification and indexing, the virus-free planting materials are dispatched to farmers by certified nurseries or approved agencies under regulatory monitoring. Documentation systems such as barcoding or QR-based digital traceability are commonly used to ensure the integrity of the supply chain. Traceability guarantees farmers access to genuine and quality material, while agencies for certification have control for compliance and accountability.

Challenges and Way Forward

Notwithstanding impressive progress in tissue culture, molecular diagnostics, and certification technology, there are numerous challenges to the universal application of virus-free planting materials in developing agricultural systems.

Major Challenges

Limited Awareness: Most farmers, especially smallholders, lack knowledge of the economic and agronomic advantages of virus-free planting materials.

High Cost and Expertise: Building tissue culture laboratories, virus-indexing stations, and managing sterile facilities involve high investment and expertise.

Inadequate Regulatory Frameworks: In some states, the absence of standard guidelines, certification standards, and enforcement systems hinders large-scale adoption.

Infrastructure Gaps: Inadequate availability of virus-indexing laboratories and certified nurseries limits timely supply and availability of clean planting materials.

Conclusion

Provision of virus-free planting material for availability and accessibility is a pillar of sustainable and resilient crop agriculture. It not only increases yield and quality of products but also protects farmers' income, enhances environmental sustainability, and enhances the competitiveness of the agricultural export industry.

The prospects of virus-free planting systems lie in concerted action among research and development institutions, government, private business and industry, and farmers. Enhancing certification systems, broadening molecular diagnostic networks, and building public consciousness will be essential moves toward a virus-free farming environment. Joint and science-based action can therefore guarantee healthier crops, better productivity, and sustainable food and livelihood security.

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Effective Management Strategies for Chilli Black Thrips (*Thrips parvispinus* (Karny)): Empowering Farmers for Successful Control

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The chilli black thrips, *Thrips parvispinus* (Karny), has recently emerged as one of the most destructive invasive pests threatening chilli cultivation in India. Native to Southeast Asia, this polyphagous pest has rapidly adapted to diverse climatic zones and now infests a wide range of crops, including vegetables, fruits and ornamentals. Its attack results in silvering of leaves, flower drop, and malformed fruits, leading to severe yield losses ranging from 40 to 80%. Due to its small size and cryptic behavior, management of this pest poses a significant challenge to farmers. This article highlights the pest's biology, host range, damage symptoms and most importantly, the integrated management strategies that empower farmers for effective control.

Concept of Virus-Free Planting Material

Chilli (*Capsicum annuum* L.) is a vital cash crop in India, both as a spice and vegetable, contributing significantly to rural livelihoods and the national economy. However, in recent years, the chilli ecosystem has been seriously threatened by the invasive thrips species *Thrips parvispinus* (Karny), commonly referred to as the "Chilli Black Thrips." Belonging to the order Thysanoptera and family Thripidae, *T. parvispinus* is a small yet formidable pest. It was originally described by Karny in 1922 and remained confined to parts of Southeast Asia. However, over the last two decades, its distribution has expanded dramatically across continents, now reported from countries like Thailand, Australia, Indonesia, Greece, Spain, and several African nations. In India, the pest was first reported on papaya in Bengaluru and since then, it has become a major concern in chilli-growing belts of Andhra Pradesh, Telangana, Karnataka, Tamil Nadu, Kerala and Gujarat.

Farmers have reported unprecedented crop losses, with damage levels often exceeding 70 to 80% in unmanaged fields. The outbreak has been aggravated by factors such as indiscriminate pesticide use, climate variability and lack of awareness of appropriate management practices. Hence, understanding the pest's biology and implementing effective Integrated Pest Management (IPM) strategies is essential for sustainable chilli production.

Distribution and Host Range

Thrips parvispinus exhibits remarkable adaptability, enabling it to thrive across tropical and subtropical climates. Initially restricted to Southeast Asia, it has now been recorded in more than 20 countries worldwide. In India, its rapid spread is attributed to the movement of infested planting materials and favorable agroclimatic conditions.

The pest is highly polyphagous, infesting over 40 plant species. Besides chilli and bell pepper, it attacks crops like brinjal, okra, bitter gourd, papaya, beans, shallot, and cotton. Among fruit and ornamental crops, gardenia, chrysanthemum, dahlia and anthurium are particularly susceptible. The pest's wide host range allows it to persist even in the absence of chilli, surviving on alternative weeds and intercrops.

Identification and Life Cycle

Adult *T. parvispinus* are small (about 1.2 mm in length), slender and dark brown, with a paler head and thorax. The antennae are seven-segmented with distinct fork-shaped sense cones on the second and third segments. The species lacks the first ocellar setae, a key feature distinguishing it from closely related thrips species.

The life cycle consists of five stages: egg, two larval instars, prepupa, pupa and adult. Under optimal temperatures (25 to 30°C), the life cycle completes within 13 to 15 days. Females lay eggs on the tender leaf or flower tissues, which hatch within 3 to 5 days. The larvae and adults prefer the undersides of leaves and flowers, where they feed and reproduce. Females live up to 8 to 9 days, laying around 30 to 60 eggs during their lifetime. This rapid life cycle and overlapping generations lead to exponential population buildup, especially under warm and dry conditions typical of many chilli-growing areas.

Nature of Damage and Economic Impact

Both nymphs and adults cause direct feeding damage by rasping the leaf surface and sucking cell sap from tender tissues. The affected leaves display silvery patches, curling and necrotic streaks. Flowers show brownish scars, fail to open properly and drop prematurely. In severe cases, developing fruits become malformed, discoloured and unmarketable.

In chilli, yield losses of 40 to 80% have been reported, while in extreme infestations, entire fields can fail. Heavy losses have been observed in Indonesia and Thailand. The pest thus poses a significant threat not only to crop productivity but also to farmers' livelihoods.

Factors Favouring Outbreaks

Several ecological and agronomic factors have contributed to the rapid spread and persistence of *Thrips parvispinus* in chilli ecosystems. The excessive and indiscriminate use of broad-spectrum insecticides has disrupted the natural balance, eliminating beneficial predators and parasitoids that normally regulate thrips populations. Continuous monocropping of chilli, along with the presence of unmanaged weed species such as *Parthenium* and *Abutilon*, provides a continuous host source for the pest even during off-seasons.

Moreover, warm and dry weather conditions, particularly temperatures ranging between 25°C and 35°C, are highly favorable for the pest's reproduction, allowing it to complete multiple generations within a short time. High application of nitrogen fertilizers also promotes the growth of succulent foliage, creating ideal feeding and breeding conditions for thrips. Collectively, these factors create a conducive environment that supports pest survival and flare-ups, making management increasingly challenging under field conditions.

Integrated Pest Management Strategies

Controlling *T. parvispinus* requires a holistic and sustainable approach, integrating cultural, mechanical, biological and chemical measures. Relying solely on chemical control often leads to resistance and pest resurgence. The following IPM-based strategies can empower farmers to achieve long-term, effective management.

1. Cultural Practices

Adoption of suitable cultural practices is crucial for reducing the incidence of *Thrips parvispinus* in chilli crops. Early sowing and transplanting during cooler months help the crop avoid peak pest activity. Resistant varieties like *Capsicum annuum* 'Keystone Resistant Giant' and *C. baccatum* 'Aji Blanco Christal' offer partial protection and reduce dependence on chemical control. Using silver-black or transparent plastic mulch alters the field microclimate, suppresses weeds and discourages thrips buildup. Balanced fertilizer application with optimum N: P: K levels should be followed, avoiding

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excessive nitrogen that promotes tender foliage favoured by thrips. Proper field sanitation by removing infested residues and weed hosts such as *Parthenium* and *Abutilon* before planting further minimizes pest carryover. Together, these cultural measures form an effective and sustainable foundation for thrips management.

2. Physical and Mechanical Measures

Physical and mechanical methods play an important role in managing *Thrips parvispinus*. Installing 25 to 30 blue sticky traps per acre soon after transplanting helps monitor and mass-trap adult thrips, as blue traps are more attractive than yellow or white ones. Border cropping with maize or sorghum serves as a barrier, limiting thrips movement between fields. Post-harvest CO_2 fumigation, using 60% CO_2 at 30°C for one hour, ensures complete mortality of thrips and is effective for managing infestations in protected and export produce without leaving chemical residues.

3. Botanical and Biopesticide Options

Botanical and microbial products provide eco-friendly options for managing *Thrips parvispinus*. Neem oil (3%) or Azadirachtin (0.003% @ 3 ml/L) effectively suppress early infestations. Plant extracts of *Tephrosia vogelii* and *Toona sureni* at 2.5 to 3.0% concentrations reduce thrips populations by over 30%. Microbial formulations like *Pseudomonas fluorescens* (1% WP @ 4 g/L) and *Bacillus albus* also lower pest incidence while improving plant health. These methods are safe for beneficial insects, cost-effective, and compatible with other IPM practices.

4. Biological Control

Biological control is an important component in managing *Thrips parvispinus*. Predators like ladybird beetles (*Menochilus sexmaculatus*), lacewings (*Chrysoperla* spp.) and predatory mites (*Amblyseius cucumeris*) feed on thrips and help regulate their population. Fungal pathogens such as *Lecanicillium lecanii* and *Beauveria bassiana* also infect and kill thrips under humid conditions. Avoiding broad-spectrum insecticides helps conserve these natural enemies. Community-based release and farmer training further strengthen biological control and reduce pest resurgence.

5. Chemical Control

When *Thrips parvispinus* infestation exceeds 2 to 3 thrips per flower, selective insecticides should be applied carefully. Rotation of insecticides with different modes of action helps prevent resistance. Recommended options include Fipronil 80% WG (0.2 g/L), Cyantraniliprole 10.26% OD (1.25 ml/L), Acetamiprid 20% SP (0.2 g/L), Spirotetramat 150% OD (0.8 ml/L), Spinetoram 11.7% SC (1 ml/L) and Tolfenpyrad 15% EC (2 ml/L). Sprays should target the lower leaf surfaces and flowers, avoid repeated use of the same chemical group and maintain 7 to10-day intervals between applications.

6. Community and Area-Wide Management

As *Thrips parvispinus* spreads quickly across fields, individual control efforts are often ineffective. Community-based, area-wide management ensures coordinated pest control through synchronized sowing and harvesting, collective weed and residue management and uniform IPM adoption. Awareness programs through Farmer Field Schools (FFS) further support timely interventions, making pest suppression more effective and reducing overall infestation in the region.

Empowering Farmers for Sustainable Control

Empowering chilli growers with the right knowledge and skills forms the foundation of sustainable pest management. Regular training programs, field demonstrations and timely pest alerts through mobile advisories or village campaigns can greatly enhance farmer awareness and preparedness. Collaboration among extension agencies, research institutions and farmer producer organizations (FPOs) is essential to promote bio-intensive IPM practices, develop thrips-resistant chilli varieties and establish pest monitoring and early warning systems. Training farmers in safe pesticide handling and residue management further

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supports responsible pest control. These farmer-centred initiatives not only help in effective pest suppression but also ensure environmental safety and improved farm profitability.

Conclusion

The invasive chilli black thrips, *Thrips parvispinus*, poses a serious threat to sustainable chilli cultivation in India, causing significant yield and quality losses. Nevertheless, effective management is possible through an integrated approach that combines cultural, biological and chemical control measures, along with active community participation and farmer empowerment. Early detection, adoption of preventive agronomic practices and the judicious use of selective insecticides can substantially reduce pest populations and minimize pesticide dependence. Strengthening farmer awareness and promoting coordinated management across regions are also essential to prevent pest resurgence. Through joint efforts by farmers, researchers and policymakers. India's chilli industry can effectively manage this invasive pest and move toward resilient, eco-friendly and residue-free chilli production in the years to come.

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Smart Sensors: A Sustainable Solution for Precision Agriculture

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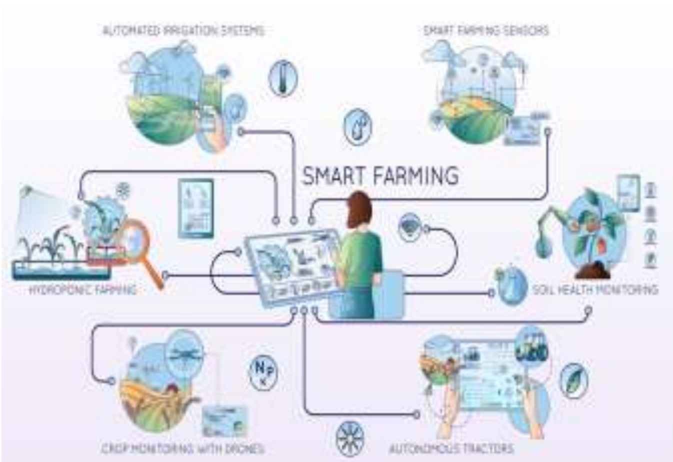
Agriculture is one of the major sectors which contribute a lot to the financial of world's population and to get quality product, proper irrigation has to be performed, to reduce man power using modern technology of internet of things IoT in today's life. Population increase, limited resources, the influence of pandemics on the workforce, financial upheaval, and unpredictable weather conditions are putting unusual pressure on agricultural operations. As they attempt to feed the world, today's farmers must struggle with increased water shortages or floods, diminishing land availability and shifting costs.

The world's population through 2050, farmers will need to boost food production by 70% to feed everyone. Several variables have a great influence on crop development. Control and knowledge of them allows a better management of necessary resources, as the term 'Precision Agriculture' points out. Precision Agriculture, also known as site-specific management, is an agricultural management plan based on monitoring and calculating agricultural parameters with precision, which is useful as a reference in taking appropriate actions. Conventional agriculture is implemented by practicing some particular tasks (such as planting, irrigation, fertilization, and harvesting) under a defined schedule. On the other hand, predictive analytics could be applied to optimize farming operations by providing real-time status on weather, soil, crop, fertilizer and even farm equipment or labour.

The IoT connects things to the internet for communicating with the sensing devices with suitable protocols and exchanging data with each other by using wireless sensor networks. Using an IoT different parameters are monitored regularly in real time without any delay. IoT gives the information in all sectors of agriculture, healthcare, home appliances etc. IoT and Cloud computing technologies provide new opportunities in IoT-based applications and services.

Smart technologies in agriculture:

The integration of digital tools including sensors, IoT, data analytics, and automation to improve farming productivity, sustainability, and efficiency is referred to as "smart technologies" in the agricultural industry. These technologies make it possible to precisely monitor and regulate agricultural characteristics such as temperature, crop health, livestock conditions, and soil moisture. Smart agricultural technologies decrease resource waste, increase yields, and tackle issues like food security and climate change by gathering data in real-time and enabling informed decision-making.



Application of IoT in smart farming

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Smart sensors in agriculture:

Smart sensors in agriculture are crucial tools for real-time monitoring and automation of farming activities. Several sensor types have been used in agricultural systems to monitor and control.

Categories of sensors currently used for agriculture

Sensor Type	Purpose	Application domain
Passive Infrared (PIR) motion sensors	To monitor movement (e.g. of pests or industry in grain storage facilities or barns	Storage of agricultural produce
Digital Humidity and Temperature (DHT) sensors	Used by farmers for planning, harvesting and monitoring crops' temperature and humidity levels	Livestock management and climate-weather monitoring
Nutrient sensors	To measure soil nutrients such as nitrogen and phosphorus	Nutrient monitoring
Pest and disease detection sensors (for example, Red, Green, Blue (RGB), Multispectral, Hyperspectral, Thermal)	To detect early signs of pest infestations or diseases in crops.	Pest and disease detection
Crop growth sensors (LIDAR (Light Detection and Ranging), ultrasonic sensors, optical sensor	Used to monitor plant growth parameters such as height and biomass	Crop management
Gas sensor	To detect toxic gases in livestock including poultry system.	Livestock monitoring
Flow Sensors, evapotranspiration (ET) sensors, wind sensors and Rain sensors	Used to monitor water content in the soil	Irrigation monitoring
Drone-mounted sensors	Unmanned Aerial Vehicles (UAVs) equipped with various sensors, multi-spectral, thermal, and LiDAR are used for real-time data collection in agriculture	Gasoline vapor (VOCs), CO sensors, O_2 sensors, NOX sensors and particle Matter (PM) sensors
Soil sensors	Used to measure soil parameters such as moisture PH, and nutrient levels	Remote sensing monitoring

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Tractor –mounted sensors (Global Positioning System (GPS), inclinometers and rotary angle, and telematics)	These sensors are installed on tractors to determine precise location, monitor tractor's angle, and position, to provide feedback for auto-steering systems and provide real-time data on the tractor's status including location, fuel consumption, and operational Efficiency	Farm machinery management

Soil Moisture light and pH Sensor

Nutrient Sensor

Soil Moisture light and pH Sensor

An IoT-based livestock system

Conclusion:

The adoption of IoT in agriculture signifies a revolutionary change toward data-driven, efficient, and sustainable farming methods. IoT makes it possible to precisely and automatically control agricultural processes using smart sensors, cutting-edge communication technologies, and real-time monitoring systems. This leads to enhanced resource management, decreased waste, and increased output. Many such challenges of high cost in the initial installation, connectivity issues, as well as data security remain. Additionally, predictive decision-making, crop and livestock management, and operational efficiency are improved by the convergence of IoT with cutting- edge technologies including artificial intelligence, machine learning, big data analytics, cloud computing, and nanotechnology. More initiatives will come from the government and private sector, including investments and research collaborations.

The ongoing development and uptake of IoT and related technologies is crucial for accomplishing sustainable development goals, guaranteeing food security, and fostering economic resilience as agriculture faces increasing demands because of population expansion and climate change. An IoT enabled agriculture is essential for the future and not just a fad. To fully exploit the potential of these technologies and to make smart farming scalable and accessible across economies.

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Urban Agriculture: A Pathway for Food Security

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Introduction

Urban agriculture is the production, processing, and marketing of food in and around peri-urban and urban cities. It is not only confined to crop cultivation but may cover other activities like livestock production, aquaculture, rooftop farming, vertical cultivation, hydroponics, and food-producing community systems. It has become a new-age, innovative, and viable solution in recent times to counter the imminent challenges of hunger, environment damage, and employment prospects in fast-growing cities.

The accelerating rate of urbanization has resulted in diminishing agricultural land, intensified competition over land use, and deepening demand-supply gaps in food. Consequently, cities experience increasing reliance on outside food supplies, increased food transport costs, and diminishing access to fresh, nutritious foods among urban dwellers. Urban agriculture helps bridge this gap by locating food production nearer the consumers, subsequently lowering the carbon footprint to transportation, improving dietary variety, and supporting local food systems.

In addition to food security, urban agriculture makes several contributions towards urban sustainability. It assists in recycling waste as organic fertilizer via composting and wastewater recycling, enhances biodiversity by providing green areas, and alleviates the urban heat island phenomenon. Further, it creates jobs, empowers women and the marginalized, and promotes community harmony through collective farming efforts. Given the context of climate change as well as population growth globally, urban agriculture is now more and more being promoted as a sustainable solution to create resilient, self-sufficient, and inclusive cities.

Significance of Urban Agriculture

Urban agriculture is essential for creating sustainable and resilient cities. Its significance goes beyond the production of food, reaching aspects of nutrition, economy, environment, and social welfare. Some of the salient points are:

1. Food Security

Urban agriculture offers fresh, healthy, and affordable food directly in cities, minimizing reliance on remote rural regions. It aids in the breakdown of food supply disturbances due to transportation problems, natural calamities, or market instability. By locally producing perishable products such as vegetables, fruits, milk, and fish, urban agriculture enhances diet diversity and malnutrition among city dwellers.

2.Job Opportunities

Urban farming generates new employment opportunities in crop production, animal rearing, aquaponics, rooftop gardening, and food processing. It involves urban youth, women, and the unemployed, thus supporting poverty alleviation and economic empowerment. Complementary services like inputs supply, marketing, value addition, and logistics further create employment opportunities.

3.Waste Management

Urban centers have high volumes of organic waste, much of which can be recycled using composting and utilized as natural fertilizer in urban agriculture. Wastewater can be treated and used for irrigation to cut down on the demand for freshwater resources. It

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promotes a circular economy system in which waste is converted into valuable inputs to produce food.

4.Environmental Impacts

Urban farming increases urban vegetation, decreases urban heat island effect, and regulates city microclimates. Carbon dioxide is absorbed by plants, pollutants are filtered, and the quality of air is improved. Rooftop and vertical gardens provide more green coverage, aiding in stormwater management, biodiversity support, and general ecological balance.

5.Social Development

Community gardens, cooperative farms, and rooftop ventures enhance collective involvement and social solidarity. They serve as learning centers for schools, NGOs, and civic groups to educate people about healthy consumption and sustainable lifestyles. Urban agriculture promotes inclusivity by engaging marginalized communities and increasing food sovereignty at the local level.

Forms of Urban Agriculture

Urban agriculture exists in various forms based on the availability of space, use of technology, and community involvement. The various models allow cities to use underutilized spaces and assets efficiently for food production. The principal forms are:

1.Rooftop and Terrace Farming

Uses rooftop spaces of residential, commercial, and institutional structures for the cultivation of vegetables, fruits, and herbs. Assists in temperature management of buildings, decreases energy usage, and improves food access. Common in high-density urban areas where land is limited.

2.Hydroponics and Vertical Farming

Soil-less growing with nutrient solution water solutions. Vertical farming employs layers of crops in multi-level stacks under controlled settings, which maintains the production process throughout the year. These techniques are characterized by high productivity, effective water usage (as much as 90% less compared to conventional farming), and compatibility with conditions found in urban areas with limited space.

3.Community Gardens

Common pieces of land in residential neighborhoods, parks, or institutions where individuals share in the growing of food crops. Promote community involvement, socialization, and sharing of knowledge. Offer cheap and convenient food and foster a feeling of ownership and mutual assistance among inhabitants.

4.Aquaponics

A closed-loop eco-friendly system that combines aquaculture (fish rearing) and hydroponics (plant growing). Fish waste acts as fertilizer for plants, and plants filter and purify water for fish. Needs minimal outside inputs and provides both vegetables and protein foods, thus a circular and resource-conserving system.

5.Kitchen/Backyard Gardens

Extensive small-scale family farming done on balconies, backyards, or small pieces of land surrounding residential areas. Maintains a constant fresh vegetable, spice, and herb supply for regular consumption. Majorly contributes to household food costs reduction and nutritional security.

(Source, Lal, 2020)

Challenges of Urban Agriculture

Even with its numerous advantages, urban agriculture has a number of challenges that

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discourage its large-scale adoption and sustainability. These challenges include:

1.Space and Access to Land

Urban high population and land pressure in cities are such that there is very little land left open for farming activities. Vacant plots, rooftops, and community space are underutilized or tied up due to property and tenancy issues. Alternating land use priorities like housing, infrastructure, and commercialization further cut down farming opportunities.

2. Water Scarcity and Contamination

Urban cities frequently experience severe water shortages, rendering irrigation a major problem. Excessive dependence on untreated wastewater for urban agriculture may result in food produce contamination and health hazards. Industrial and domestic water pollution further aggravates the situation, reducing the availability of safe water.

3. Lack of Awareness and Technical Knowledge

Urban dwellers are largely unaware of new agricultural methods like hydroponics, vertical farming, or aquaponics. Limited technical skills, poor training, and absence of extension services limit adoption. Misunderstanding of the feasibility, profitability, and returns of urban agriculture discourages potential practitioners.

4.Policy and Regulatory Barriers

Urban agriculture is not well defined in urban planning and development policies in most countries. Limitations in the use of land, zoning ordinances, and absence of incentives from the government discourage investment in urban farming. Lack of organized markets and certification for peri-urban produce impacts profitability and scalability as well.

Way Forward

1.Encouragement of Rooftop and Vertical Farming: Urban planning must ensure rooftop, terrace, and vertical farming models to utilize scarce space to the fullest.

2.Capacity Building and Training: Periodic training sessions and awareness programs can impart modern farming skills and knowledge to urban dwellers.

3. Policy Support and Incentives: Government policies, subsidies, and tax incentives must facilitate investment and engagement in urban agriculture initiatives.

4. Integration with Waste and Energy Systems: Integrating urban farming with waste recycling, composting, and renewable energy can optimize sustainability and efficiency of resources.

5. Public-Private Partnerships: Public, private sector, and community partnerships can offer infrastructure, technology, and market facilitation to scale up.

Conclusion

Urban agriculture is more than producing food it is a step towards resilient, sustainable, and autonomous urban communities. By integrating farming into urban ways and policies, cities can become closer to achieving food security, environmental sustainability, and improved quality of life for their citizens.

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Nature's Secret Weapon: How Bio fumigation Cover Crops Protect Plants and Rebuild the Soil in Natural Farming

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In the heart of India's farms, a quiet revolution is taking root. Farmers are turning back to the wisdom of their ancestors through *Natural Farming*—a way of growing food in harmony with the earth. No chemicals, no synthetic fertilizers—just the rhythms of nature and the strength of local knowledge. By working with livestock, covering their fields with green mulch, and harvesting rainwater, they are rebuilding the living soil beneath their feet. Their fields now hum with life: rich microbes, fertile soil, and crops that thrive together. Costs go down, yields diversify, and the earth breathes again. Natural Farming isn't just a method—it's a movement toward balance, abundance, and resilience. By using local wisdom and natural methods—like mulching, composting, rainwater harvesting, and planting multiple crops—farmers can boost soil fertility, save water, reduce costs, and grow healthier food. With stronger soils, more organic matter, and thriving microorganisms, farms become more resilient and productive—all while protecting nature for future generations.

The principle of Natural Farming emphasises on sustainability and working in harmony with the natural ecosystem. There are several principles in the natural farming; cover crops are one among those to combat diseases.

Plant diseases

Soilborne diseases are a significant challenge to crop production, leading to reduced crop performance, decreased yields and increased production costs worldwide. This section covers the control of soilborne pathogens using biofumigant cover crops. Research in France highlighted that planting *Brassica juncea* reduced the incidence of root rot (caused by *Rhizoctonia solani*) in sugar beets. The severity of the disease and *R. solani* incidence level reduced in subsequent years after incorporating mustard cover crops in soil from nearly 30% in 2005 to 15% in 2007, which is significantly lower than the control bare soil. *In-vitro* investigations on the impact of Brassica species on *Phytophthora* spp. demonstrated that *B. juncea* inhibited the mycelial growth of *Phytophthora* spp. Rotating crops with canola and rapeseed (*B. napus*) helps reduce Rhizoctonia disease in potatoes. Biofumigation cover crops can also help manage soilborne diseases in nursery soils. In 2020 greenhouse trials, yellow mustard (White Gold), arugula (Astro), mighty mustard (Pacific Gold), rape (Dwarf Essex), turnip (Purple Top Forage), brown mustard (Kodiak) and mustard green (Amara) effectively reduced disease severity from *R. solani* and *P. nicotiane* in viburnum and hydrangea, except for radish, when incorporated two weeks before planting. Brassica crops like *B. nigra*, *B. juncea* and *B. carinata* release high amounts of propenyl isothiocyanate, which helps suppress *Fusarium oxysporum* in nursery soils. Using brassica cover crops can be an effective strategy for disease management through biofumigation.

Nematode control

Nematodes are microscopic worms present in almost all environments, from aquatic to terrestrial (soil). The majority of nematode species play crucial roles in nutrient cycling and organic matter decomposition. But some are plant parasitic and pose significant threats to agricultural production. Species such as root-knot nematodes (*Meloidogyne spp.*), cyst nematodes (*Heterodera spp.*) and root-lesion nematodes (*Pratylenchus spp.*) feed on plant roots, causing damage that leads to reduced water and nutrient uptake, stunted growth and yield losses. Chemical fumigation and synthetic nematicides are

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commonly used to control nematodes, which can be expensive and environmentally harmful. As a result, alternative strategies, such as the use of biofumigant cover crops, are gaining popularity as eco-friendly and cost-effective solutions for nematode management. A greenhouse study in New Mexico showed that broccoli (Arcadia) had the least root-knot nematode damage, while mustard (Caliente 61, Caliente 199 and Pacific Gold) increased nematode numbers. In 2012, yellow mustard was found to decrease population densities of the plant-parasitic nematode *Globodera rostochiensis* in potatoes. A greenhouse study in Australia found that mixing broccoli tissue into nematode-infested soil reduced root-knot nematode (*M. incognita*) levels, with the highest rate (20 g per pot) lowering infestation to 5%, compared to 100% in untreated soil. Brassica cover crops can suppress root-knot nematodes, but effectiveness varies by species, location and biomass produced. In Australia, fodder radish significantly reduced root-knot nematodes in vegetables, showing resistance. due to genetic traits rather than just glucosinolates. Another study found that cultivating radish as a cover crop effectively reduced the egg population of *M. japonica*, supporting their use in nematode management.

Conclusion

Natural Farming (NF) represents a sustainable, chemical-free agricultural practice integrating livestock-based systems and diversified cropping patterns, deeply embedded in Indian traditional ecological knowledge. NF emphasizes the application of locally adapted agro-ecological principles and technologies that evolve according to specific regional contexts. by involving /working with livestock, covering their fields with green mulch, and harvesting rainwater, they are rebuilding the living soil beneath their feet. Their fields now hum with life: rich microbes, fertile soil, and crops that thrive together. Costs go down, yields diversify, and the earth breathes again. Natural Farming isn't just a method—it's a movement toward balance, abundance, and resilience.

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Fertilizer Shortage in India: A Crisis Beneath the Soil

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At dawn, In Odisha's Ganjam district, hundreds of farmers queue outside cooperative stores, hoping to secure a single bag of urea. Many return empty-handed, while some are forced to buy it in the black market at nearly double the price. The shortage of fertilizers this season is more than just a supply problem, it strikes at the heart of farmer livelihoods and India's food security

Why Fertilizers are Crucial for Indian Farmers?

India is one of the world's biggest users of chemical fertilizers, ranking just after China. In about 2022, Indian farmers consumed about 20.21 Mmt (million metric tons) of Nitrogen based fertilizers; a massive amount, but still lower than China's consumption of 24.81 Mmt in that same year. These Nitrogenous fertilizers, such as urea, are widely applied to boost crop yields, especially for staples like rice and wheat. When it comes to phosphatic fertilizers, which support root development and flowering, India again stands second after China. India's consumption reached 7.92 Mmt, while China led with around 11 Mmt (Figure 1). These figures highlight just how fertilizer dependent India's agricultural sector has become, reflecting both its vast farming population and the pressure to ensure food security for over a billion people. However, the heavy reliance on fertilizers also raises concerns. Overuse can harm soil health, reduce long term fertility, and contribute to water pollution. Policymakers are therefore working to strike a balance: ensuring farmers have access to fertilizers for high productivity, while also encouraging sustainable practices like balanced nutrient use, organic alternatives, and integrated soil management.

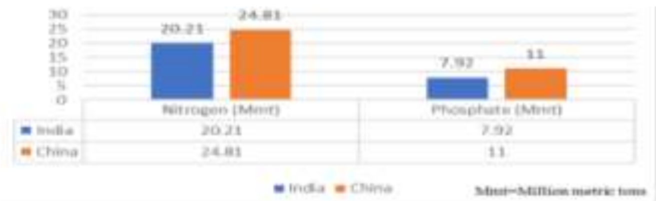

Figure 1. Fertilizer consumption India vs China (2022)
Data Source: Statista, Source: Author's Compilation

Heavy Import Reliance

India's vast fertilizer demand cannot be met by domestic production alone, making the country heavily dependent on imports. In fiscal year 2022, the country imported approximately 6.51 Mmt of nitrogen fertilizers, 3.74 Mmt of phosphates, and 1.86 Mmt of potash from international markets. This dependence is especially crucial for potash, since India has little to no natural reserves and must rely almost entirely on foreign suppliers. In comparison, exports were negligible. Only 44,500 t (metric tons of nitrogen), 16,000 t of phosphate, and 5,700 t of potash left the country (Figure 2). This stark imbalance underscores the structural reality: India is overwhelmingly an importer than an exporter of fertilizers. Such reliance makes India vulnerable to global price swings, supply chain disruptions, and geopolitical tensions. For example, conflicts or trade restrictions in major supplier countries can quickly affect availability and affordability for Indian farmers. Recognizing these risks, policymakers have been pushing for measures such as long-term supply agreements, joint ventures abroad, diversification of sourcing partners, and investment in domestic production capacity. At the same time, there is growing emphasis on efficient fertilizer use and alternatives like bio fertilizers to reduce the import burden over time.

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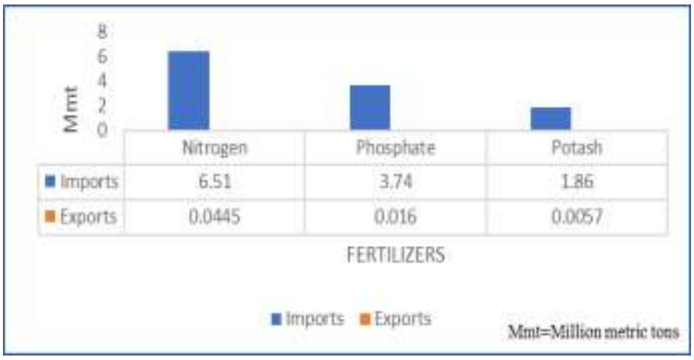

Figure 2. India Fertilizers import vs export
Data Source: Statista, Image, Source: Author's Compilation

Urea: The Cornerstone of Indian Farming

When it comes to fertilizers, Urea stands unmatched in India's agricultural landscape. It is the most widely used input across the country's fields, valued for its affordability, high nitrogen content, and immediate impact on crop growth. In the financial year 2023 alone, Indian farmers consumed over 35.7 Mmt of urea; by far the highest among all fertilizers. This extraordinary scale of use highlights urea's critical role in sustaining crop productivity, especially for staples like rice, wheat, and maize. For many small and marginal famers, urea is often the first choice because it delivers quick results and is heavily subsidized by the government, keeping prices low. However, the key reliance on urea also brings challenges. Overuse can lead to soil nutrient imbalance, declining fertility, and environmental issues such as water pollution and greenhouse gas emissions. Policymakers and scientists are therefore encouraging balanced fertilizer practices, blending urea with phosphatic and potassic nutrients, and promoting alternatives like coated or slow-release urea to improve efficiency. Even with these concerns, urea continues to be the backbone of Indian farming, powering the food security of more than a billion people.

Implications for Farmers

- Fertilizers particularly Urea are vital for sustaining high crop yields. Without adequate access, farmers are likely to experience reduced harvests, which directly affects both income and livelihood security.
- With a significant share of fertilizers sourced from imports, fluctuations in global supply and pricing quickly translate into higher domestic costs. Subsidy support is therefore indispensable, as most small, and marginal farmers cannot afford fertilizers at open markets rates.
- Fertilizer availability is closely tied to overall food production. Any disruption in supplying risks lowering output, which in turn can trigger food inflation and potential shortages, making the issue a matter of national concern rather than just an agricultural challenge.

Table 1. Fertilizer Consumption, Imports, Exports, and Urea Sales in India (2022-23)

Metric	**Value** *(Mmt-Million metric tons, kt-Kilotons)*
Nitrogen Fertilizer Consumption (2022)	20.21 Mmt
Phosphate Fertilizer Consumption (2022)	7.92 Mmt
Imports (2022)	N: 6.51 Mmt, P: 3.74 Mmt, K: 1.86 Mmt
Exports (2022)	N: 44.5 kt, P: 16.07 kt, K: 5.68 kt
Urea Sale (Fy 2023)	35.7 Mmt

Source: Statista

Government Measures and Policy Responses

The Indian government has been addressing fertilizer shortages in a number of ways since realising how they affect national food security and farmer livelihoods. The core of these initiatives are subsidy programs, with urea receiving significant subsidies to

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keep farmers able to afford it. In order to balance nutrient application and lessen an excessive reliance on nitrogenous fertilizers, the Nutrient-Based Subsidy (NBS) program also encourages the use of phosphatic and potassic fertilizers. With new projects launched under the "Aatmanirbhar Bharat" vision and the revival of several closed fertilizer plants, there has been a push for domestic production to increase self-reliance. In order to lessen its vulnerability from depending too much on a single supplier, India is aggressively pursuing import diversification at the same time, signing agreements with nations like Canada, Jordan, and Russia. The Soil Health Card program aims to encourage farmers to use fertilizer in a balanced manner according to scientific recommendations, while programs like, "One Nation One Fertilizer" (**Pradhanmantri Bharatiya Jan Urvarak Pariyojana)** have been introduced to standardise branding and improve transparency (Figure 3). There are still issues in spite of these efforts. Imports are becoming more expensive due to rising global prices, geopolitical unrest, and currency fluctuations, underscoring the urgent need for long-term plans to guarantee fertilizer security.

Figure 3. One Nation One Fertilizer Scheme
Image Source: Sarkari Yojana

Sustainable Innovations and Alternatives

Policymakers and scientists are pushing for sustainable alternatives to lessen India's excessive reliance on imported chemical fertilizers. Utilising organic fertilisers, such as compost, farmyard manure, and green manures, is one of the most crucial strategies since they enhance soil health and increase its resilience and fertility over the long run. The capacity of biofertilizers, such as microbial inoculants like Rhizobium and Azotobacter, to fix atmospheric nitrogen and naturally increase crop productivity without having negative side effects is also drawing attention. Nano urea, created by IFFCO, has been a ground-breaking invention in recent years. Nano urea, which comes in tiny bottles that may eventually take the place of large urea bags, promises to decrease waste, lower storage and transportation expenses, and improve nutrient efficiency at the farm level. In addition, the use of precision farming technologies like digital sensors, drones, and soil testing guarantees that fertilisers are applied in the proper amount at the right time, reducing financial expenses and environmental damage Integrated Nutrient Management (INM), which blends chemical, organic, and biological inputs to maintain a balanced nutrient supply, is another crucial strategy. India can eliminate its reliance on imports and preserve soil health for future generations by incorporating these practices into a more farmer-friendly, climate-resilient, and sustainable fertilizer system.

Global Context and Lessons for India

The lack of fertilizer in India is not a unique problem; rather, it is a component of a larger global trend that is influenced by market forces, geopolitical conflicts, and policy decisions. The 2021 ban on chemical fertilizers in Sri Lanka is a notable example; it was meant to encourage organic farming but instead resulted in sharp drops in yields, food shortages, and unstable economic conditions. This emphasises the dangers of abrupt and ill-thought-out changes to fertilizer policy. Meanwhile, China, the world's largest fertilizer producer, has restricted exports to secure its domestic needs. These curbs have disrupted global supply chains and directly impacted India, which relies heavily on imports of phosphates and potash. Similarly, many African nations are struggling with fertilizer affordability and accessibility due to rising global prices and supply

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constraints, underlining the worldwide nature of the crisis. The main takeaway for India is obvious: an excessive reliance on imports leaves the nation vulnerable to external shocks, such as trade restrictions, price volatility, or conflicts like the Russia-Ukraine war. India needs to strengthen its domestic production base, diversify sourcing agreements, and build strategic reserves to ensure that farmers access to vital nutrients is not jeopardised by outside disruptions.

Long Term Path to Fertilizer Security

More than temporary solutions are needed to ensure fertilizer security in India; a thorough long-term plan is needed. Increasing domestic production capacity is a top priority, especially for urea, phosphates, and potash. Farmers will become less reliant on imports and be protected from worldwide disruptions if idle plants are revived, new units are established, and private sector involvement is encouraged. Investing in research and development is equally important. Innovations that can improve nutrient use efficiency and decrease waste include slow-release formulations, climate-smart alternatives, and nano fertilizers. International cooperation and public-private partnerships will be essential to the development of these technologies and their widespread availability to farmers. At the policy level, India ought to look into international joint ventures to guarantee a consistent supply of raw materials while also accumulating strategic reserves to protect against changes in world prices. Farmer education is also very important. By means of awareness campaigns and extension services, farmers can be taught how to use fertilizer in a balanced and effective manner, avoiding excessive urea use and promoting the use of sustainable substitutes. Fertilizer security needs to be connected to SDG 13 (Climate Action) and SDG 2 (Zero Hunger) within the larger development framework. India can guarantee that its transition to fertilizer self-reliance also supports international climate commitments and long-term agricultural resilience by coordinating food production objectives with sustainability imperatives.

Conclusion: The Road Ahead

Food security, farmer incomes, and national stability are all directly threatened by fertilizer shortages, which are not just an agricultural issue. Crop yields fall, production costs increase, and the likelihood of hunger and rural distress increases in the absence of consistent access to fertilizers. A vision that strikes a balance between affordability, accessibility, and sustainability is needed to address this challenge. In the short term, India must continue managing imports efficiently, diversifying supply chains, and protecting farmers through subsidies and targeted support. At the same time, a long-term shift towards self-reliance and innovation is essential. Expanding domestic production, investing in research, and promoting sustainable practices like organic manures, biofertilizers, and nano urea will create a more resilient system. In the end, India's fertilizer policy needs to change from crisis management to resilience building in order to guarantee that no farmer's field is left bare due to a lack of nutrients. In addition to safeguarding the livelihoods of millions of farmers, a well-rounded, proactive strategy will fortify the pillars of national food security.

"Without fertilizers, fields lie fallow; but with timely action, India's food security can flourish."

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Pokkali Rice: Kerala's Saline-Resilient Heritage Crop at a Crossroads

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The Origin of Pokkali Rice…

The story of Pokkali begins with a great flood that washed the seeds of this prolific grain from the Western Ghats to the low lying saline plains. There pokkali rice evolved as a strong contender against the ravages of nature, to nurture the communities that lived harmoniously. Pokkali is the oldest variety of rice in Kerala which has a tradition of at least 3000 years in rice cultivation. It is also one of the world's oldest known crops grown using organic agricultural practices.

Significance of Pokkali Rice

The pokkali variety of rice is known for its saltwater resistance and flourishes in the rice paddies of coastal Alappuzha, Ernakulam and Thrissur districts of Kerala. The single-season paddy is raised in saltwater fields between June and November followed by a season of fish-farming. The uniqueness of the rice has brought it the Geographical Indication (GI) tag and is the subject of continuing research.Several foreign research institutes, including the International Rice Research Institute in the Philippines, have been studying Pokkali's gene pools and have identified a portion of DNA on one of its chromosomes that is crucial for salt tolerance. Given its ability to thrive under harsh climatic conditions and produce high yield, it can help in promoting climate-resilient agriculture. Pokkali has medicinal properties and its higher value of antioxidants and low carbohydrate content makes it preferable to those on a low sugar diet. Vyttila-11 is the latest variety of Pokkali developed by the Kerala Agricultural University. It yields about 5 tonnes per hectare and the crop duration is about 110 days.

Farming method

In more than 90 % of the single cropped Pokkali lands, rice cultivation is done during the low saline phase from May-June to September-October. The traditional prawn filtration is taken up during the high saline phase which sets in during December-January. The bunds are strengthened by April and sluices (wooden gates) are repaired for regulating water level. The fields are drained during low tide and then sluices are closed. The monsoon rain washes down the dissolved salts in the mounds formed in the previously dried fields. The mounds act as elevated in-situ nursery and protect the seedlings from flash floods. The Pokkali system mainly depends on traditional Pokkali cultivars and high yielding varieties derived from these cultivars. Pokkali, Churuttu Pokkali, Chettyviruppu, Anakkondan and Cheruviruppu are the traditional cultivars prevalent in this tract.

Seeds Preparation

A method unique to Pokkali is adopted for sprouting the seeds. The seeds are tightly packed in baskets made of plaited coconut leaves the inside of which are lined by banana or teak leaves. These baskets are then immersed in fresh water ponds for 12 – 15 days. After which they are taken out and stored in shade. During this time the seeds sprout and remain dormant for more than 30 days in that condition. When the soil and weather conditions become favourable for sowing, the baskets containing the seeds are resoaked for 3 to 6 hours before sowing. The mounds in the field are then raked and levelled, the sprouted seeds are sown on the top of mounds which act as nursery in-situ.

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Pokkali fields in Kuttanad.

Fertilization

Generally manuring or plant protection operations are not necessary for Pokkali farming systems. The crop matures in a trout for 12 days. The average yield of rice with traditional rice varieties is 1500 kg / ha. After harvest of rice the field is used for fish or prawn capture, which provides a substantial subsidiary income to the farmer. Prawn filtration is resorted in areas where tidal amplitude is high. Keeping the water level low in the field during high tide, water is let into the field by opening the shutters, which allows the prawn larvae into the fields along with the inflow. A hurricane lantern is hung at the sluice mouth to attract the prawn larvae. During low tide water is let out through a bamboo screen, which prevents escape of fish and prawn already entered into the field and brings down the water level, so that water can again be taken in during high tide. The actual fishing operation starts by the middle of January coinciding with the lunar phase. The prawn filtration net is also unique to the Pokkali farming methods. It is conical in shape having a total length of 4-5 feet with a trap system in the middle and a valve at the code end for easy collection of the catch. Luring in of prawns continues simultaneously along with fishing till the end of March, when the fields are finally drained for paddy cultivation. In Pokkali cultivation where no chemical fertilizers are added, tidal ingress plays an important role in maintaining the nutrient status of the soil. In addition a plethora of microorganisms flourish in the system which ultimately keep the soil very productive. But more significant is the annual transition from low saline to high saline phase such that the stenohaline fauna and flora dies out, decomposes and adds to soil fertility.

Integrated Farming Method

Pokkali integrated farming of rice and prawn is considered to be an essential part of farming systems in the low-lying lands. Rice-Prawn rotational culture in Pokkali fields is undertaken on a collective basis. With limited expenses under this system, a fish yield of 3 to 5 tons per hectare is attained on an average. Moreover, the rotational farming of rice and fish improves the soil conditions and thereby increases rice yields in the next season up to 15-20 per cent. Since rice farming in Pokkali fields is purely organic, the cost of chemical fertilizers would be zero. It is estimated that the traditional paddy farming yields a profit of only 25,000/- per ha. whereas paddy and prawn together (as in Pokkali) yield a profit of INR 50,000- per ha. This could be augmented to 1.3 Lakhs per ha in the newly introduced Paddy-shrimp-cage culture integrated system introduced by Central Marine Fisheries Research Institute (CMFRI). Subsequent to the success of this integrated farming, the Fish Farmers Development Agency (FFDA) under the State Government has initiated a subsidy scheme – Integrated fish farming in Pokkali fields. Prawns constitute about 80% of the catch and fishes (and occasionally crabs) about 20%. The Prawns species are Metapenaeus dobsoni, Metapenaeus monoceros, Penaeus indicus, Penaeus monodon etc. Fishes include Tilapia mossambicus, Etroplus suratensis, Etroplus maculatus, Mugil cephalus, Anabas testudineus etc

Current Scenario and challenges faced in Pokkali Rice Farming

Increasing impacts of climate change, such as rising sea levels, erratic rainfall, and heightened soil and water salinity, even the hardy Pokkali rice is struggling to adapt. Moreover, the area under Pokkali

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cultivation has been steadily declining, as many farmers are shifting entirely to aquaculture, which promises higher short-term profits but disrupts the traditional and ecologically balanced rice–fish rotational system.

The situation is further worsened by acute labor shortages, lack of mechanization suited for saline and waterlogged fields, and the diminishing interest of younger generations in continuing this labor-intensive practice. Despite the Pokkali system being organic and holding a Geographical Indication (GI) tag, farmers face poor market support, low economic returns, and limited access to certified seeds or agricultural subsidies. As a result, many fields remain fallow or are converted for intensive shrimp farming, which affects soil health and leads to biodiversity loss in these fragile ecosystems

Importance of Pokkali Rice in climate resilient Agriculture

To Escalate Rice production: Rice is the staple meal of Kerala, still, there is not enough Pokkali rice being produced to meet demand. In this current era where organic farming acquiring social, political, and scientific acceptance for its contribution to sustainable agriculture, promoting rice production for stress-prone areas in a purely organic system like Pokkali, is vital to attain an evergreen revolution in rice.

To Save avifauna habitat: The wetland ecosystem is an Important Bird Area (IBA that serves as a habitat for avifauna and a stopover area for migratory birds. They utilize wetland ecosystems for breeding,feeding, roosting, nesting, and rearing chicks. Water birds are salient indicators of ecological wellness, productivity, and contamination of wetlands. The depletion in Pokkali farming has induced the diminishing of avian fauna.

For wetland conservation: Kerala is well known for wetlands and one-fifth of the state's total landmass is wetlands. Thousands of people rely on wetlands for their livelihood, wellbeing and poverty mitigation. Wetlands can act like a sponge to hold water during flooding, storms, or whenever the water levels are high, which helps in maintaining normal river levels and filtration and purification of surface water. When the water levels are low, it releases water. Wetlands are the home for many plants, fishes, and wildlife. It also avails in the migration and reproduction of animals that live in other habitats. But urbanization, and development activities are demolishing wetlands and their vegetation. Industrial pollution and improper sewage management have resulted in a decrement in biota, fish mortality, and ammonia accretion in water.

Conclusion

Pokkali rice farming stands as a living example of how traditional agricultural wisdom can harmonize with nature to create a resilient and sustainable food system. Rooted in Kerala's coastal heritage, it offers not only a model for organic and climate-resilient cultivation but also preserves biodiversity and supports rural livelihoods. Yet, the system now faces an uncertain future due to environmental stress, economic pressures, and social neglect. Revitalizing Pokkali farming requires a collaborative approach empowering farmers with institutional support, ensuring fair market access, integrating appropriate technologies, and raising awareness of its ecological and nutritional value. With the right interventions, Pokkali can continue to thrive as a symbol of sustainability, resilience, and cultural pride in an era of growing climate uncertainty.

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Aquaculture: Navigating the Blue Frontier of Food Security

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"Aquaculture is not just about feeding the world today; it's about ensuring we can feed it tomorrow sustainably."

Dr. QU Dongyu,
(Director-General, FAO)

The cultivation of aquatic organisms has emerged as an essential foundation within the worldwide food production landscape. Fish farming and related aquatic cultivation practices now stand alongside traditional agriculture and livestock husbandry as one of the critical components supporting humanity's nutritional needs.

This vital sector has transcended its once-supplementary role to become an indispensable element in feeding the global population. As a fundamental pillar of modern food systems, aquaculture provides crucial protein sources, contributes to diverse diets, and offers sustainable nutrition pathways across developed and developing regions alike.

The strategic importance of aquaculture extends beyond mere production volumes—it represents a transformative approach to resource utilization, offering efficient protein conversion ratios and the ability to operate in environments unsuitable for conventional farming. Its essential position in global food security frameworks continues to strengthen as technological innovations enhance productivity while addressing sustainability challenges.

This practice involves the controlled cultivation of aquatic organisms, including fish, crustaceans, molluscs, and various aquatic plants in both freshwater and marine environments. As traditional capture fisheries reach their sustainable limits, aquaculture has emerged as a critical solution to meet the growing worldwide demand for protein and nutritional security.

The significance of aquaculture extends beyond mere food production—it supports livelihoods, contributes to economic development, and when managed responsibly, can operate in harmony with natural ecosystems. With innovations in sustainable practices, this sector continues to evolve as a vital component of our collective food future.

With wild fish stocks plateauing or declining due to overfishing, climate change, and habitat degradation, aquaculture has stepped in, to bridge the gap between rising demand and dwindling supply. As of 2025, it stands at a pivotal juncture—balancing unprecedented growth with the urgent need for sustainability. This article examines aquaculture's current landscape, where it's headed in the coming decades, and the groundbreaking approaches that may shape its contribution to global food security.

As fish farming continues its remarkable expansion, understanding its present conditions, developmental direction, and technological frontiers becomes increasingly vital for addressing nutritional needs worldwide.

The analysis delves into how aquaculture stands today—its achievements, challenges, and regional variations—while also forecasting its evolution as populations increase and demand for protein sources grows. Particular attention is given to emerging techniques and sustainable practices that

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could transform how we cultivate aquatic species to efficiently and responsibly feed billions more people.

By examining both current realities and future possibilities, we get an insight into aquaculture's pivotal role in creating resilient food systems capable of meeting humanity's nutritional requirements while preserving marine ecosystems for generations to come.

The Food and Agriculture Organization's (FAO) comprehensive State of World Fisheries and Aquaculture (SOFIA) 2024 assessment reveals that aquaculture production worldwide achieved an all-time high in 2022, reaching a remarkable total of 223.2 million tonnes. The aquaculture industry has achieved remarkable production levels, with total output reaching an impressive, combined figure. The FAO also stated that Farmed Aquatic animals constitute the primary component, contributing a substantial 185.4 million tonnes to the overall yield. Complementing this, Algae cultivation operations generate an additional 37.8 million tonnes, further enhancing the sector's productive capacity. Together, these two distinct branches of aquatic farming demonstrate the significant scale and economic importance that aquaculture has attained in global food production systems.

This historic milestone underscores the accelerating expansion of controlled aquatic farming practices across the globe. The significant volume of both animal and plant production demonstrates how the aquaculture sector has evolved from a supplementary food source to a dominant force in global seafood provision, reflecting the technological advancement, improved farming techniques, and increased investment throughout the industry.

The substantial algae cultivation component highlights the diversification within modern aquaculture beyond traditional fish and shellfish cultivation, pointing to the sector's increasing sophistication and its expanding role in both food production and industrial applications.

In a significant turning point for global food production, Aquaculture has now exceeded traditional fish catching, in the supply of aquatic animals. The practice of farming fish and other aquatic organisms in controlled environments has surpassed traditional fishing to become the predominant source of seafood protein consumed by people globally.

Aquaculture systems ranging from coastal net pens and inland recirculating tanks to traditional pond cultivation, produce more than 50 percent of all aquatic animals destined for human consumption. This transition parallels historical agricultural revolutions where humans moved from hunting to farming for their food supplies.

As ocean stocks face mounting pressures from overharvesting and environmental changes, The role of aquaculture represents a crucial adaptation in global food systems, helping to meet increasing protein demands while potentially relieving pressure on threatened wild populations.

This historic shift represents a fundamental change, from conventional fishing populations to actively cultivating aquatic species in controlled environments.

The emergence of aquaculture as the dominant source of seafood marks a transformation comparable to the agricultural revolution thousands of years ago when humans transitioned from hunting to farming for terrestrial food production. This development carries profound implications for food security, environmental sustainability, and economic opportunities in coastal communities around the globe.

As fishing sources face increasing pressure of overfishing and environmental changes, rise of aquaculture offers both solutions and challenges that will shape how we feed growing populations in the coming decades.

March 2025, projections suggest the figure has climbed to approximately 230 million tonnes,

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driven by a 4-5% annual growth rate. Asia dominates the sector, accounting for 70% of global production, with China leading at 36%, followed by India (8%), Indonesia (7%), and Vietnam (5%). Global per capita consumption of aquatic foods has risen to 20.7 kg in 2022, expected to reach 21.3 kg by 2032, reflecting growing dietary preferences and urbanization.

The economic value of aquaculture is equally staggering. The fisheries and aquaculture sector generated an estimated USD 472 billion in first-sale value during 2022, highlighting its substantial economic significance in the global marketplace. Industry projections suggest this figure will exceed USD 500 billion by 2025, driven by increasing consumer demand and expanding export markets. However, this growth is uneven—while countries like Norway and Chile excel in high-value species like salmon, many low-income nations in Africa and Asia lag, producing only 7% and struggling to tap their potential.

India has established itself as a global leader in the aquaculture sector, ranking second in the world after China in terms of aquaculture production. Additionally, our country is recognized as the third-largest fish producer worldwide contributing 8% to the fish production globally, reflecting the rapid growth and expansion of its fisheries and aquaculture industries.

This progress highlights India's significant contribution to global seafood supply, driven by supportive policies, technological advancements, and a strong network of coastal and inland fisheries (Ministry of Fisheries, Animal Husbandry & Dairying, 2025).

India's aquaculture sector has experienced remarkable growth, with inland fish production more than doubling over the past nine years, reaching 13.1 million tonnes.

In addition to its production capabilities, India is a major player in the global seafood export market. India's seafood export industry reached a major milestone in the fiscal year 2023–2024. (source: https://pib.gov.in/PressReleaseIframePage.aspx%3FPRID%3D2026456).

We exported a record 1.78 million metric tonnes of seafood, with a 2.67% increase in tonnage over the previous year 2022-2023, earning an impressive revenue of ₹60,523.89 crore.

This performance marks a significant milestone for India's seafood industry and demonstrates its increasing presence in the global export market, driven by high-quality production and expanding international demand (Ministry of Fisheries, Animal Husbandry & Dairying, 2025). This reflects a significant increase from ₹609.95 crore in 2003-04, highlighting the sector's expanding global reach. (blitzindiabusiness.com/Business)

Despite challenges in major export markets such as the United States, European Union, and the United Kingdom, the total export value reached ₹60,523.89 crore (approximately USD 7.38 billion). Frozen prawns accounted for 40.19% of export volume and 66.12% of total revenue in US dollars, solidifying their position as the leading export commodity in the aquaculture sector. *(Ministry of Fisheries, Animal Husbandry & Dairying, 2025)*

Largest Fish Producing States in India

India produced 17.45 million metric tonnes (MMT) of fish in 2022–2023. (source: https://www.seafoodsource.com/news/premium/supply-trade/india-aims-to-produce-20-million-metric-tons-of-fish-by-2023)

By March 2025, provisional estimates from the Ministry of Fisheries, Animal Husbandry, and Dairying suggest production has risen to 17.5 MMT, with aquaculture accounting for over 13 MMT.

Shrimp, particularly L. Vannamei, dominates India's aquaculture exports, which hit a record 1.73 MMT worth USD 8.09 billion in FY 2022-23—a 26.73% growth over the previous year. Andhra Pradesh leads

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the way by harnessing its vast coastline and abundant freshwater resources, with West Bengal, Odisha, and Tamil Nadu following closely behind.

Significance of fishery in both economic and social aspects is highlighted by the fact that it accounts for 1.24% of India's GVA and 7.28% of the agricultural GVA (Ministry of Fisheries, Animal Husbandry & Dairying, 2025).

With a per capita fish consumption of 9 kg—well below the global average—India's domestic demand is poised for growth, fuelled by rising health consciousness and affordability of fish as a protein source.

Government of India Schemes Supporting Aquaculture

India's government has recognized aquaculture's potential through ambitious schemes:

- **Pradhan Mantri Matsya Sampada Yojana (PMMSY)**: Launched in 2020, the Introduced in 2020, the PMMSY is a pivotal government initiative aimed at fostering sustainable and responsible development within India's fisheries sector. The PMMSY aims to attract investments totaling ₹20,050 crore (approximately USD 2.4 billion), with ambitious targets to boost fish production by an additional 7 million tonnes by 2024–2025. The scheme also envisions increasing fisheries export earnings to ₹1 lakh crore and creating approximately 5.5 million employment opportunities, both directly and indirectly. (https://www.nabard.org/auth/writereaddata/careernotices/0905220144export-credit.pdf)
- The scheme focuses on infrastructure development, modernization of fishing vessels, and strengthening the value chain to achieve these objectives (Prime Minister of India, 2020).
- **Fisheries and Aquaculture Infrastructure Development Fund (FIDF)**: With INR 7,522 crore (USD 900 million), FIDF supports the creation of modern facilities like harbours, landing centres, and processing units. Its extension in 2023 ensures continued momentum.
- **Pradhan Mantri Matsya Kisan Samridhi Sah-Yojana (PM-MKSSY)**: Announced in 2024 with INR 6,000 crore (USD 720 million), this sub scheme under PMMSY targets micro and small enterprises, offering insurance against crop losses and boosting export competitiveness.
- **National Fisheries Development Board (NFDB)** which has its main office in Hyderabad, is essential to the growth of the fishing industry. It provides financial and technical support to various state and union territory governments, promoting species diversification and the adoption of sustainable fishing practices. The National Fisheries Development Board (NFDB) has tailored its initiatives to support the objectives of the Pradhan Mantri Matsya Sampada Yojana (PMMSY), contributing significantly to the advancement and modernization of India's fisheries sector. (Drishti, 2024).

Other Initiatives

- **Infrastructure Development**: Establishing fishing harbours, cold storage chains, and processing units to reduce post-harvest losses and add value to fishery products.
- **Support for Fish Farmers**: Providing financial assistance for the construction of ponds, hatcheries, and adoption of modern aquaculture techniques.
- **Marketing and Export Promotion**: Developing marketing strategies and export

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infrastructure to boost the global competitiveness of Indian fishery products.

These initiatives underscore India's commitment to a "Blue Revolution," aligning with the Aatma Nirbhar Bharat vision of self-reliance.

The Food and Agriculture Organization (FAO) projects that global aquatic animal production will reach 205 million tonnes by 2032, highlighting the sector's significant growth potential. This represents a substantial 10% expansion compared to production levels recorded in 2022. The remarkable growth trajectory is primarily attributed to continued advancements and expansion in aquaculture operations worldwide.

Unlike traditional wild-capture fishing, which faces natural limitations and sustainability concerns, aquaculture continues to demonstrate considerable potential for sustainable growth. Fish farming and related aquatic cultivation methods are positioned to be the primary engines driving this projected increase in global seafood availability over the coming decade.

This forecast highlights the increasing importance of farmed aquatic species in meeting global protein demands and addressing food security challenges as the world population continues to grow. The shift toward cultivated seafood production represents a fundamental transformation in how humanity sources nutrition from water environments, with potentially far-reaching implications for both economic development and environmental management practices.

By 2050, as the global population nears 10 billion, demand for blue foods could double, requiring aquaculture to produce over 100 million tonnes annually. Innovations like offshore farming, integrated multi-trophic aquaculture (IMTA), and biofloc technology will be pivotal. However, sustainability remains a concern—climate change, disease outbreaks, and feed dependency could derail progress if unchecked.

Under PMMSY, India wants to produce 22 MMT of fish by 2025, with aquaculture accounting for more than 70% of that total.

According to a study by the IMARC Group, the Indian aquaculture industry is set for substantial growth, with production expected to rise from 14.4 million metric tons (MMT) in 2024 to 28.8 MMT by 2033. This expansion reflects a compound annual growth rate (CAGR) of 7.57%, driven by several key factors shaping market dynamics (IMARC Group, 2025).

The growing demand for seafood, attributed to its nutritional benefits and shifting dietary preferences, is a primary catalyst. Furthermore, production and sustainability are being enhanced by developments in aquaculture technology, such as better breeding methods and disease control.

Government initiatives, such as the Pradhan Mantri Matsya Sampada Yojana, are also playing a crucial role by providing financial support and infrastructure development to boost the sector's growth (IMARC Group, 2025).

As the industry evolves, the adoption of sustainable practices and technological innovations will be pivotal in meeting the increasing demand for aquaculture products while ensuring environmental sustainability.

The focus will shift toward high-value species like shrimp, carp, and tilapia, alongside untapped resources like reservoirs (3.15 million hectares) and brackish waters. By 2030, export revenue might surpass USD 12 billion, solidifying India's place as a world leader.

Transforming Adversity into Success

The inspiring journeys of four exceptional individuals—Sultan Singh, Yatindra Kashyap, Sukhpal Singh, and Aarti Burman—who have leveraged aquaculture to build prosperous ventures, uplift communities, and advance India’s food

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security framework illustrate the sector's potential to drive rural prosperity and food security.

Sultan Singh: A Pioneer in Haryana's Aquaculture Development

Sultan Singh, farmer from Haryana with his innovative methods and commitment have played a

crucial role in advancing the region's aquaculture sector. Being honored with the Padma Shri award, Singh's contributions to eco-friendly and integrated farming systems have been nationally recognized. He transformed unproductive land into flourishing fishponds, leveraging scientific techniques to cultivate species like carp and catfish. His integrated approach—blending fish farming with poultry and horticulture—optimizes resource use while significantly reducing environmental impact. By mentoring local farmers and sharing expertise, he has catalysed a regional shift toward aquaculture, bolstering food security and economic stability in rural Haryana.

Yatindra Kashyap: Bihar's Beacon of Entrepreneurial Success

In Bihar, Yatindra Kashyap has emerged as a symbol of entrepreneurial triumph in aquaculture. Starting with modest resources, Kashyap ventured into fish farming, focusing on high-yield species such as rohu and tilapia. His adoption of modern techniques, including pond aeration and feed optimization, has significantly boosted productivity. Kashyap's success has not only elevated his family's economic status but also inspired a ripple effect in his village, where numerous farmers have embraced aquaculture. His story underscores the potential of fish farming to transform rural economies, providing a scalable model for food security and poverty alleviation in India's hinterlands.

Sukhpal Singh: Redefining Punjab's Agricultural Narrative

Punjab, traditionally known for its wheat and paddy fields, is witnessing a quiet revolution through farmers like Sukhpal Singh, who transitioned from conventional farming to aquaculture, cultivating species suited to Punjab's agro-climatic conditions. His strategic shift has yielded impressive profits, demonstrating aquaculture's viability as a lucrative alternative to traditional farming. By adopting biofloc systems and sustainable water management, Singh has minimized environmental impact while maximizing output. His success highlights aquaculture's role in diversifying agricultural practices, enhancing food security, and ensuring economic resilience in the face of climate variability.

Aarti Burman: Empowering Communities in Bengal

In West Bengal, a state renowned for its pisciculture heritage, Aarti Burman stands out as a visionary woman entrepreneur. Her focus on species like pangasius and Indian major carps has not only generated substantial income but also created employment opportunities for local communities, particularly

women. Burman's inclusive approach fosters social and economic empowerment, demonstrating aquaculture's potential to drive equitable growth. Her enterprise serves as a beacon of sustainable development, contributing to food security while uplifting marginalized groups.

The stories of Sultan Singh, Yatindra Kashyap, Sukhpal Singh, and Aarti Burman illuminate the transformative power of aquaculture in India.

Best Practices from Around the World

1. **Norway's Salmon Farming**: Norway's use of automated feeding systems, real-time water quality monitoring, and offshore cages minimizes environmental impact while maximizing yield. India could adopt similar technologies in coastal states.
2. **Vietnam's Pangasius Model**: Vietnam's smallholder-driven pangasius industry thrives on low-cost, farm-made feeds and efficient supply chains Carp farmers in India could adopt this economical strategy.
3. **Chile's IMTA Systems**: Chile integrates salmon, mussels, and seaweed farming to recycle nutrients and reduce waste. India's coastal regions could pilot IMTA to enhance sustainability.
4. **Bangladesh's Community-Based Aquaculture**: Bangladesh empowers rural communities through cooperative farming, boosting inclusivity. Such approaches for small-scale fishermen could be incorporated into India's PM-MKSSY.
5. **Israel's Biofloc Technology**: Israel's closed-loop systems use microbial flocs to recycle waste into feed, reducing water use by 90%. This could revolutionize India's inland aquaculture.

Global Challenges

- **Environmental Impact**: Pollution from farm effluents and habitat loss threaten ecosystems.
- **Disease Outbreaks**: Pathogens like tilapia parvovirus (reported in India in 2023) cause significant losses.
- **Feed Dependency**: Reliance on fishmeal and terrestrial crops strains resources.
- **Climate Change**: Rising temperatures and extreme weather disrupt production cycles.

Indian Challenges

- **Inadequate Regulation**: Insufficient enforcement of water quality standards and stocking regulations poses significant risks to public health and environmental sustainability in aquaculture practices.
- **Environmental Concerns**: Issues such as water pollution, habitat degradation, and disease outbreaks can adversely affect aquaculture operations.
- **Financial Access**: Small farmers struggle to secure loans for modern equipment.
- **Technological Lag**: The insufficient implementation of innovative technological solutions presents a significant barrier to productivity enhancement in the sector, creating a technological deficit that impedes operational efficiency and competitive advancement (Kumar & Rodriguez, 2024)..
- **Market Access and Infrastructure**: Inadequate infrastructure for storage, processing, and transportation leads to post-harvest losses and limits market reach.
- **Market Volatility**: Fluctuating fish prices and export competition challenge profitability.

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Overcoming Challenges in India

1. **Stricter Regulation**: Enforce species-specific guidelines on stocking density and antimicrobial use, as suggested by the Madras High Court's 2024 ruling on illegal farms.
2. **Subsidized Technology**: Expand PMMSY to include grants for biofloc and cage culture systems.
3. **Disease Management**: Establish regional diagnostic labs and promote biosecurity training.
4. **Climate Adaptation**: Develop climate-smart systems like solar-powered aerators and resilient species.
5. **Market Stabilization**: Create regulated fish markets and promote value-added products like fish fillets.
6. **Public-Private Partnerships**: Collaborations between government agencies, private sector players, and local communities can lead to the development of necessary infrastructure and market linkages, ensuring the growth and sustainability of the aquaculture sector.
7. **Capacity Building and Training**: Providing training and extension services to farmers on best practices, biosecurity measures, and financial literacy can empower them to manage their operations more effectively.

Financial Institutions: Leveraging Aquaculture Opportunities

Aquaculture presents a lucrative avenue for banks and financial institutions to expand their portfolios:

- **Loan Products**: Offer microcredits and low-interest loans for small-scale farmers to adopt modern technologies. In 2023, NABARD disbursed INR 2,500 crore in fisheries loans—a figure that could double with targeted schemes.
- **Insurance Partnerships**: such collaborations with the companies under the Pradhan Mantri Matsya Sampada Yojana can offer accessible crop damage protection, thereby minimizing financial risks for lending institutions (Sharma & Patel, 2023).
- **Investment in Startups**: Fund Agritech ventures developing feed alternatives or IoT-based farm monitoring, tapping into India's startup ecosystem.
- **Export Financing**: Support exporters with trade credit to meet global demand, leveraging India's USD 8 billion market.

By 2030, the aquaculture financing market in India could exceed INR 50,000 crore (USD 6 billion), offering banks a high-return, low-risk opportunity aligned with sustainable development goals.

Way Forward: Innovative Ideas for Aquaculture

1. **Smart Aquaculture**: Deploy IoT sensors and AI-driven platforms like AQUA Sightline for real-time monitoring of water quality, feed efficiency, and fish health, cutting costs by up to 35%.
2. **Blockchain for Traceability**: Implementing blockchain technology can enhance transparency in the supply chain, ensuring the authenticity and quality of aquaculture products, which is crucial for international markets.
3. **Renewable Energy Integration**: Utilizing renewable energy sources, such as solar or wind power, for aquaculture operations can reduce costs and promote environmental sustainability.
4. **Alternative Feeds**: Invest in insect-based or algae-based feeds to reduce fishmeal dependency, as pioneered by companies like Protix in the Netherlands.

5. **Offshore Expansion**: Develop floating farms in India's 2.02 million sq.km Exclusive Economic Zone (EEZ), inspired by Norway's success.
6. **Circular Economy**: Integrate aquaculture with agriculture (e.g., rice-fish farming) to recycle nutrients and boost rural incomes.
7. **Youth Engagement**: Launch skill development programs under NFDB to train young entrepreneurs in Aquapreneurship, addressing unemployment.
8. **Carbon Credits**: Monetize sustainable practices through carbon markets, incentivizing eco-friendly farming.

Conclusion

Aquaculture is positioned at a critical juncture of innovation, with tremendous potential to address global nutritional security challenges while simultaneously serving as a catalyst for economic development (World Aquaculture Society, 2024). Aquaculture has evolved from a specialized sector into a major global food source, showcasing human innovation and adaptability. In India, the journey is equally compelling—a nation blessed with vast water resources and government support is steadily carving its niche as an aquaculture powerhouse. The latest data—230 million tonnes globally and 17.5 MMT in India—underscores this momentum, yet the path forward demands vigilance.

Despite promising prospects, the aquaculture sector faces substantial obstacles including environmental deterioration, pathogen outbreaks, and socioeconomic disparities that could significantly impede its sustainable advancement (Food and Agriculture Organization [FAO], 2022). Financial institutions stand at a pivotal crossroads where they can significantly contribute to the expansion of aquaculture while simultaneously achieving both financial returns and environmental objectives. By strategically investing in sustainable seafood production, these institutions can create what researchers have described as "mutually beneficial outcomes" that serve both profit motives and ecological imperatives (Jensen & Garcia, 2023).

This approach aligns with what Stevens (2024) characterizes as the "dual-benefit paradigm" in sustainable finance, where traditional financial metrics and sustainability goals are not competing priorities but complementary aspects of sound investment strategy.

Aquaculture's future hinges on balance—between scale and stewardship, technology and tradition, profit and planet. India has the potential to lead this charge, not just as a producer but as a model for inclusive, sustainable growth. By embracing innovation and collaboration, we can ensure that the blue frontier doesn't just feed us today but thrives for generations to come. The tide is rising—let's ride it wisely.

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Nano DAP: Low Cost and High Yield for Meeting Future Food Requirements

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The growing global population and increasing food demand necessitate advancements in agricultural practices and technologies. Di-ammonium Phosphate (DAP) is a widely used fertilizer critical for plant growth, yet traditional DAP faces challenges like nutrient leaching and low nutrient use efficiency. The advent of nanotechnology offers innovative solutions to these issues, with Nano Di-ammonium Phosphate (Nano DAP) emerging as a promising alternative. Nano DAP, consisting of nano-sized DAP particles, significantly enhances nutrient uptake efficiency due to its larger surface area and better interaction with plant roots and soil. This paper explores the importance of phosphorus and nitrogen in agriculture, the composition and benefits of Nano DAP, and its application techniques. Nano DAP shows potential in reducing environmental impact, increasing crop yields, and lowering costs for farmers. However, challenges such as production costs, regulatory hurdles, and safety concerns must be addressed. Future research directions include optimizing formulations, extensive field trials, and integration with precision agriculture technologies. Nano DAP represents a significant advancement in sustainable agriculture, offering a path to meet future food requirements while minimizing environmental impact.

Introduction

Agricultural productivity is the cornerstone of food security and economic stability globally. As the world population continues to grow, the demand for food is projected to increase significantly, necessitating advancements in agricultural practices and technologies. Fertilizers play a crucial role in enhancing crop yields and sustaining agricultural output. Among the various types of fertilizers, Di-ammonium Phosphate (DAP) is one of the most widely used phosphorus fertilizers, crucial for the growth and development of plants. Traditional DAP has been instrumental in providing essential nutrients, particularly phosphorus and nitrogen, to crops. However, the inefficiencies associated with conventional fertilizers, such as nutrient leaching, environmental pollution, and low nutrient use efficiency, have prompted the exploration of more advanced solutions.

In recent years, the advent of nanotechnology has revolutionized various sectors, including medicine, electronics, and environmental science. The agricultural sector is no exception. Nanotechnology offers the potential to address some of the most pressing challenges in agriculture, such as improving nutrient use efficiency, reducing environmental impact, and enhancing crop productivity. Nano-fertilizers, a product of this technological advancement, have garnered significant attention for their ability to deliver nutrients more effectively to plants compared to traditional fertilizers.

Nano Di-ammonium Phosphate (Nano DAP) is a nanotechnology-based fertilizer that consists of nano-sized particles of di-ammonium phosphate. These particles, typically ranging from 1 to 100 nano-meters, exhibit unique physical and chemical properties that differ significantly from their bulk counterparts. The nano-scale size of these particles results in a much larger surface area-to-volume ratio, which enhances their reactivity and interaction with plant roots and soil. This increased surface area leads to better solubility and availability of nutrients, thereby improving the efficiency of nutrient uptake by plants.

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Phosphorus is a vital nutrient for plants, playing a key role in several physiological and biochemical processes. It is a critical component of nucleic acids, ATP (adenosine triphosphate), and phospholipids, which are essential for energy transfer, genetic information transmission, and cellular structure, respectively. Phosphorus also contributes to root development, flowering, and seed production, making it indispensable for plant growth and development. Despite its importance, phosphorus is often a limiting nutrient in many agricultural soils, necessitating its supplementation through fertilizers like DAP.

While traditional DAP has been effective in supplying phosphorus and nitrogen to crops, it is not without its challenges. One of the primary issues is the low nutrient use efficiency, where a significant portion of the applied fertilizer is not utilized by plants and is lost through processes such as leaching, volatilization, and runoff. This inefficiency not only leads to economic losses for farmers but also contributes to environmental problems such as water pollution and eutrophication of water bodies. Additionally, the overuse of phosphorus fertilizers can lead to soil degradation and imbalance of soil nutrients, further complicating agricultural sustainability.

Nano DAP presents a promising solution to the limitations of traditional fertilizers. The nano-sized particles enhance the solubility and bioavailability of phosphorus, ensuring that a higher percentage of the applied fertilizer is absorbed by plants. This improved efficiency translates to reduced application rates, lower costs, and minimized environmental impact. Moreover, the controlled release properties of Nano DAP can provide a steady supply of nutrients over an extended period, reducing the need for frequent applications and further enhancing nutrient use efficiency.

Importance of Nitrogen and Phosphorus in Agriculture

1. **Nitrogen (N):**

- **Role in Plants:** Nitrogen is crucial for the synthesis of amino acids, proteins, and chlorophyll. It directly impacts the growth, leaf development, and yield of crops.
- **Deficiency Symptoms:** Yellowing of leaves, stunted growth, and poor yield.

2. **Phosphorus (P):**

- **Role in Plants:** Phosphorus is essential for energy transfer (ATP), photosynthesis, and the formation of nucleic acids. It supports root development and flowering.
- **Deficiency Symptoms:** Dark green foliage, purple tinge to leaves, and delayed maturity.

Conventional DAP: An Overview

Traditional DAP $(NH_4)_2HPO_4)$ is composed of nitrogen and phosphorus in a 1:1 ratio. It is popular due to its high nutrient content and ability to provide a quick release of nutrients. However, it has several drawbacks, including nutrient leaching, volatilization, and environmental pollution.

Advancements in Nanotechnology

Nanotechnology involves manipulating materials at the atomic or molecular level to create structures with novel properties. When applied to fertilizers, it aims to improve nutrient uptake, reduce losses, and minimize environmental impact.

Nano DAP: Composition and Production

Nano DAP consists of DAP particles reduced to nano-scale dimensions, typically ranging from 1 to 100 nano-meters. This nano-sizing process can be achieved through various methods such as:

- **Top-Down Approaches:** Mechanical milling, high-pressure homogenization.

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- **Bottom-Up Approaches:** Chemical precipitation, sol-gel processes.
- Nano DAP is a nano technology based agri input developed by the Indian farmer fertilizer cooperative limited limited (IFFCO).it will have 8% nitrogen and 16% phosphorus compared to 18% nitrogen and 46% phosphorus content in the conventional granular bag.

Benefits of Nano DAP

1. **Enhanced Nutrient Uptake:**"Nano DAP have high concentration so the amount of DAP is less production received high" Nano DAP particles have a larger surface area to volume ratio, increasing the contact area with plant roots and enhancing nutrient absorption.
2. **Reduced Environmental Impact:**Minimizes nutrient leaching and volatilization, reducing water and air pollution.
3. **Increased Efficiency:**Higher nutrient use efficiency (NUE) means that plants absorb more nutrients per unit of fertilizer applied, leading to better growth with less fertilizer.
4. **Targeted Delivery:**Controlled release mechanisms can be integrated into nano DAP formulations, ensuring a steady supply of nutrients over time.
5. **Environmental Benefit:**
   - Reduces the run-off of excess fertilizers into water bodies, mitigating eutrophication and water pollution.
   - Lowers greenhouse gas emissions associated with fertilizer production and application.
6. **Economic Benefit:**
   - Potential cost savings for farmers due to the reduced need for frequent fertilizer applications.
   - Improved crop yields and quality can lead to better market prices and profitability.

Application Techniques

1. **Foliar Application:**Nano DAP can be applied directly to plant leaves, facilitating rapid absorption and immediate effects.

   Spraying- dissolve nano DAP in water to create a foliar spray solution.Apply the solution to the leaves of the plant by sprayer
2. **Soil Application:**When mixed with soil, nano DAP particles can be more evenly distributed around the root zone.
3. **Seed Coating:**Seeds can be coated with nano DAP to ensure that emerging seedlings have immediate access to essential nutrients.

Challenges and Limitations

1. **Production Costs:**The synthesis and scaling up of nano DAP production can be expensive compared to conventional fertilizers.
2. **Regulatory Hurdles:**Regulatory frameworks for nano-materials in agriculture are still evolving, and approval processes can be lengthy and complex.
3. **Safety and Environmental Concerns:**The long-term impacts of nano-materials on soil health, microorganisms, and human health need comprehensive evaluation.

Future Prospects and Research Directions

1. **Optimizing Formulations:**On-going research aims to optimize nano DAP formulations to balance cost, effectiveness, and safety.
2. **Field Trials and Data Collection:**Extensive field trials are necessary to gather data on the performance of nano DAP across different crops, soil types, and climatic conditions.
3. **Integration with Other Technologies:**Combining nanoDAP with precision agriculture technologies can further

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enhance its benefits by ensuring precise application rates and timing.

Conclusion

Nano DAP represents a significant advancement in the field of agricultural fertilizers, offering potential benefits in terms of efficiency, environmental sustainability, and economic viability. While challenges remain, on-going research and development efforts are likely to address these issues, paving the way for broader adoption of nano DAP in modern agriculture. The transition to nano fertilizers could play a critical role in meeting the growing global demand for food while minimizing the environmental footprint of agricultural practices.

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Meta analysis for sesame (*Sesamum indicum* L.) growth via integrated nutrient management of cultivation

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Among the integrated nutrient management practices, application of N5 (75% RDF + FYM@ 5t ha^{-1} + Sulphur@ 40kg ha^{-1} + $ZnSO_4$@ 25kg ha^{-1} + Boron @ 1.5kg ha^{-1}) recorded maximum plant height (154.41 and 157.27cm), number of branches plant^{-1} (17.40 and 17.59) (Gajraj Yadav *et al.,* 2022). The crop growth was better with integrated application of 50% recommended dose of NPK through fertilizer (RDF), 50% N through vermicompost (VC) or FYM along with *Azospirillum* incresee the growth in sesame(Ghosh *et al.,* 2013). The treatments five integrated nutrient management system (N_1-RDF alone, N_2- RDF + FYM @5t ha$_{-1}$, N_3- RDF+FYM @ 5t ha^{-1} + sulphur@40kg ha^{-1}, N_4- RDF + FYM @ 5t ha^{-1} + sulphur @ 40kg ha^{-1} + ZnSo4 @ 25kg ha^{-1} and N5- RDF+FYM @ 5t ha^{-1} + sulphur @ 40kg ha^{-1} + ZnSo4@ 25kg ha^{-1} + B @ 1.5kg ha^{-1} here FYM majorly involved for higher growth. (Gajraj Yadav *et al*., 2022).

Introduction

Sesamum (*Sesamum indicum* L.) also known as Till or Gingelly belongs to the genus sesamum and family Pedaliaceae. Sesamum is one of the important oilseed crops in India. Most sesamum wild relatives are found in sub-Saharan Africa (Bedigian 2003), but these are also present in India in small numbers (Desai, 2004) . Sesamum is a pioneer among the domesticated oilseed crops being still cultivated throughout the world in about 70 countries, out of which 26 are located in Africa and 24 in Asia. It is grown worldwide over an area of 75 million hectares producing 60,000 t seeds (FAOSTAT, 2008). Myanmar, Sudan, China and India are the leading sesamum-producing countries in the world. In India, total Oilseeds production is (33.42mt). Integrated use of organic manures and mineral fertilizers helps in maintaining stability in crop production, besides improving soil physical conditions. Sulphur has long been recognized as one of the essential elements for plant growth, particularly for oilseed crops. Sulphur is a constituent of three amino acids commonly found in plants *viz*., cystine, cystenine, and methionine, which are essential components of proteins. Sowing of sesamum as an intercrop with pigeonpea may fulfill this requirement as the growth habit of sesamum is mostly suited for modification in the planting systems (Darshan *et al*. 2009). The demand for vegetable oil in India is increasing steeply owing to increase in population, improvement in standard of living, increasing industrial requirement besides the current global pressure on bio-fuels. Except for a brief period of satisfaction during 1986-90 wherein the country had witnessed near self sufficiency in vegetable oils, in spite of continuous increase in domestic oilseeds production, only of 50% the requirement of vegetable oil is met and nearly half is made through imports at a huge cost of 9.7 billion US dollars as incurred during 2011-12 (Hegde et al., 2012). Sesame (*Sesamum indicum* L.) is one of the important oilseed crops in Indian agriculture. Sesame seeds are rich source of food, nutrition, edible oil and bio-medicine. Its oil has excellent nutritional, medicinal, cosmetic and cooking qualities for which it is known as 'the queen of oils'. It is cultivated on a large area in the states of Maharashtra, Uttar Pradesh, Rajasthan, Orissa, Andhra Pradesh, Madhya Pradesh, Tamil Nadu, West Bengal, Gujarat, Karnataka, Kerala, Bihar, Assam and Punjab and to a limited extent, in Tripura and Himachal Pradesh (Ghosh *et al.,* 2013).

Discussion

This might be ascribed to differential growth habit of sesamum crop grow in a non-competitive environment. Fig 1.,Different fertility levels significantly influence the plant height was recorded under N5 (75% RDF + FYM@5t ha^{-1} + Sulphur@40kg ha^{-1} + ZnSO4@25kg ha^{-1} + Boron@1.5kg ha^{-1}) during both the years of experimentation. Maximum plant height (154.41cm in 2019-20 and 157.27cm in 2020-21) was recorded with N5 (75% RDF + FYM@5t ha^{-1} + Sulphur@40kg ha^{-1} + ZnSO4@25kg ha^{-1} + Boron@1.5kg ha^{-1}) which was significantly higher over N1 (RDF alone) and while, at par with N4 (75% RDF + FYM@5t ha^{-1} + Sulphur@40kg ha^{-1} + ZnSO4@25kg ha^{-1}) during both the years of experimentation. Minimum plant height was recorded in RDF alone (135.95cm in 2019-20 and 138.12cm in 2020- 21) respectively. The beneficial effect of organic manure (FYM) on plant height also is due to the increased supply of all essential nutrients in available form by FYM which is good organic manure applied in combination with the nutrient management system. Maximum number of branches $plant^{-1}$ (17.40 in 2019-20 and 17.59 in 2020-21) was found with the treatment N5 (75% RDF + FYM@5t ha^{-1} + Sulphur@40kg ha^{-1} + ZnSO4@25kg ha^{-1} + Boron@1.5kg ha^{-1}) which was significantly higher over N1 (RDF alone) and statically at par with N4 (75% RDF + FYM@5t ha^{-1} + Sulphur@40kg ha^{-1} + ZnSO4@25kg ha^{-1}) during both the years of experimentation. Minimum number of branches $plant^{-1}$ was recorded in RDF alone (9.28 in 2019-20 and 9.66 in 2020-21) respectively. Drymatter production $plant^{-1}$ was increased significantly under application of N5 (75% RDF + FYM@5t ha^{-1} + Sulphur@40kg ha^{-1} + ZnSO4@25kg ha^{-1} + Boron@1.5kg ha^{-1}) over N1 (RDF alone) during both the year study. Maximum dry matter production $plant^{-1}$ (12.47g and 12.61g) was found with N5 (75% RDF + FYM@5t ha^{-1} + Sulphur@40kg ha^{-1} + ZnSO4@25kg ha^{-1} + Boron@1.5kg ha^{-1}) followed by N4 (75% RDF + FYM@5t ha^{-1} + Sulphur@40kg ha^{-1} + ZnSO4@25kg ha^{-1}), N3 (75% RDF + FYM@5t ha^{-1} + Sulphur@40kg ha^{-1}), N2 (75% RDF + FYM@5t ha^{-1}) and N1 (RDF alone) during both the years of experimentation. Minimum dry matter production $plant^{-1}$ was recorded in RDF alone (12.47g plant-1 in 2019-20 and 12.61g plant-1 in 2020-21) respectively. The higher production of dry matter in plant might have improved the value of stover yield due to combination of inorganic and organic (FYM) fertilizers. It indicates the role of integrated nitrogen management for improving the seed and stover yield during the both year of experimentation. This suggested that plant responded to nitrogen application more in comparison to P and K application. The growth characters such as plant height, number of branches and number of leaves provided better opportunity for higher sunlight interception. Similar result found by the Ahirwar, *et al*. (2017), Salame *et al.* (2020), Haruna, I.M., (2011), Yadav *et al*. (2019) and Ghosh, *et al.* (2013).

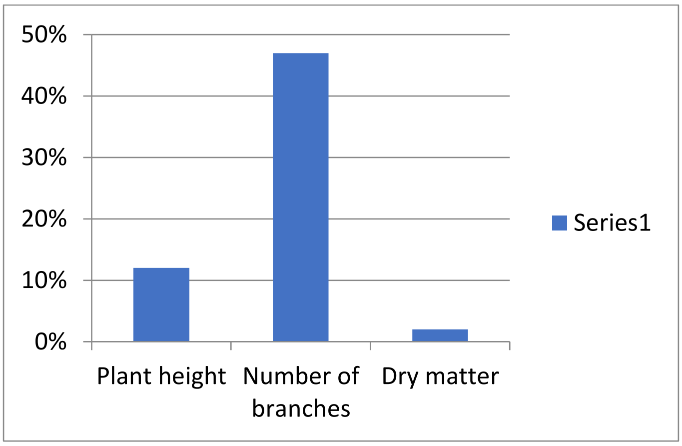

Fig 1.Increasing growth percentage through INM

Conclusion

Maximum plant height, number of branches $plant^{-1}$ and dry matter production $plant^{-1}$ was recorded with N5 (75% RDF + FYM@ 5t ha^{-1} + Sulphur@ 40kg ha^{-1} + ZnSO4@ 25kg ha^{-1} + Boron @ 1.5kg ha^{-1}) which was significantly higher over N1 (RDF alone) while, at par with N4(75% RDF

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+ FYM@ 5t ha^{-1} + Sulphur@ 40kg ha^{-1} + ZnSO4@ 25kg ha^{-1}) during the increasing growth percentage through integrated nutrient management plant height 12 %, Number of branches 45%, Dry matter production 2% increased in both the years of experimentation.

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Sustainable Aquaculture Farming Practice

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Innovative technology, environmentally conscious design, and business acumen are all combined in sustainable aquaculture to supply the world's expanding seafood demand while preserving the environment. By converting waste into useful microbial protein, methods like zero-waste and bio floc systems improve animal health and water quality. Insect larvae, microalgae, and plant-based components are examples of alternative feeds that improve nutrition and lessen dependency on wild fish stocks. By improving water filtration, enriching biodiversity, and sequestering carbon, including mangroves into pond designs unleashes climate advantages. Recycling nutrients and reusing byproducts are two circular economy strategies that increase productivity and reduce environmental impact. Disease control, fair access to education and funding, consistent certification, and careful ecological management are still obstacles, though. To develop sustainable aquaculture as a robust, inclusive route to global food security, these obstacles must be removed.

Introduction

variety of tactics are included in sustainable aquaculture farming operations, which aim to increase output while reducing the harmful effects on the environment and resources. By zero waste and Bio floc technology, sustainable and alternative feed and Restoring Nature further improve sustainability. Depressing energy use and preserving ideal water quality without resorting to chemicals (Kassem et., al 2021). Bivalve and seaweed farming are examples of non-fed aquaculture that contributes to water quality and biodiversity by contribution ecosystem services including nutrient removal and habitat provision. In order to meet global food demands while protecting environmental health, sustainable aquaculture requires a combination of technical innovation, ecosystem-based management, and supportive policies. Circular economy principles, such as nutrient recycling and zero-waste systems that integrate aquaculture with horticulture, help turn by-products into valuable resources, increasing overall efficiency and reducing environmental footprints. However, there are still issues, such as the need for better management practices, disease control, smallholders' access to training and financing, and the creation of comprehensive certification systems to ensure prevalent adoption of sustainable methods.

Waste not – Zero Waste and Bio floc Technology

A cutting-edge method in aquaculture, Bio floc technology (BFT) confrontations the problems of resource scarcity, waste management, and environmental sustainability. Obsolete aquaculture systems frequently produce large amounts of waste, such as uneaten feed, and toxic metabolites, which can degrade water quality and negatively impact the ecosystem. By allowing zero or very little water exchange, Bio floc technology provides a remedy by stopping the release of nutrient-rich wastewater into natural water bodies. This is accomplished by adding carbohydrates, which promote the growth of heterotrophic bacteria, and incessantly aerating the solution to maintain high levels of microbial floc in suspension. By breaking down organic matter and turning nitrogenous waste into microbial protein that fish and shrimp may eat, these bacteria resourcefully recycle nutrients within the system and lessen the requirement for outside feed inputs. Zero waste goals

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are strongly aligned with the fundamental idea of Bio floc technology. Bio floc technology improves aquaculture operations' sustainability and diminishes environmental pollution by turning waste materials into useful resources. The microbial communities in bio floc serve as natural probiotics and immunostimulants, improving the health, growth, and disease resistance of cultured aquatic animals in addition to improving water quality by eliminating harmful nitrogen compounds. Furthermore, by constraining the entrance of external pathogens and lowering the likelihood of disease outbreaks, its encourages the value-adding of solid residues in addition to recycling garbage(Chandan *et al.*,2023) In order to further close the waste loop and add economic value to what would otherwise be a disposal burden, recent studies have investigated the extraction of valuable substances, like as polyphenols, from bio floc sludge for application in green nanotechnology. This strategy shows the adaptability and potential of bio floc residues in wider biotechnological applications by lecturing the sustainability gap related to solid waste in bio floc technology and creating new opportunities for the synthesis of antibacterial and antibiofilm agents.

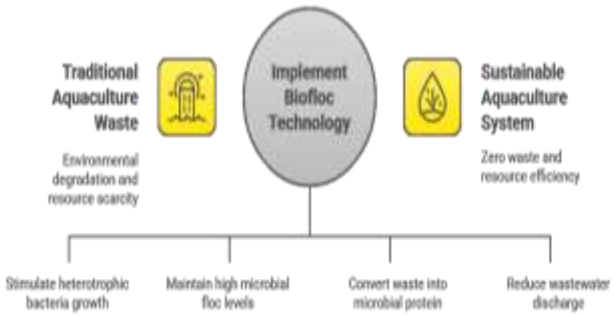

Figure No.1: Implement Biofloc Technology (Chandan *et al.*,2023)

Feed the Future: Sustainable and Alternative Feeds

As the demand for seafood increases globally, exertions are being made to ensure the long-term viability of aquaculture, with a focus on sustainable and alternative feeding. Fishmeal and fish oil, which come from wild fish stocks and pose serious sustainability issues because of overfishing, growing costs, and environmental effects, are major components of traditional aquafeeds. Researchers and industry participants are investigating a variety of novel feed additives in order to address these problems. Because of their high protein content, effective nutrient utilization, and capacity to be produced on organic waste, insect-based feeds like those made from black soldier fly larvae are becoming more and more popular. These feeds can augment fish growth, immunity, and meat quality, but there are still issues with digestibility, especially because of the chitin content, and the need for regionally consistent regulations. Interestingly, chitin and its derivatives may also function as immunomodulators and prebiotics, which would further improve fish health (Fantatto *et a*l., 2024).

Another intriguing option is microalgae, which require little land and water and provide vital amino acids, vitamins, healthy fats, and pigments. Their addition to aquafeeds can boost immunological function, increase pigmentation, and improve the nutritional profile of farmed fish. High production costs and certain digestibility issues, however, are currently preventing wider adoption, while developments in cultivation and processing technology are assisting in removing these obstacles. As sustainable and affordable substitutes, plant-based components and animal byproducts including those made from food industry waste—are also being explored. These components can lessen dependence on terrestrial crops and wild fisheries, but they must be handled sensibly to guarantee food safety and nutrient bioavailability.

Restoring Nature: Mangrove and Habitat Integration

A sustainable strategy to strike a equilibrium between environmental preservation and food production is the restoration of mangroves and their addition into aquaculture systems. When compared to traditional aquaculture ponds, integrated mangrove-aquaculture systems where mangroves are conserved or returned alongside aquaculture ponds have been demonstrated to intensely lower greenhouse gas emissions like nitrous oxide and methane, supporting efforts to alleviate climate change. Restoring mangroves in regions that were formerly used for aquaculture can retain significant amounts of carbon, which helps nations achieve climate targets. These systems also give significant advantages in terms of blue carbon. Furthermore, by filtering nutrients and organic matter, mangrove integration enhances water quality, additional treatment would still be required to get ideal conditions for aquaculture. From an biological perspective, integrated systems support higher biodiversity and ecosystem functions than unvegetated ponds, though they may not fully match the effort and services of intact mangrove forests. Restoration also enhances soil nutrient cycling and microbial assortment, which are crucial for ecosystem pliability and productivity. However, the success of these systems depends on careful design, such as maintaining a high mangrove-to-pond ratio and restoring natural hydrology, as well as ongoing management to address challenges like acid sulfate soils and heavy metal accumulation. Social and economic factors are also important, as the integration of mangroves and aquaculture can sustenance local livelihoods, but must address farmers' concerns about productivity and technical challenges, such as selecting suitable mangrove species and maintaining stable pond conditions. Community engagement and supportive policies are essential for long-term success, ensuring that renovation efforts do not lead to further conversion of intact mangroves and that both conservation and livelihood goals are met. Inclusive, integrating mangrove restoration with aquaculture presents a promising pathway for sustainable coastal management, offering climate, ecological, and socio-economic benefits when implemented thoughtfully.

Importance of sustainable aquaculture farming practices

It is becoming more widely acknowledged that sustainable aquaculture production is essential to supplying the growing demand for protein worldwide while reducing negative environmental effects and sanctioning food security. Sustainable aquaculture lowers its carbon footprint, conserves freshwater and land resources, and lowers greenhouse gas emissions by implementing novel farming techniques, better feed management, and increased production efficiency. These expansions guarantee aquaculture's continued sustainability as a dependable food supply while also assisting in the preservation of ecosystems. Additionally, by boosting local economies and generating jobs, sustainable aquaculture promotes social and economic progression. There are still issues, though, like the requirement for efficient management plans to deal with pollution, habitat destruction, and overuse of resources.

Conclusion

Aquaculture is redefining itself by implementing strategies like bio floc technology and zero-waste systems, which transform the production of fish and shrimp into effective, self-recycling systems. These systems improve water quality and animal health by converting waste into microbial protein in addition to limiting the release of hazardous wastewater. This breakthrough represents a substantial parting from the traditional, resource-intensive approach. The drive for alternative feeds is equally momentous. By reducing reliance on wild-caught fishmeal, insect-based diets, microalgae, and plant-derived proteins preserve nutritional requirements while alleviating the strain on marine ecosystems. Mangrove preservation or restoration contributes to carbon sequestration, wastewater filtration, and wildlife habitat. They meaningfully increase climatic resilience and promote greater biodiversity than traditional ponds, demonstrating how aquaculture may coexist peacefully with nature rather than

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conflict with it. This strategy endorses healthy ecosystems, creates economic opportunities, and increases food security in ways that go beyond simple productivity gains.

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Green technologies for extraction of essential oils

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Introduction

Green technologies for the extraction of essential oils represent a sustainable and eco-friendly alternative to conventional extraction methods, aiming to minimize environmental impact while enhancing efficiency and product quality. These technologies focus on reducing the use of toxic solvents, lowering energy consumption and preserving the natural integrity of bioactive compounds. Modern green extraction techniques include supercritical carbon dioxide (CO_2) extraction, microwave-assisted extraction, ultrasound-assisted extraction and enzyme-assisted extraction. Supercritical CO_2 extraction, for example, uses carbon dioxide as a safe, non-toxic solvent, producing high-purity oils without residual chemicals. Similarly, microwave and ultrasound methods enhance the release of essential oils by disrupting plant cell walls, significantly reducing extraction time and solvent use. Enzyme-assisted extraction employs natural biocatalysts to break down plant tissues gently, further improving yield and selectivity. Overall, these green technologies align with the principles of sustainable development and green chemistry, offering efficient, safe, and environmentally responsible methods for obtaining high-quality essential oils.

Advantages over traditional methods

Green technologies for the extraction of essential oils offer numerous advantages over traditional methods such as steam distillation and solvent extraction. These modern techniques are more environmentally friendly, as they use non-toxic or natural solvents like supercritical carbon dioxide and consume less energy and water, thereby reducing pollution and waste generation. They also operate under milder conditions, preventing the thermal degradation of sensitive bioactive compounds and preserving the natural aroma, color and therapeutic properties of the oils. Additionally, green extraction methods such as microwave-assisted, ultrasound-assisted and enzyme-assisted extraction significantly reduce processing time and enhance extraction efficiency, leading to higher yields and better quality oils. Unlike conventional solvent extraction, which often leaves harmful residues, green methods produce pure, solvent-free essential oils that are safer for use in food, cosmetics and pharmaceuticals. Overall, these technologies align with the principles of green chemistry and sustainable development by promoting cleaner, faster and more efficient extraction processes that ensure both product excellence and environmental protection.

Different methods of extraction

1. **Supercritical Carbon Dioxide (CO_2) Extraction Method**

Supercritical Carbon Dioxide (CO_2) extraction is an advanced green technology used to obtain high-quality essential oils and other bioactive compounds from plant materials. In this method, carbon dioxide is used as a solvent under supercritical conditions above its critical temperature (31°C) and critical pressure (74 bar) where it exhibits both gas-like and liquid-like properties. This allows CO_2 to diffuse easily through plant material like a gas while dissolving compounds like a liquid. The process involves compressing and heating CO_2 until it reaches the supercritical state, which is then passed through an extraction vessel containing the plant material. The supercritical CO_2 dissolves the essential oils and when the pressure is released, CO_2 returns to its gaseous state, leaving behind pure, solvent-free oil. This method is considered

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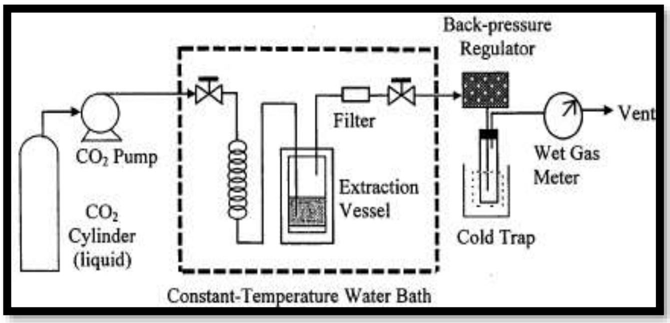
environmentally friendly because CO_2 is non-toxic, non-flammable and can be recycled within a closed-loop system. Additionally, extraction occurs at relatively low temperatures, preventing the degradation of heat-sensitive components and preserving the natural aroma and therapeutic properties of the oils. Supercritical CO_2 extraction offers excellent selectivity, high purity and efficiency, making it ideal for producing premium-quality essential oils used in pharmaceuticals, cosmetics and food industries.

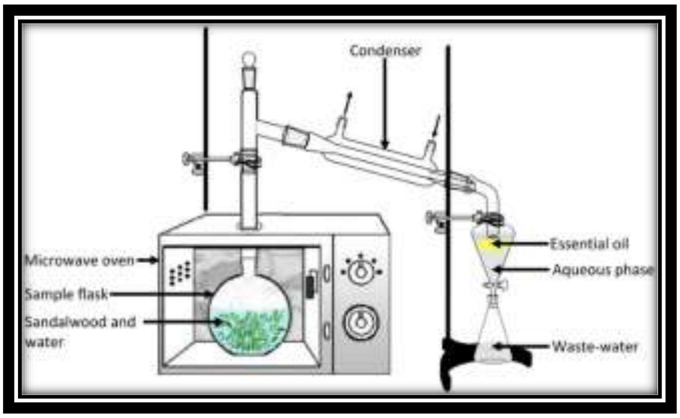


2. Microwave Assisted Extraction (MAE) of Essential Oils

Microwave-Assisted Extraction (MAE) is a modern, green technique used to extract essential oils and other bioactive compounds from plant materials by using microwave energy to rapidly heat the plant-solvent system. In this method, microwaves (typically around 2.45 GHz) are applied to a mixture of plant material and a small amount of solvent or sometimes even just the plant's own moisture. The rapid internal heating causes localized pressure and enhances the rupture of plant cell walls, which in turn facilitates the release of volatile compounds and oils.

In this practice, the process goes roughly as follows: the plant material is dried or partially dried, often ground to increase surface area and placed in a microwave-reactor flask. A solvent (which might be water, ethanol or no additional solvent in case of solvent-free MAE) is added. The microwave irradiation causes dielectric heating of the solvent and/or plant moisture as pressure builds inside the cells, the essential oil glands break open and release their contents. A condenser is often used to collect the volatile oils which may be carried over by steam or vapor and then condensed.

MAE offers several noted advantages such as it significantly reduces extraction time (for example, extraction times of 10-40 minutes versus several hours under conventional hydrodistillation) and also lowers the energy consumption. For instance, when used for extracting oil from *Lavandula angustifolia* (lavender), MAE achieved a yield of about 3.19 % in 40 minutes under optimized conditions (500 W, 17 mL/g liquid-to-solid ratio), compared to about 120 minutes required for conventional hydrodistillation.



3. Ultrasound-Assisted Extraction (UAE)

Ultrasound-Assisted Extraction (UAE) is an advanced and eco-friendly technique used to extract bioactive compounds, essential oils and phytochemicals from plant, microbial or animal materials. The method relies on high-frequency sound waves (typically 20–100 kHz) to induce acoustic cavitation in the extraction solvent. Cavitation involves the formation, growth and violent collapse of microscopic bubbles, which generates localized high temperatures and pressures. This process disrupts plant cell walls, increases solvent penetration and accelerates mass transfer, allowing compounds to be released more efficiently into the solvent.

UAE offers several advantages over conventional extraction methods, including shorter extraction times, higher yields, lower solvent consumption and

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preservation of heat-sensitive compounds. It is widely applied in the food, pharmaceutical and cosmetic industries for extracting essential oils, antioxidants, pigments and other valuable phytochemicals. The efficiency of UAE depends on several factors, such as ultrasound power, frequency, extraction time, solvent type, temperature and solid-to-solvent ratio. UAE can also be combined with other techniques like enzyme-assisted extraction or microwave-assisted extraction to further enhance extraction performance, making it a versatile, sustainable and efficient extraction method.

4. **Enzyme-Assisted Extraction (EAE) of Essential Oils**

It is a green and efficient method that uses specific enzymes to break down the structural components of plant cell walls, such as cellulose, hemicellulose and pectin, to facilitate the release of essential oils. Traditional extraction methods like steam distillation may not efficiently release oils trapped in plant tissues, whereas EAE enhances yield without requiring high temperatures or toxic solvents.

In EAE, cell wall-degrading enzymes such as cellulases, pectinases and hemicellulases are added to the plant material, often in an aqueous medium. These enzymes hydrolyze the polysaccharide matrix of the cell wall, increasing cell wall permeability and allowing the essential oil to diffuse more easily into the solvent. This method is particularly useful for delicate or heat-sensitive essential oils, as it operates under mild temperature and pH conditions, minimizing thermal degradation and preserving aromatic and bioactive compounds.

5. **Pressurized Liquid Extraction (PLE)**

Pressurized Liquid Extraction (PLE) is also known as Accelerated Solvent Extraction (ASE), is an advanced sample preparation technique used to extract compounds from solid or semi-solid matrices using liquid solvents at elevated temperatures and pressures. By maintaining the solvent in a liquid state above its normal boiling point through high pressure, PLE significantly increases the solubility and diffusion rates of target analytes, allowing for faster and more efficient extraction compared to traditional methods like Soxhlet extraction. The process involves placing the prepared sample in a sealed extraction cell, introducing a suitable solvent and heating the system under controlled pressure, after which the extract is collected for further analysis. PLE offers numerous advantages, including reduced solvent consumption, shorter extraction times, automation capability and high reproducibility, making it particularly useful in environmental, food, pharmaceutical and natural product analyses. However, it requires specialized equipment and may not be suitable for thermally sensitive compounds. Overall, PLE is a versatile and efficient method that has become a standard technique in modern analytical laboratories.

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The Anatomy and Botany of Water Chestnut

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Water chestnut (Trapa natans) is an aquatic plant that thrives in freshwater environments. Its unique anatomy and botany make it a fascinating subject for study.

Botanical Classification

Water chestnut belongs to the family Trapaceae (or Lythraceae) for *Trapa natans*, and Cyperaceae for *Eleocharis dulcis*. Its botanical classification is:

- **Kingdom:** Plantae
- **Division:** Magnoliophyta
- **Class:** Magnoliopsida (for *Trapa natans*) or Liliopsida (for *Eleocharis dulcis*)
- **Order:** Myrtales (for *Trapa natans*) or Poales (for *Eleocharis dulcis*)
- **Family:** Trapaceae (or Lythraceae) for *Trapa natans*, and Cyperaceae for *Eleocharis dulcis*
- **Genus:** *Trapa* (for water caltrop) or *Eleocharis* (for Chinese water chestnut)
- **Species:** *Trapa natans* or *Eleocharis dulcis*

Floral Characteristics

- **Flower lower lip length:** 0 mm
- **Flower number:** 1
- **Flower position:** The flowers are above the surface of the water
- **Flower symmetry:** There are two or more ways to evenly divide the flower (the flower is radially symmetrical)

Inflorescence type:

• The flowers grow out of the axil (point where a branch or leaf is attached to the main stem)
• The inflorescence has only one flower on it

- **Nectar spur:** The flower has no nectar spurs
- **Number of carpels:** 2
- **Ovary position:** The sepals and/or petals are attached above the ovary
- **Palate on corolla:** NA
- **Petal and sepal arrangement:** The flower includes two cycles of petal- or sepal-like structures
- **Petal appearance:** The petals are thin and delicate, and pigmented (colored other than green or brown)
- **Petal color:** White
- **Petal fringed edges:** The petals are not fringed
- **Petal hairs on inner/upper surface:** There are no hairs on the inner/upper petal surface
- **Petal length:** 7–10 mm
- **Petal number:** 4
- **Petal or sepal number:** There are four petals, sepals, or tepals in the flower
- **Sepal appearance:** The sepals resemble leaves in color and texture
- **Sepal number:** 4

Sepals fused only to sepals:

• The sepals are fused to each other (not other flower parts), at least near their bases
• The sepals are separate from one another

- **Spur length:** 0 mm
- **Stamen number:** 4

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- **Stamen position relative to petals:** The stamens are lined up with the sepals
- **Stamens fused to petals:** The stamens are fused near the bases of the petals or tepals
- **Style number:** 1
- **Fruit length:** 18–30 mm
- **Fruit type (general):** The fruit is dry but does not split open when ripe
- **Fruit type (specific):** The fruit is a nut (dry and indehiscent, with a hard wall, usually containing only one seed and usually subtended by an involucre)
- **Fruit width:** 20–45 mm
- **Sap:** The sap is clear and watery
- **Lifespan:** The plant lives only a single year or less
- **Root septa:** The roots do not have transverse septa
- **Underground organs:** There are only slender roots on the plant

Leaf position:

• Some of the leaves are floating at the surface of the water
• The leaves are all submerged underwater

Leaf arrangement:

• Alternate: there is one leaf per node along the stem
• Opposite: there are two leaves per node along the stem

- **Leaf blade length:** 40–60 mm
- **Petal or sepal number:** There are four petals, sepals, or tepals in the flower
- **Petal color:** White
- **Specific leaf type:** The leaf is not divided; rather, the blade is made up of one segment
- **Floating leaf shape:** The leaf blade is triangular, with the stalk or attachment point on one of the sides
- **Underwater leaf blade width:** 40–80 mm
- **Fruit type (general):** The fruit is dry but does not split open when ripe
- **Underwater leaf length:** 40–60 mm

Anatomy

The water chestnut plant consists of:

- **Corms:** Small, round, and edible; corms are covered with a papery brown skin and have crisp white flesh.
- **Stems:** Hollow, air-filled, and up to 12–16 feet long; stems have fine roots that anchor the plant to the soil.
- **Leaves:** Two types of leaves exist:
    - *Submerged leaves:* Feather-like and oppositely paired along the stem.
    - *Floating leaves:* Triangular with saw-toothed edges, forming a rosette around a central point.
- **Flowers:** Tiny, white, and four-petaled; flowers bloom in June or July.
- **Fruits and seeds:** Fruits have sharp spines with barbs and contain seeds that can remain viable for up to 12 years.

Morphological Adaptations

Water chestnut has adaptations that enable it to thrive in aquatic environments, including:

- **Aerenchyma:** A type of tissue that provides buoyancy and allows for gas exchange.
- **Waxy coatings:** Leaves and stems have waxy coatings that prevent water loss and reduce transpiration.

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Ecological Significance

Water chestnut plays a crucial role in aquatic ecosystems, providing food and habitat for various animals. However, it can also be an invasive species, altering ecosystem dynamics.

Cultivation and Uses

Water chestnut is cultivated for its edible corms, which are used in various cuisines. It is also used in traditional medicine and has potential applications in phytoremediation.

Conclusion

The anatomy and botany of water chestnut reveal its unique adaptations to aquatic environments. Understanding its structure and function can provide insights into its ecological significance, cultivation, and potential uses. By appreciating the intricate details of this plant, we can better utilize and manage it in various contexts.

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Role of Agri-Startups in Reshaping India's Rural Economy

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Introduction

India's agricultural sector, the backbone of the national economy, is undergoing a transformative shift driven by technology, innovation and entrepreneurship. The rise of agri-startups has become one of the most significant developments in recent years, helping to modernize traditional agricultural practices, increase farmer income and enhance rural livelihoods. Agri-startups are bridging the gap between farmers and technology by addressing inefficiencies in the supply chain, credit access, marketing and production systems. Their emergence signifies a new era of rural transformation where innovation meets grassroots needs.

EVOLUTION OF AGRI-STARTUPS IN INDIA

The concept of agri-startups began to gain momentum in India after 2015, coinciding with the rapid expansion of digital technology, rural internet penetration and government initiatives like Startup India and Digital India. Initially, these startups focused on connecting farmers with buyers, but over time, their scope has expanded to include farm mechanization, precision agriculture, agri-finance, agri-insurance and sustainability-driven models. The number of registered agri-startups in India has grown from fewer than 100 in 2014 to over 5,000 by 2024, according to the Ministry of Agriculture. This evolution highlights a shift from subsistence agriculture toward a market-oriented, tech-enabled ecosystem.

Major Segments of Agri-Startups

Agri-startups in India operate across multiple domains, contributing to the modernization of every stage of the agricultural value chain.

Input Supply and Advisory: Startups like AgroStar, DeHaat and Gramophone provide farmers with high-quality seeds, fertilizers, pesticides and expert agronomic advice through mobile applications.

Precision Agriculture: Firms such as Fasal and CropIn use IoT, satellite data and AI to offer farm monitoring, weather forecasting and pest prediction services.

Market Linkages: Ninjacart and EM3 Agri Services have revolutionized how farmers sell their produce, ensuring better prices and reducing dependence on middlemen.

Agri-Fintech: Companies like Jai Kisan and Samunnati are improving farmers' access to loans, insurance and financial literacy.

Post-Harvest Management: Startups such as Stellapps and WayCool focus on storage, logistics and cold-chain systems to reduce post-harvest losses.

Sustainability and Waste Utilization: Firms like S4S Technologies and Carbon Masters work on solar drying, carbon recycling and biofuel production, promoting circular agriculture.

Economic Contribution of Agri-Startups

Agri-startups have created measurable impacts on the rural economy by enhancing productivity, efficiency and income levels. Their economic contribution can be analyzed under several dimensions.

Enhancing Farmers' Income: By connecting farmers directly with markets and buyers, startups

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eliminate middlemen and ensure fair price realization. For example, Ninjacart's direct farmer-to-retailer model has increased farmers' earnings by 15–25%.

Employment Generation: Agri-startups have created thousands of direct and indirect jobs, particularly for youth in rural areas, reducing migration to cities.

Boosting Agri-Exports: With improved traceability and quality control, agri-tech innovations have enhanced India's export competitiveness in commodities such as spices, fruits and vegetables.

Promoting Rural Entrepreneurship: Startups are nurturing local entrepreneurs through franchise-based models and rural service centers, empowering small businesses in villages.

Strengthening Supply Chain Efficiency: By leveraging AI, blockchain and data analytics, agri-startups reduce wastage, enhance logistics and ensure timely delivery of farm produce.

Government Initiatives and Policy Support

The Indian government has recognized the potential of agri-startups and introduced several policies to promote their growth. The Startup India initiative provides funding support, tax exemptions and mentorship opportunities. NABARD, through its Agri-Business Incubation Centres (ABICs), supports innovative agripreneurs with seed funding and incubation facilities. Schemes like RKVY-RAFTAAR (Remunerative Approaches for Agriculture and Allied Sector Rejuvenation) encourage youth-led agribusinesses. The Ministry of Agriculture's Innovation and Agri-Entrepreneurship Programme has also established over 25 agri-incubation centers across India to foster innovation.

Case Studies of Successful Agri-Startups

DeHaat: Founded in Bihar, DeHaat offers end-to-end agricultural services including input supply, advisory, credit and market linkage to over 1.5 million farmers across India. Its platform combines AI-based crop advisory with last-mile delivery, drastically reducing input costs and improving profitability.

Ninjacart: A Bengaluru-based startup, Ninjacart connects farmers directly to retailers and restaurants, cutting out intermediaries. It has successfully reduced food wastage by nearly 20% and enhanced farmgate prices for perishable goods.

Stellapps: Operating in the dairy sector, Stellapps digitizes the milk supply chain by monitoring production, procurement and quality. It has benefited thousands of small dairy farmers with transparent pricing and digital payments.

Role in Sustainable Agriculture

Sustainability has become a central theme in the agri-startup ecosystem. Startups are promoting climate-smart practices, renewable energy use and resource-efficient technologies.

Water Management: Companies like Fasal optimize irrigation through AI-based monitoring, reducing water use by up to 30%.

Organic Farming Support: Agri-startups facilitate organic input supply and certification, making sustainable produce more accessible to markets.

Carbon and Waste Recycling: Firms such as Carbon Masters convert agricultural waste into biofuels, contributing to carbon neutrality and circular agriculture.

Challenges Faced By Agri-Startups

Despite their potential, agri-startups encounter several barriers:

Limited Rural Infrastructure: Poor internet connectivity, transport and cold-chain infrastructure restrict scaling in remote regions.

Financial Constraints: Many startups face challenges in securing long-term funding, especially during early stages.

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Farmer Awareness and Adoption: Traditional practices and lack of trust in digital platforms slow down technology adoption.

Policy and Regulatory Hurdles: Unclear data-sharing norms and slow policy execution often discourage innovation.

Climate and Market Risks: Dependence on monsoon and fluctuating commodity prices can impact startup sustainability.

Future Prospects and Strategic Recommendations

To realize the full potential of agri-startups, the following strategic measures are essential:

Integration with Research Institutions: Collaboration with agricultural universities and ICAR institutes can accelerate innovation and field validation.

Strengthening Rural Infrastructure: Investments in digital connectivity, cold chains and logistics will enhance startup scalability.

Policy Reforms: Simplified regulations for agritech operations and agri-data usage can foster confidence among investors.

Encouraging Youth Participation: Promoting entrepreneurship programs in rural colleges can nurture a new generation of agripreneurs.

Sustainability Focus: Startups should align with climate-smart goals to ensure long-term viability and environmental balance.

Conclusion

Agri-startups represent a revolutionary force reshaping India's rural economy by integrating technology, entrepreneurship and sustainability into the agricultural ecosystem. They are not only enhancing productivity and market efficiency but also empowering farmers with knowledge and access. With supportive policies, adequate infrastructure and collaboration across stakeholders, agri-startups can become the cornerstone of a self-reliant, prosperous and resilient rural India. The next decade holds immense promise, as agri-innovation continues to redefine the future of Indian agriculture and rural development.

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Climate-Smart Agriculture and Resilience: A Sustainable Pathway for the Future of Indian Farming

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Climate change poses severe risks to global and Indian agriculture, causing unpredictable rainfall, prolonged droughts, floods, heat waves, and pest outbreaks. These climatic disruptions threaten food security, farmer livelihoods, and ecosystem stability. Climate-Smart Agriculture (CSA) is an integrated approach introduced by the Food and Agriculture Organization (FAO) to address these challenges. It focuses on three core pillars—sustainably increasing productivity, enhancing resilience (adaptation), and reducing greenhouse gas emissions (mitigation). This paper explores the need, significance, challenges, and management strategies of CSA with real-world examples from India, including BAIF's Climate Smart Village Programme, the women-led model in Marathwada, and water-management initiatives in Bundelkhand. The article concludes that scaling CSA practices, backed by policy support, technology, and community participation, is essential for achieving sustainable and resilient agriculture in India.

Introduction

Agriculture is one of the most climate-sensitive sectors in the world. In India, where nearly **58% of the population** depends on agriculture directly or indirectly, the effects of climate variability are becoming increasingly evident. Rising temperatures, erratic monsoons, water scarcity, soil degradation, and emerging pest and disease patterns are reducing productivity and profitability.

To confront these threats, the **FAO (2013)** introduced the concept of *Climate-Smart Agriculture (CSA)*—a holistic framework aimed at transforming and re-orienting agricultural systems to support food security under the new realities of climate change. CSA does not advocate a single practice but rather an adaptive, context-specific strategy that simultaneously promotes **productivity, adaptation, and mitigation**.

In India, where diverse agro-climatic zones exist—from flood-prone Bengal to drought-stricken Marathwada—climate-smart solutions are vital for ensuring both resilience and sustainability in farming systems.

Need for Climate-Smart Agriculture

The need for CSA arises from the growing gap between traditional farming practices and the changing climatic environment. Key reasons include:

1. **Increasing Climate Vulnerability:** Over the last few decades, India has witnessed more frequent droughts and floods. For instance, delayed monsoons in states like Bihar and Madhya Pradesh have reduced rice and maize yields by up to 20%.
2. **Declining Soil Fertility and Water Resources:** Intensive monocropping and overuse of chemical fertilizers have degraded soil health. Groundwater levels are declining in many parts of North and Central India, threatening future cultivation.
3. **Food Security and Livelihood Risks:** Climate shocks not only lower yields but also affect farmer incomes, leading to distress migration and reduced access to nutritious food.
4. **Emission Pressures:** Agriculture contributes around **18% of India's total greenhouse gas emissions**,

primarily from livestock and paddy fields. CSA offers methods to minimize these emissions while maintaining productivity.

Significance of CSA and Building Resilience

The significance of CSA lies in its **triple-win approach**:

- **Productivity:** Sustains and increases yields under adverse climate conditions.
- **Adaptation (Resilience):** Enhances the ability of farmers and systems to absorb shocks like drought or floods.
- **Mitigation:** Reduces GHG emissions and increases carbon sequestration.

Resilience in agriculture refers to the capacity of systems to **absorb stress, recover, and transform**. In India, building resilience is crucial because 60% of the net sown area is rain-fed. CSA strengthens resilience through improved water management, diversified cropping, and better access to technology and climate information.

For example, **BAIF's Climate Smart Village Programme** in Bihar and Madhya Pradesh improved productivity by 140% and reduced carbon emissions by 55%, demonstrating how CSA practices directly enhance both resilience and environmental outcomes.

Challenges in Implementing CSA

Despite its promise, the widespread adoption of CSA faces multiple challenges:

1. **Financial Constraints:** Small and marginal farmers, who make up over 80% of India's farming population, lack access to credit and funds to invest in CSA technologies like drip irrigation or precision tools.
2. **Knowledge and Capacity Gaps:** Lack of awareness, technical know-how, and limited extension services slow the adoption of CSA practices.
3. **Data and Information Barriers:** Many farmers lack access to real-time climate and market information that could support decision-making.
4. **Institutional and Policy Limitations:** CSA adoption requires coordinated policies across water, energy, and agriculture sectors—something still lacking in most Indian states.
5. **Socio-Economic Inequalities:** Gender gaps, land fragmentation, and poverty further hinder the implementation of large-scale CSA programmes.

Solutions and Management Strategies

To overcome these challenges, an integrated management approach is required. Some key strategies include:

1. **Water Resource Management:** Efficient irrigation, rainwater harvesting, and watershed management can reduce drought vulnerability.
   Example: In Bundelkhand, constructing check-dams and percolation tanks significantly improved soil moisture and crop productivity.
2. **Crop Diversification and Climate-Resilient Varieties:**
   Promoting short-duration, drought-tolerant, and flood-resistant varieties helps farmers adapt. Rotating cereals with pulses and millets improves soil fertility and reduces risk.
3. **Soil Health Improvement:** Adopting conservation agriculture—minimum tillage, organic amendments, and cover cropping—enhances soil carbon and water retention.
4. **Use of ICT and Early-Warning Systems:** Digital weather advisories and mobile-based tools can inform farmers about rainfall, pest attacks, and market trends.

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Example: Studies in Haryana found that farmers using ICT tools were more adaptive to climate risks.

5. **Policy and Financial Incentives:** Governments can promote CSA through crop-insurance schemes, low-interest green loans, and carbon credit markets.
6. **Community-Based Models:** Empowering local communities, particularly women, ensures sustainable adoption. *Example:* In Maharashtra's Marathwada region, a women-led CSA model improved food security and soil health across 800 villages.

Benefits of Climate-Smart Agriculture

- **Sustainability:** Maintains long-term productivity without depleting natural resources.
- **Economic Stability:** Increases income through efficient resource use and diversification.
- **Environmental Protection:** Reduces emissions, improves biodiversity, and restores degraded land.
- **Social Inclusion:** Empowers smallholders, especially women, to participate in decision-making.
- **Food Security:** Ensures availability and accessibility of food even under climate stress.

Overall, CSA bridges the gap between agricultural productivity and environmental conservation.

Conclusion

Climate-Smart Agriculture represents the future of sustainable farming. In the face of escalating climate threats, India's agricultural sector must transition from reactive crisis management to proactive resilience building. CSA provides the framework to achieve this by integrating productivity, adaptation, and mitigation into a single, coherent strategy.

Scaling CSA requires collaborative efforts among farmers, researchers, policymakers, and financial institutions. When supported by strong policy, local innovation, and education, CSA can transform Indian agriculture—making it not only more climate-resilient but also economically and environmentally sustainable for generations to come.

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Call for Articles

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Agriculture Bulletin, a monthly publication on agriculture trends, is now accepting submissions for its November 2025 edition. We invite ***popular articles, case studies, opinion, reviews, and latest innovation updates*** *from researchers, professionals, and enthusiasts in the field.*

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