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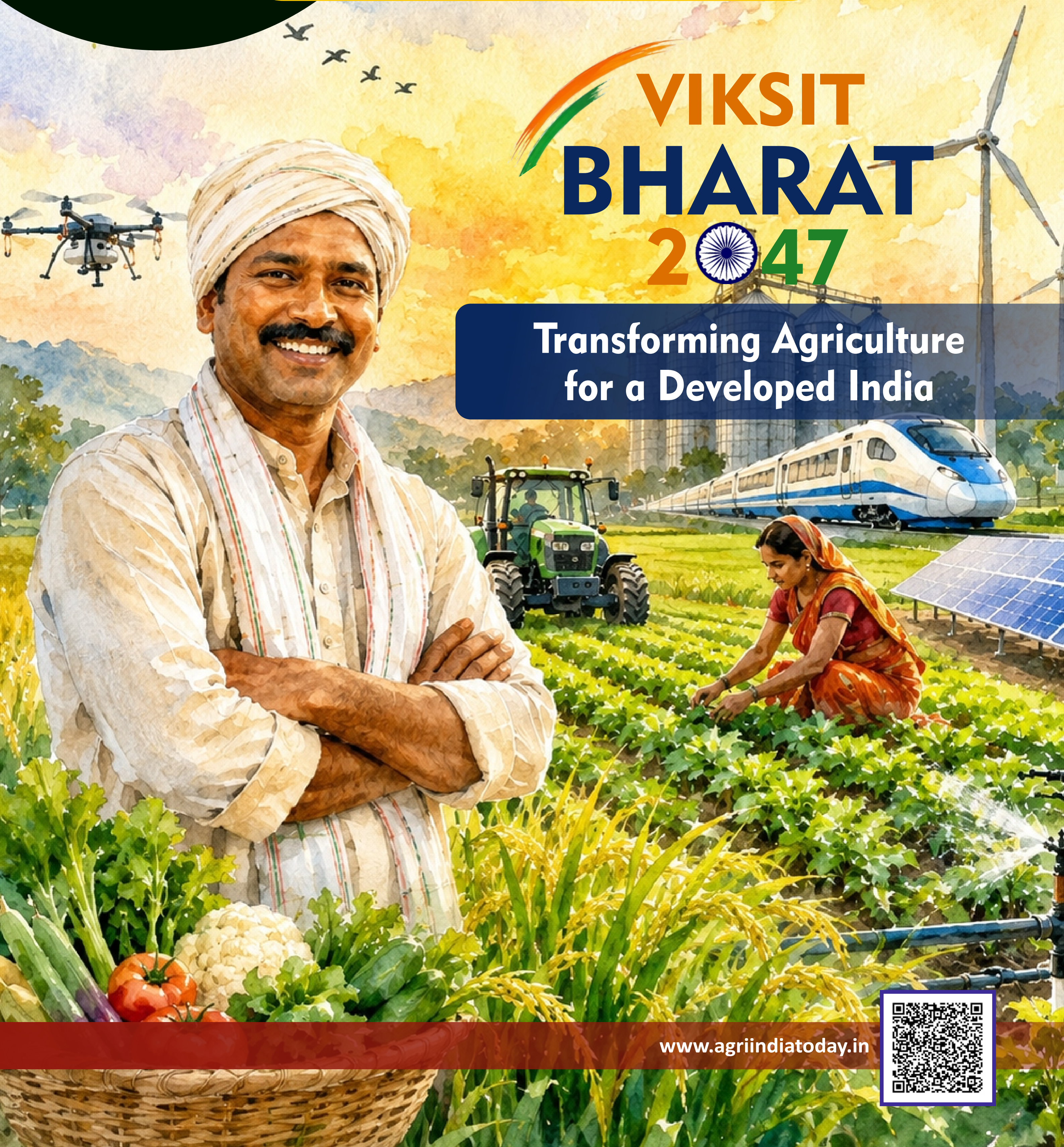
VIKSIT BHARAT 2047

Transforming Agriculture for a Developed India



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Editorial Board

FROM THE DESK OF THE EDITOR

(Special Issue | June 2026)

Dear Readers,

It is a matter of great pleasure to present this Special Issue of *AgriIndia Today* dedicated to the transformative vision of **Viksit Bharat 2047**. This national mission reflects India's collective aspiration to emerge as a developed, prosperous, inclusive, and globally respected nation by the centenary year of its independence.

The vision of Viksit Bharat is founded upon the pillars of sustainable economic growth, technological innovation, environmental stewardship, social equity, quality education and empowered communities. Achieving this ambitious goal requires the active participation of all sectors of society, particularly agriculture, science, technology, education, entrepreneurship and rural development, which continue to shape the foundation of India's progress.

As India advances towards becoming a global leader, the role of research, innovation and knowledge dissemination becomes increasingly significant. This special issue brings together scholarly contributions from researchers, academicians, policymakers and professionals who offer valuable perspectives on the opportunities and challenges associated with building a developed India. The articles presented herein highlight innovative approaches, emerging technologies, sustainable development practices, and policy interventions that can contribute meaningfully to the realization of the Viksit Bharat vision.

Agriculture and allied sectors remain central to India's developmental journey. Ensuring food security, promoting climate-resilient farming systems, conserving natural resources, enhancing rural livelihoods, and fostering technological adoption will be critical in achieving sustainable and inclusive growth. The insights shared in this issue underscore the importance of integrating scientific knowledge with practical solutions to address contemporary challenges and unlock new avenues for national development.

I extend my sincere appreciation to all the authors for their valuable contributions, the reviewers for their constructive assessments and the editorial team for their dedicated efforts in bringing this special issue to fruition. Their commitment to academic excellence and nation-building is truly commendable.

As we embark on this journey towards Viksit Bharat 2047, let us reaffirm our commitment to innovation, sustainability and collective progress. May this special issue inspire meaningful dialogue, informed action and collaborative efforts in shaping a brighter future for our nation.

Wishing you an enriching and thought-provoking reading experience.

Jai Hind!

SKS

Prof. Shailesh Kumar Singh
Special Editor-in-Chief

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AGRICULTURE: THE FOUNDATION OF VIKSIT BHARAT 2047

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Abstract

Agriculture is the backbone of the Indian economy and plays a crucial role in achieving the vision of Viksit Bharat 2047. This paper highlights the importance of agriculture in ensuring food security, rural employment, economic growth and sustainable development. It discusses the present status of Indian agriculture, including record food grain production, growth in horticulture and dairy sectors and increasing use of modern technologies. The paper also examines major challenges faced by Indian farmers such as small and fragmented landholdings, climate change, water scarcity, post-harvest losses, limited market access and rising production costs. Special emphasis has been given to the role of women empowerment, Farmer Producer Organisations (FPOs), Self-Help Groups (SHGs), digital agriculture and climate-smart farming practices in strengthening rural livelihoods. The paper concludes that transforming villages into economically self-reliant, technologically advanced and environmentally sustainable communities is essential for building a prosperous, inclusive and self-reliant India by 2047.

Introduction

Agriculture remains the backbone of the Indian economy and plays a crucial role in food security, employment generation and rural development. Nearly half of India's population depends directly or indirectly on agriculture and allied sectors for livelihood (Government of India, 2024). Indian agriculture is largely dominated by small and marginal farmers, who constitute about 85 percent of the farming community. Despite challenges such as fragmented landholdings, rising production costs, climate variability and unstable markets, these farmers make a major contribution to national food production and rural sustainability (FAO, 2023). They also help preserve traditional agricultural knowledge, biodiversity and rural culture, making agriculture central to inclusive national development.

Over the years, India has achieved remarkable progress in food grain production, horticulture, dairy and allied sectors through technological advancement, government support and farmer participation. Today, India is among the world's leading producers of rice, wheat, milk, fruits and vegetables (NITI Aayog, 2023). However, the sector continues to face several structural problems, including declining farm profitability, water scarcity, soil degradation, post-harvest losses, inadequate infrastructure and increasing climate-related risks. Frequent droughts, floods, heat waves and pest outbreaks are creating uncertainty in agricultural production and threatening rural livelihoods (IPCC, 2022). Limited access to institutional credit, digital technologies, storage facilities and organised markets further restricts the growth of small farmers.

The vision of Atmanirbhar Bharat and Viksit Bharat 2047 recognises agriculture as a key pillar of India's future development. The vision promotes self-reliance, sustainable agriculture, rural prosperity, women empowerment, digital transformation and strong local food systems.

Strengthening agriculture and allied sectors can generate employment, reduce poverty, improve nutritional security and encourage rural entrepreneurship (Ministry of Agriculture & Farmers Welfare, 2024). This paper explains how agriculture can become the strongest foundation of Viksit Bharat. It discusses the present status of Indian agriculture, major farmer challenges, climate-smart farming, women empowerment, digital technologies, rural infrastructure and the role of Farmer Producer Organisations (FPOs) and Self-Help Groups (SHGs) in strengthening rural economies and building a self-reliant, developed India by 2047.

Present Status of Indian Agriculture

Agriculture has played a central role in India's economic and social development since Independence. Over the decades, the country has achieved remarkable progress in food production and agricultural growth through the hard work of farmers, scientific advancements, irrigation development and supportive government policies (Government of India, 2024). Today, India is among the world's leading producers of food grains, milk, fruits, vegetables, pulses and several other agricultural commodities. The Green Revolution, White Revolution and improvements in agricultural research and extension services have helped the country move from food scarcity to food self-sufficiency (Rao & Birthal, 2022). Agriculture not only ensures food security for the nation's large population but also provides livelihood opportunities to millions of rural families, contributing significantly to rural employment and national economic growth (FAO, 2023).

Record Food Production and Agricultural Growth

India's total food grain production has crossed 353 million tonnes, reflecting the dedication and resilience of Indian farmers (Ministry of Agriculture & Farmers Welfare, 2024). Production of major crops such as wheat, rice, maize and pulses has increased significantly over the years due to the adoption of improved seed varieties, balanced fertilizer use and expansion of irrigation facilities. The horticulture sector has also shown remarkable growth, with India becoming one of the largest producers of fruits and vegetables in the world. Similarly, the dairy sector has expanded rapidly, making India the largest milk producer globally. Fisheries, poultry and livestock sectors are also contributing significantly to agricultural income, nutritional security and rural employment generation.

The growth of agriculture has been supported by farm mechanisation, agricultural research, digital technologies and various government programmes aimed at improving productivity and farmer welfare. Schemes related to crop insurance, direct income support, rural roads, irrigation and agricultural credit have strengthened agricultural infrastructure and rural development. The increasing use of mobile phones, digital platforms and agricultural advisories has also started transforming farming practices in many parts of the country by helping farmers access weather forecasts, market information and scientific crop management techniques (NITI Aayog, 2023).

Need for Inclusive Agricultural Development

Despite record production, the benefits of agricultural growth have not reached all farmers equally. High production alone cannot guarantee rural prosperity unless farmers receive fair prices, stable incomes and reliable market opportunities. Many farmers continue to face high production costs due to expensive seeds, fertilizers, pesticides, labour and machinery. Small and marginal farmers often struggle to recover their investments because of fluctuating market prices, weak bargaining power and dependence on middlemen.

Proper storage, cold chain and processing facilities are still inadequate in many rural areas, resulting in large post-harvest losses, especially in fruits and vegetables. Better market access and value addition facilities are essential to improve farmers' incomes and reduce food wastage. Climate change has emerged as another major challenge, with droughts, floods, heat stress and irregular rainfall affecting agricultural productivity and farmer livelihoods. Therefore, climate-resilient agriculture, water conservation and sustainable farming practices are becoming increasingly important for long-term agricultural sustainability (IPCC, 2022).

Modern technologies such as precision farming, digital agriculture, artificial intelligence, drones and mobile-based advisory services can help improve productivity and reduce farming risks. However, access to such technologies remains limited for many rural farmers due to lack of awareness, technical knowledge, training and financial resources. Expanding digital literacy, strengthening extension services and improving institutional support will be crucial for ensuring inclusive agricultural development and achieving the vision of *Viksit Bharat 2047*.

Challenges Before Indian Farmers

Present Status of Indian Agriculture and Challenges Before Farmers Indian agriculture has made remarkable progress since Independence and today India is among the world’s leading producers of food grains, milk, fruits and vegetables. The country’s total food grain production has crossed 353 million tonnes, reflecting the dedication and hard work of Indian farmers. Significant growth has been observed in wheat, rice, pulses, horticulture and dairy production, contributing greatly to national food security and rural employment. Despite these achievements, high production alone cannot ensure rural prosperity. Farmers also require fair prices, reduced production costs, better storage facilities, improved market access, climate protection and modern technologies to achieve sustainable growth and improved livelihoods.

Small and Fragmented Landholdings

One of the biggest challenges facing Indian agriculture is the small and fragmented nature of landholdings. The average farm size in India is around 0.7 hectare, which limits the adoption of advanced machinery and modern farming practices. Small farmers often cannot afford tractors, harvesters, irrigation systems and other costly technologies individually. As a result, production costs remain high while productivity and profitability remain comparatively low. Limited bargaining power in purchasing inputs and selling produce further weakens farmer incomes and increases dependence on intermediaries.

Dependence on Rainfall and Climate Change

A large portion of Indian agriculture still depends on monsoon rainfall. Nearly 61 percent of cultivated land is rain-fed, making farming highly vulnerable to irregular rainfall, droughts and floods. Climate change has intensified these risks through rising temperatures, heat waves, unseasonal rains, pest outbreaks and water scarcity. Sudden weather changes frequently damage standing crops and reduce agricultural productivity, threatening both farmer livelihoods and national food security. Therefore, climate-resilient agriculture and sustainable water management have become essential for future agricultural sustainability.

Low Irrigation Coverage and Water Stress

Although irrigation plays a crucial role in stable crop production, the adoption of efficient irrigation systems remains limited. Modern micro-irrigation methods such as drip and sprinkler irrigation help conserve water and improve productivity, yet their coverage remains low in many regions. Many farmers continue using traditional irrigation methods that waste water and increase cultivation costs. Expanding irrigation infrastructure and promoting water-saving technologies are necessary for improving water-use efficiency and conserving groundwater resources.

Post-Harvest Losses and Poor Market Infrastructure

Inadequate storage, transportation and processing facilities cause heavy post-harvest losses in India, particularly in fruits and vegetables. Many farmers are forced to sell produce immediately after harvest at low prices due to the absence of warehouses, cold storage units and efficient supply chains. Poor rural roads and weak market infrastructure further reduce profitability and increase food wastage. Strengthening cold chains, food processing and rural infrastructure can significantly improve farmer incomes and market efficiency.

Limited MSP Benefits and Rural Indebtedness

Although the Minimum Support Price (MSP) system provides price support for selected crops, only a limited number of farmers directly benefit from government procurement systems. Many small farmers continue to sell their produce at low prices in local markets. In addition, dependence on informal credit sources and moneylenders continues in rural areas, increasing indebtedness and financial insecurity. Strengthening institutional credit, expanding procurement systems and improving market access are essential for ensuring long-term agricultural prosperity and achieving the vision of a developed India by 2047.

Why Small Farmers Are the Real Strength of India

Small and marginal farmers form the backbone of Indian agriculture and play a crucial role in ensuring national food security and rural development. Although they own only about 24 percent of the total agricultural land, small farmers contribute nearly 41 percent of the country’s food grain production and around 70 percent of vegetable production, highlighting their high productivity and hard work (Government of India, 2024). These farmers sustain millions of rural households and support the country’s food supply despite facing challenges such as limited land, inadequate irrigation, low access to markets and rising production costs (FAO, 2023). Strengthening small farmers through improved technology, credit access and market support can significantly enhance agricultural growth and rural prosperity.

Importance of Local Food Systems

Local food systems are becoming increasingly important for building self-reliant and sustainable rural economies. A strong local food system includes local production, processing, storage, marketing and employment generation within villages and nearby towns (NITI Aayog, 2023). Such systems reduce dependence on distant markets and improve the resilience of rural communities. Farmers benefit by selling produce directly to consumers, which helps them receive better prices and increases farm income. Local food processing and value addition activities such as dairy processing, flour mills and fruit preservation also generate employment opportunities for rural youth and women (Rao & Birthal, 2022).

Local storage and processing facilities help reduce post-harvest losses and food wastage, especially for perishable commodities such as fruits and vegetables (Ministry of Agriculture & Farmers Welfare, 2024). In addition, shorter supply chains reduce transportation costs, fuel consumption and environmental pollution. Money earned through local food systems circulates within villages, strengthening the rural economy and promoting inclusive development. Therefore, supporting small farmers and local food systems is essential for achieving the vision of Viksit Bharat 2047.

Viksit Gram: The Foundation of Viksit Bharat

The concept of **Viksit Gram** (developed village) is central to achieving the vision of Viksit Bharat 2047 because India’s true development depends on the prosperity of its villages (NITI Aayog, 2023).

A developed village is characterised by good roads, pucca houses, irrigation facilities, digital connectivity, employment opportunities, financially empowered women and modern farming systems (Government of India, 2024). Strong rural infrastructure improves agricultural productivity, market access and quality of life for rural communities. Better irrigation, education, healthcare and skill development further improve rural livelihoods and reduce migration to urban areas (Ministry of Rural Development, 2024).

Digital technologies and modern farming practices help farmers increase efficiency and income, while women's participation in Self-Help Groups and rural enterprises strengthens economic development (FAO, 2023). Therefore, prosperous and self-reliant villages are essential for inclusive growth, sustainable agriculture and building a strong, developed and self-reliant India by 2047 (Rao & Birthal, 2022).

Women Empowerment in Agriculture

Women are emerging as major drivers of rural transformation and agricultural development in India. Their contribution to farming and allied sectors is essential for ensuring household food security, nutritional well-being and rural livelihoods. Nearly 80 percent of rural women participate in agriculture as farmers, agricultural labourers, dairy workers, entrepreneurs and members of Self-Help Groups (SHGs) (FAO, 2023). Despite their significant role, women often face challenges such as limited land ownership, restricted access to credit, technology, training and decision-making opportunities. Strengthening women's participation in agriculture is therefore essential for achieving inclusive rural development and the vision of Viksit Bharat 2047.

Contribution of Women in Rural Agriculture:

- Women contribute extensively to crop production, livestock management, seed preservation, food processing and kitchen gardening.
- They play a vital role in sowing, transplanting, weeding, harvesting and post-harvest operations, contributing significantly to farm productivity and household income (Government of India, 2024).
- Women are also custodians of traditional agricultural knowledge, especially in preserving indigenous seeds and maintaining biodiversity.
- Their involvement in dairy farming, poultry, mushroom cultivation and small-scale food enterprises supports rural entrepreneurship and nutritional security (Rao & Birthal, 2022).
- Furthermore, SHGs have empowered rural women financially by promoting savings, credit access and small business activities, thereby improving their social and economic status (NITI Aayog, 2023).

Empowering women through education, skill development, digital literacy and access to resources can greatly strengthen sustainable agriculture and rural prosperity.

Lakhpati Didi Initiative

The ***Lakhpati Didi Initiative*** is an important government programme aimed at empowering rural women economically by helping them earn an annual income of more than ₹1 lakh through sustainable livelihood activities. The initiative is closely linked with Self-Help Groups (SHGs) under the *Deendayal Antyodaya Yojana–National Rural Livelihood Mission (DAY-NRLM)* and focuses on improving women's financial independence, entrepreneurship and participation in rural development (Ministry of Rural Development, 2024). The programme supports skill development, access to credit, market linkages and enterprise promotion for rural women across the country.

Women-Led Rural Enterprises

Millions of rural women are already benefiting from the initiative through activities such as dairy farming, mushroom cultivation, food processing, poultry farming, beekeeping and small-scale businesses. These income-generating activities not only improve household earnings but also create employment opportunities within villages (Government of India, 2024). Women-led enterprises contribute significantly to strengthening local food systems, improving nutritional security and promoting rural entrepreneurship. Participation in SHGs has also increased women's confidence, decision-making ability and financial inclusion (NITI Aayog, 2023).

The initiative has further encouraged women to adopt modern technologies, value addition and market-oriented production systems. Women entrepreneurs involved in dairy cooperatives, food processing units and agri-based enterprises are helping strengthen village economies and reducing dependence on external markets (FAO, 2023). Empowering women through such initiatives plays a crucial role in achieving inclusive growth, rural prosperity and the vision of Viksit Bharat 2047 (Rao & Birthal, 2022).

Self-Help Groups (SHGs): Rural Economic Revolution

Self-Help Groups (SHGs) have emerged as powerful instruments of rural transformation and women empowerment in India. The country has nearly 9 million SHGs involving more than 100 million rural women who are actively participating in savings, credit management, entrepreneurship and community development activities (Ministry of Rural Development, 2024). SHGs promote financial inclusion by encouraging regular savings and providing easy access to small loans for livelihood activities. These groups help rural women become economically independent and socially empowered while strengthening household income and food security.

Role of SHGs in Rural Development

SHGs support a wide range of activities such as collective farming, dairy farming, food processing, poultry, handicrafts and small-scale enterprises. Through group-based approaches, rural women gain access to institutional credit, training programmes and market opportunities that are often difficult to access individually (NITI Aayog, 2023). SHGs also promote social awareness, leadership development and community participation among women. Many SHGs are successfully involved in food processing, value addition and local marketing activities, which create employment opportunities and strengthen village economies (FAO, 2023). As a result, SHGs are becoming major engines of inclusive rural development and poverty reduction.

Farmer Producer Organisations (FPOs)

Farmer Producer Organisations (FPOs) are collective groups formed by farmers to improve production, marketing and profitability through cooperation and collective action. FPOs enable farmers to work together for input purchase, machinery sharing, storage, processing, marketing and export of agricultural produce (Ministry of Agriculture & Farmers Welfare, 2024). These organisations are particularly beneficial for small and marginal farmers who individually face difficulties in accessing markets, technology and financial resources.

Benefits of FPOs

FPOs improve farmers' bargaining power by enabling collective marketing and better price negotiation. Bulk purchase of seeds, fertilizers and other inputs reduces production costs and increases profitability. Shared machinery and custom hiring centres also make modern technologies affordable for small farmers (Rao & Birthal, 2022). In addition, FPOs help farmers access larger markets, digital trading systems and e-NAM platforms, thereby improving market linkages and reducing dependence on middlemen. By strengthening collective action, SHGs and FPOs are playing a crucial role in promoting sustainable agriculture, rural entrepreneurship and the vision of Viksit Bharat 2047.

Role of Technology in Viksit Bharat Agriculture

Technology is becoming a major driving force in transforming Indian agriculture into a more productive, profitable and sustainable sector. Modern agriculture requires smart technologies that can help farmers improve efficiency, reduce production costs and manage climate-related risks. The vision of Viksit Bharat 2047 strongly emphasises the use of digital technologies, artificial intelligence and data-driven farming systems to strengthen rural livelihoods and agricultural sustainability (NITI Aayog, 2023). Technological advancement can help farmers make informed decisions and improve farm productivity while conserving natural resources.

Digital Agriculture: Digital agriculture is playing an increasingly important role in improving agricultural management and farmer awareness. Digital tools and mobile-based applications help farmers access weather forecasting, pest alerts, soil testing services, crop advisory information and real-time market prices (Government of India, 2024). These services enable farmers to take timely decisions regarding sowing, irrigation, fertilizer application and pest management. Mobile apps and digital platforms also help reduce farming risks by providing scientific recommendations and improving market transparency. In addition, digital payment systems and e-commerce platforms are improving farmers’ access to financial services and agricultural markets (FAO, 2023).

Artificial Intelligence (AI) and IoT in Agriculture: Artificial Intelligence (AI) and Internet of Things (IoT) technologies are revolutionising modern farming practices. AI-based systems can support precision farming, water management, fertilizer efficiency and pest detection through data analysis and sensor-based monitoring (Jat *et al.,* 2023). IoT devices such as soil moisture sensors, smart irrigation systems and automated weather stations help optimise resource use and improve crop productivity. These technologies not only increase efficiency but also reduce input costs, labour requirements and environmental impacts. Precision agriculture can therefore contribute significantly to climate-smart and sustainable farming systems.

Digital Krishi Sakhis: Digital Krishi Sakhis are village-level trained women who help farmers adopt digital technologies and improve agricultural knowledge. They assist rural communities in using smartphones, agricultural applications, digital payment systems and online marketing platforms (Ministry of Agriculture & Farmers Welfare, 2024). Such local support systems are especially important for small and marginal farmers who may lack technical knowledge and digital literacy. Digital Krishi Sakhis act as a bridge between technology providers and rural farmers, helping expand the adoption of modern agricultural innovations. Therefore, technology-driven agriculture combined with community-based support systems can play a crucial role in achieving the vision of Viksit Bharat 2047.

Importance of Climate-Smart Agriculture

Climate change is becoming one of the biggest challenges for Indian agriculture, making climate-smart agriculture essential for ensuring future food security and sustainable rural development. Rising temperatures, irregular rainfall, droughts, floods and pest outbreaks are negatively affecting crop productivity and farmer income (IPCC, 2022). Therefore, future agriculture must become climate resilient by adopting sustainable farming practices that improve productivity while conserving natural resources. Climate-smart agriculture not only helps farmers adapt to changing climatic conditions but also reduces environmental degradation and improves long-term agricultural sustainability.

Climate-Smart Agricultural Practices: Farmers should increasingly adopt climate-smart practices such as crop diversification, cultivation of millets and coarse cereals, drip irrigation, organic manure application, mulching, agroforestry and water harvesting techniques. Crop diversification reduces the risk of total crop failure and improves farm income stability. Drip irrigation and water harvesting help conserve water and improve irrigation efficiency, especially in drought-prone regions (Ministry of Agriculture & Farmers Welfare, 2024). Similarly, mulching and organic manure improve soil moisture retention, soil fertility and microbial activity while reducing dependence on chemical fertilizers. Agroforestry systems also support biodiversity conservation, carbon sequestration and additional income generation for farmers (FAO, 2023).

Millets: Future Crops for India: Millets such as bajra, jowar and ragi are emerging as future crops for climate-resilient agriculture. These crops are highly drought tolerant, require less water and can grow well under harsh climatic conditions (ICAR, 2023). Millets are also rich in nutrients, fibre, iron and minerals, making them important for improving nutritional security. Promoting millet cultivation can therefore support both environmental sustainability and healthier diets while reducing pressure on water-intensive crops.

Importance of Indigenous Knowledge: Traditional Indian farming knowledge also has great value in sustainable agriculture. Indigenous agricultural practices help preserve biodiversity, improve soil health, conserve local seed varieties and reduce chemical dependency (NITI Aayog, 2023). Farmers have historically used mixed cropping, organic manure and traditional water conservation techniques to maintain ecological balance. Combining traditional wisdom with modern scientific innovations can create resilient, sustainable and environmentally friendly farming systems that support the vision of Viksit Bharat 2047.

Agricultural Infrastructure for Rural Prosperity

Strong agricultural infrastructure is essential for improving farmer income, reducing post-harvest losses and promoting sustainable rural development. Rural prosperity depends not only on higher agricultural production but also on efficient storage, processing, transportation and energy systems. Inadequate infrastructure often forces farmers to sell their produce immediately after harvest at low prices, reducing profitability and increasing food wastage (Government of India, 2024). Therefore, strengthening agricultural infrastructure is a key requirement for achieving the vision of Viksit Bharat 2047.

Cold Storage and Warehouses: Proper storage facilities such as warehouses and cold storage units play a crucial role in protecting agricultural produce and stabilising farmer income. Scientific storage helps farmers avoid distress sales during periods of low market prices and preserves the quality of grains, fruits and vegetables for longer durations (FAO, 2023). Village-level cold chains are especially important for perishable commodities because they reduce spoilage and post-harvest losses. Improved storage infrastructure also enables farmers to wait for better market prices and participate more effectively in organised supply chains. Expanding rural warehouses, cold storage facilities and refrigerated transportation systems can significantly strengthen local food systems and rural economies.

Food Processing and Value Addition: Food processing is another important component of agricultural infrastructure that adds value to farm produce and creates employment opportunities. Processing activities such as tomato sauce preparation, pickle making, fruit juice production, flour milling and dairy product manufacturing increase the shelf life and market value of agricultural commodities (Ministry of Food Processing Industries, 2024). Food processing industries generate rural employment for youth and women while improving farmer income through value addition. Small-scale processing units established near villages also reduce transportation costs and strengthen local entrepreneurship.

Solar Energy in Agriculture: Solar-powered irrigation systems are becoming increasingly popular in Indian agriculture because they provide reliable and environment-friendly energy solutions. Solar pumps help reduce electricity and diesel costs while ensuring timely irrigation for crops (MNRE, 2023). Farmers can also generate additional income by selling surplus solar power to the grid, a concept often described as “solar as a third crop.” Solar energy not only improves farm profitability but also supports clean energy adoption and sustainable agricultural development. Therefore, investment in agricultural infrastructure and renewable energy systems is essential for building resilient and prosperous rural communities.

Role of Government Schemes in Viksit Bharat Agriculture

Government schemes are playing a major role in strengthening Indian agriculture, improving rural livelihoods and supporting the vision of Viksit Bharat 2047. These programmes focus on farmer welfare, irrigation development, rural infrastructure, skill development, financial inclusion and climate resilience. Through various initiatives, the government is helping farmers increase productivity, reduce risks and improve income security (Government of India, 2024). Effective implementation of these schemes is essential for achieving sustainable agricultural growth and inclusive rural development.

PM-KISAN and Irrigation Development: The Pradhan Mantri Kisan Samman Nidhi (PM-KISAN) scheme provides direct income support to farmers, helping them manage agricultural expenses and household needs. This financial assistance strengthens the economic security of small and marginal farmers and improves their ability to invest in farming activities (Ministry of Agriculture & Farmers Welfare, 2024). Similarly, the Pradhan Mantri Krishi Sinchai Yojana promotes irrigation expansion, water conservation and efficient water management through micro-irrigation systems such as drip and sprinkler irrigation. These measures improve water-use efficiency and support climate-resilient agriculture.

MGNREGA and Agricultural Infrastructure: The Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) creates rural employment opportunities while developing productive community assets such as farm ponds, rural roads and water harvesting structures (Ministry of Rural Development, 2024). These assets strengthen agricultural productivity and rural infrastructure. In addition, the Agriculture Infrastructure Fund supports the development of warehouses, cold storage units and food processing facilities, helping reduce post-harvest losses and improve market access for farmers. Improved infrastructure promotes value addition and strengthens local food systems (FAO, 2023).

Skill Development and Financial Inclusion: The *Deen Dayal Upadhyaya Grameen Kaushalya Yojana* provides skill development training in food processing, agri-business and rural entrepreneurship, creating employment opportunities for rural youth and women (NITI Aayog, 2023). Financial inclusion is equally important for achieving Viksit Bharat 2047. Every farmer should have access to bank accounts, affordable loans, crop insurance and digital payment systems. Crop insurance schemes protect farmers against droughts, floods, pest attacks and other natural disasters, reducing financial risks and improving agricultural resilience.

Role of Panchayats in Rural Development: Village panchayats are key drivers of rural development and play an important role in planning local development activities, implementing government schemes, managing water resources and developing rural infrastructure. Strong panchayats ensure better coordination among different government programmes and encourage community participation in village development activities (Rao & Birthal, 2022). Therefore, empowering panchayats and strengthening local governance systems are essential for building prosperous and self-reliant villages under the vision of Viksit Bharat 2047.

Agriculture and Rural Employment

Agriculture remains the primary source of livelihood for millions of rural families in India, but farming alone often does not provide sufficient and stable income for small and marginal farmers (Government of India, 2024). Therefore, diversified livelihood opportunities are essential for improving rural economic stability and reducing poverty. Activities such as dairy farming, poultry, fisheries, beekeeping, mushroom cultivation, food processing and rural enterprises provide additional income and employment opportunities for rural households (FAO, 2023). These allied sectors help farmers reduce dependence on seasonal crop income and improve resilience against climate and market risks.

Importance of Diversified Livelihoods

Dairy farming and poultry provide regular daily income, while fisheries and beekeeping support nutrition and entrepreneurship development. Mushroom cultivation and food processing create value-added products and employment opportunities for rural youth and women (NITI Aayog, 2023). Rural enterprises also encourage self-employment and strengthen local economies. Diversified farming systems improve economic security, generate year-round employment and contribute significantly to sustainable rural development and the vision of Viksit Bharat 2047 (Rao & Birthal, 2022).

Agriculture and Environmental Sustainability

Sustainable agriculture is essential for protecting natural resources, ensuring food security and supporting future generations. Indian agriculture faces increasing pressure from soil degradation, water scarcity, climate change and excessive chemical use, making environmentally sustainable farming practices more important than ever (FAO, 2023). Sustainable agriculture focuses on improving productivity while conserving soil, water and biodiversity. Such practices help maintain ecological balance, reduce environmental pollution and improve long-term agricultural resilience, which is vital for achieving the vision of Viksit Bharat 2047.

Key Sustainable Practices

Soil health management is one of the most important components of sustainable agriculture. Farmers are encouraged to use organic manure, crop rotation and green manuring to improve soil fertility, increase organic carbon and enhance microbial activity (Ministry of Agriculture & Farmers Welfare, 2024). These practices reduce dependence on chemical fertilizers and improve long-term soil productivity. Water conservation is equally important because agriculture consumes a large share of India's freshwater resources. Rainwater harvesting, drip irrigation and farm ponds help improve water-use efficiency and support climate-resilient agriculture (NITI Aayog, 2023). Balanced fertilizer application and reduced chemical use further protect soil and water quality while reducing environmental damage.

Economic Multiplier Effect of Local Agriculture

Local agriculture also creates a strong economic multiplier effect within rural communities. When farmers earn higher incomes, rural businesses, transport services and local markets also benefit, leading to greater employment opportunities and economic growth (Rao & Birthal, 2022). Increased agricultural income supports local shops, food processing units and service sectors, improving the overall rural economy. Youth employment and rural entrepreneurship also increase as local agricultural activities expand. Therefore, sustainable and locally driven agriculture not only protects the environment but also strengthens rural livelihoods and promotes inclusive economic development.

Economic Multiplier Effect of Local Agriculture

Local agriculture creates a strong economic multiplier effect by generating employment, increasing rural income and strengthening village economies. When money is spent within local food systems, it circulates among farmers, traders, transporters and rural businesses, thereby creating additional economic activity (FAO, 2023). Higher farmer income increases demand for transport services, agricultural inputs and local market goods, which supports rural shops and small enterprises (NITI Aayog, 2023). Improved agricultural prosperity also creates employment opportunities for rural youth in food processing, marketing and agri-based enterprises. Therefore, agriculture not only provides food security but also acts as the foundation of sustainable rural economic development and inclusive growth (Rao & Birthal, 2022).

Pathway from Dependency to Dignity

India’s agricultural transformation must move farmers from subsistence farming to prosperity, dignity and self-reliance. Farmers should shift from unorganised markets to digital platforms and modern value chains that ensure fair prices and better market access. Collective farming through FPOs and cooperatives can help small farmers access technology, finance and markets more effectively. Rural development must also promote entrepreneurship, food processing and rural industries to generate employment and reduce migration. By 2047, Indian villages should become digitally connected, economically self-reliant, climate-resilient, technologically advanced and environmentally sustainable. Villages should emerge not only as food producers but also as centres of innovation, entrepreneurship and rural economic growth, forming the foundation of Viksit Bharat.

Summary and Conclusion

Agriculture remains the backbone of India’s economy and the strongest foundation for achieving the vision of Viksit Bharat 2047. Indian agriculture has made remarkable progress in food grain production, horticulture, dairy development and rural infrastructure. However, farmers still face several challenges such as small and fragmented landholdings, climate change, water scarcity, post-harvest losses, limited market access and rising production costs. The paper emphasises that strengthening small farmers, promoting local food systems and improving rural livelihoods are essential for building a self-reliant and prosperous India.

The importance of women empowerment, Self-Help Groups (SHGs), Farmer Producer Organisations (FPOs), digital agriculture and climate-smart farming practices in transforming rural India has been fully recognised. Sustainable agriculture, efficient water management, renewable energy, food processing and rural entrepreneurship can create employment opportunities and improve farmers' income. Government schemes, rural infrastructure and empowered panchayats also play a crucial role in achieving inclusive agricultural growth.

In conclusion, India's journey towards Viksit Bharat 2047 depends on prosperous villages, empowered farmers and sustainable agriculture. If every village becomes digitally connected, economically self-reliant, climate-resilient and technologically advanced, agriculture will not only feed the nation but also drive innovation, rural prosperity and national development.

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DIGITAL TRANSFORMATION AND SMART AQUACULTURE: A DRIVE FOR INDIA'S AGRICULTURAL PROGRESS TOWARDS VIKSIT BHARAT 2047

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Abstract

The vision of Viksit Bharat 2047 aims to transform India into a developed and technologically advanced economy, with agriculture playing a key role. Aquaculture, as a rapidly growing sector, contributes significantly to food security, livelihoods, and export earnings but faces challenges such as climate variability, disease outbreaks, and inefficiencies in resource utilization. Implementing smart aquaculture and digital transformation are essential in overcoming these challenges and boosting sectoral productivity. Innovative technologies, such as Internet of Things (IoT)-based monitoring, artificial intelligence (AI) driven analytics, remote sensing, and blockchain-enabled traceability, facilitate precision aquaculture by enabling real-time decision-making, optimizing resource utilization, and enhancing supply chain transparency. Despite the challenges associated with costs, digital literacy, and scalability, the integration of smart technologies has the potential to enhance sustainability, resilience, and competitiveness, thereby positioning aquaculture as a vital component of agricultural transformation within the framework of Viksit Bharat 2047.

Keywords: Artificial Intelligence, Internet of Things, Smart Aquaculture, Precision, Viksit Bharat 2047

Introduction

India's vision of Viksit Bharat 2047 aimed to transform the nation into a developed, inclusive, and technology- oriented economy, with agriculture serving as a key component of this transition. In this context, aquaculture has emerged as one of the fastest-growing and rapidly expanding agri-food sectors, contributing substantially to food security, export earnings, and rural livelihoods (FAO, 2022). However, the sector continues to encounter ongoing difficulties, including climate fluctuations, disease outbreaks, resource inefficiencies, and restricted access to real-time farm management tools (Bostock *et al*., 2010; Troell *et a*., 2014). Conventional aquaculture practices are often exhibit low input optimization and inadequate monitoring of essential parameters such as water quality and feed efficiency, leading in fiscal losses and environmental concerns. Recently, the advent of digital technologies has opened new avenues for transforming aquaculture into a more precise, efficient, and sustainable practice. Developments such as Internet of Things (IoT)-based sensors, artificial intelligence (AI), big data analytics, and blockchain-enabled traceability are facilitating data-driven decision-making optimize resource use, ensure traceability and improving productivity while minimizing risks (Nasir *et a*., 2020; Verdouw *et a*., 2016). Alignment with national programs such as the Pradhan Mantri Matsya Sampada Yojana (PMMSY) and the Blue Economy framework, smart aquaculture holds the promise of expediting sectoral modernization. By integrating digital technologies with traditional practices, it is possible to improve production efficiency, promote environmental sustainability, and fortify value chains. Therefore, smart aquaculture and digital transformation have the potential to drive India's agricultural future and achieving the goals of Viksit Bharat 2047.

Aquaculture in India: Current Status and Significance

India's aquaculture industry has witnessed significant expansion, with production surpassing 16 million tonnes, playing a crucial role in food security and export revenues (FAO, 2022). The shrimp farming segment, especially *Penaeus vannamei*, leads in exports and makes a considerable contribution to foreign exchange (Naylor *et a*., 2021). However, the productivity per unit area is still below global benchmarks, underscoring the necessity for technological advancements and enhanced farm management strategies (Troell *et al*., 2014).

Concept of Smart Aquaculture

Conventional aquaculture methods encounter several limitations like disease outbreaks (Lightner, 2011), environmental fluctuations that impact growth and survival rates (FAO, 2022), inefficiencies in feed usage led to increased pollution and elevated costs (Boyd *et al*., 2024), absence of real-time monitoring that results in suboptimal decision-making. These issues highlight the need for the implementation of advanced technologies. The phrase "smart aquaculture" refers to the integration of advanced technologies such as the IoT, AI, and cloud computing to optimize aquaculture operations. IoT devices, which include water quality sensors, cameras, feeding machines, and environmental monitoring systems, continuously collect data from aquaculture facilities. Following this, AI algorithms process this data to provide insights and support the automated management of farming activities. For example, smart aquaculture platforms can aggregate data from multiple sensors, providing farmers with a comprehensive dashboard that presents real-time information on pond conditions, animal behaviour, and feeding schedules. Automated control systems can adjust aeration, feeding, and water exchange based on AI predictions (Figure 1). These integrated systems enhance farm productivity, minimize labour needs, and promote sustainable production. Smart aquaculture integrates digital technologies into aquaculture systems to improve productivity and sustainability. It enables real-time monitoring, automation, and data-driven decision-making (Nasir *et al*., 2020). This transition from conventional to precision aquaculture is critical for future growth.

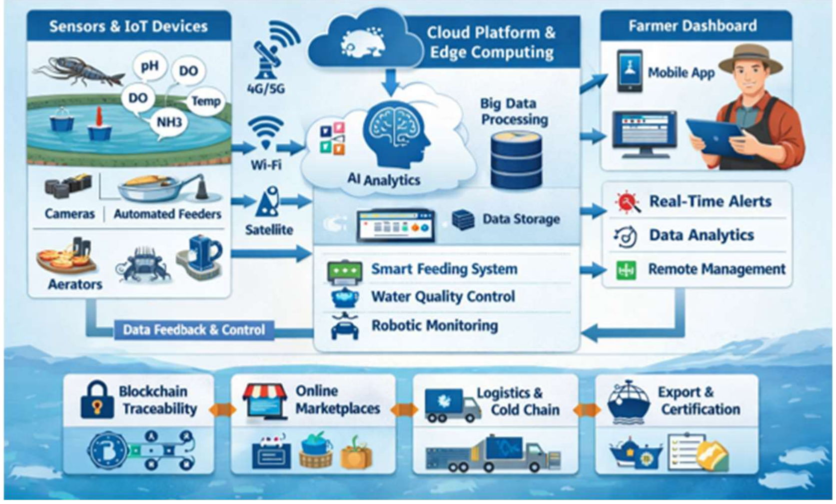

Figure 1. Smart Aquaculture system

Digital transformation: Applications in smart aquaculture

Water quality monitoring

The quality of water plays a crucial role in aquaculture, having a direct impact on the health of fish and shrimp. Key parameters such as temperature, dissolved oxygen, pH, salinity, ammonia, and turbidity need to stay within optimal limits. Systems powered by AI utilize sensor data and cloud-based analytics to continuously monitor these parameters, identify anomalies, and initiate alerts or automated responses like aeration. Furthermore, AI has the capability to forecast future changes in water quality, allowing for preventive measures that minimize stress and mortality while enhancing overall production efficiency.

Precision feeding and feed management

Feed constitutes the largest expense in aquaculture, accounting for 50–70% of costs, which makes efficient feeding crucial. AI-driven systems leverage sensors, cameras, and machine learning to observe animal behaviour and optimize both the timing and quantity of feed in real time. Technologies such as computer vision are employed to identify feeding activities and mitigate the risk of overfeeding, while predictive models modify feeding strategies based on factors like temperature, size, and growth stage. In the context of shrimp farming, intelligent feeding trays equipped with image recognition technology further enhance accuracy, leading to improved feed efficiency and a reduction in environmental waste.

Disease detection and health monitoring

Disease outbreaks pose a significant risk in aquaculture, leading to considerable economic losses. AI facilitates early detection by employing computer vision and machine learning to recognize unusual behaviour, physical symptoms, and hazardous environmental conditions. Sophisticated systems equipped with biosensors can identify pathogens or stress signals and notify farmers in real time. This capability enables prompt interventions, thereby decreasing mortality rates and enhancing the efficiency of disease management.

Automated animal counting

Precise estimation of stock and biomass is crucial in aquaculture; however, conventional methods tend to be labour-intensive and stressful. AI-driven computer vision systems utilize cameras or drones to automatically count fish and shrimp, even within dense populations. These systems monitor growth, estimate biomass, and track changes in population, facilitating improved decision-making regarding feeding, stocking, and harvesting, particularly in large-scale operations.

Production Forecasting

AI aids in forecasting aquaculture output by examining elements such as water quality, feeding practices, disease prevalence, and environmental conditions. Machine learning algorithms utilize past data to anticipate growth rates, feeding requirements, and harvest outputs, facilitating improved scheduling of stocking, feeding, and harvesting activities. These technologies also assist both the industry and governmental bodies in anticipating production patterns and market availability.

Challenges in smart aquaculture

Despite its advantages, smart aquaculture encounters obstacles including elevated costs, gaps in digital literacy, and limitations in infrastructure (FAO, 2022). One of the main limitations is the substantial initial investment for installing AI-based monitoring systems, sensors, and automated machinery. Small-scale farmers may find it difficult to invest in advanced technologies without financial assistance. Another challenge is the lack of high-quality data necessary to train AI models. In many aquaculture regions, farm data is often not systematically documented, making it difficult to develop precise predictive algorithms. Additionally, technical expertise is essential to operate and maintain AI systems. Farmers may need training to effectively interpret AI-generated recommendations and incorporate them into their daily farm management practices. Furthermore, environmental variability in aquaculture systems can sometimes reduce the accuracy of AI predictions, particularly when models are developed using limited datasets. Addressing these challenges will necessitate collaboration among researchers, technology developers, governments, and aquaculture producers. Nevertheless, the rise in investment in agri-tech and backing from the government offers substantial opportunities for expansion.

Future Perspectives

AI is expected to assume a progressively significant in the future of aquaculture. Developments in machine learning, sensor technologies, and cloud computing will render AI systems more affordable and accessible to farmers. In the years ahead, AI could facilitate entirely automated aquaculture farms where feeding, water quality management, and disease monitoring are managed by intelligent systems. The integration of satellite data, climate models, and genetic information may further improve the precision of aquaculture management tools. Moreover, AI technologies can aid in promoting more sustainable aquaculture by reducing feed waste, minimizing environmental impacts, and improving resource efficiency. As the global demand for seafood continues to grow, the implementation of smart technologies such as AI will be crucial for boosting aquaculture productivity while ensuring environmental sustainability.

Conclusion

Artificial intelligence is transforming aquaculture management by offering innovative solutions for monitoring, decision-making, and automation. Applications such as AI-based water quality monitoring, precision feeding, disease detection, automated counting, and production forecasting are already improving the efficiency of aquaculture operations. Despite challenges related to cost, data availability, and technical expertise, ongoing technological advancements are anticipated to boost the adoption of AI in aquaculture. By integrating AI with IoT and smart farming technologies, the aquaculture industry can progress towards more sustainable, efficient, and resilient production systems. The use of AI in aquaculture represents a significant step toward precision aquaculture, where data-driven management can improve productivity, mitigate risks, and foster the long-term growth of the global aquaculture sector.

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INTEGRATING CLIMATE-SMART AND DIGITAL AGRICULTURE UNDER MISSION LIFE FOR VIKSIT BHARAT 2047: A SMALLHOLDER-CENTRIC ROADMAP

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Introduction

Indian agriculture must simultaneously deliver food and nutrition security, raise farm incomes, and respond to accelerating climate risks over the next two decades. Recent assessments highlight that climate change is already manifesting through rising temperatures, erratic monsoons, and more frequent extreme events, all of which directly affect production and livelihoods (Drishti IAS, 2026). Small and marginal farmers—who constitute the overwhelming majority of cultivators—are particularly vulnerable because of their limited assets, thin risk-bearing capacity, and high dependence on rain-fed production systems (Asia Foundation, 2024; TRIF, 2023).

The national vision of Viksit Bharat 2047 demands that agriculture become more productive, resilient, resource-efficient, and inclusive in order to advance Sustainable Development Goals (SDGs) 2 (Zero Hunger), 12 (Responsible Consumption and Production), and 13 (Climate Action). To achieve this, India has adopted an integrated approach combining climate-smart agriculture (CSA), digital and precision agriculture, and Mission LiFE (Lifestyle for Environment) as complementary pillars of transformation (Government of India, 2023; Ministry of Environment, Forest and Climate Change [MoEFCC], 2022).

This article argues that integrating CSA and digital agriculture within the behavioral and institutional framework of Mission LiFE can provide a robust, smallholder-centred pathway to agricultural transformation by 2047. It outlines the conceptual foundations, reviews current initiatives, develops a simple analytical framework with equations, and proposes a roadmap consistent with the thematic focus areas of the special issue such as climate-smart agriculture, digital farming, natural and regenerative practices, farmer producer organizations (FPOs), and policy reforms.

Climate-Smart Agriculture: Concept and Relevance

The Food and Agriculture Organization (FAO) defines climate-smart agriculture as an approach that "sustainably increases productivity, enhances resilience (adaptation), reduces or removes greenhouse gas emissions (mitigation) where possible, and enhances achievement of national food security and development goals" (Lipper et al., 2014, as cited in CGIAR, 2015). This definition emphasizes three interlinked pillars: (a) productivity and income enhancement, (b) adaptation and resilience, and (c) mitigation through reduced emissions or increased carbon sequestration (FAO, 2010; World Bank, 2023).

FAO conceptualizes CSA as a pathway based on these pillars, noting that specific practices must be tailored to local agro-ecological and socio-economic conditions (FAO, 2010). Typical CSA interventions include conservation tillage, integrated nutrient management, stress-tolerant varieties, agroforestry, improved water management, and diversified farming systems that spread risk and enhance ecosystem services (United Nations Framework Convention on Climate Change [UNFCCC], 2021).

In India, several case studies show that CSA practices can stabilize yields under climate stress, reduce input costs, and improve the resilience of smallholders (GeoJournal, 2023; Asia Foundation, 2024). For example, district-level research in Punjab has documented how crop diversification, residue management, and water-saving technologies improve both productivity and resilience relative to conventional practices (GeoJournal, 2023).

Mission LiFE: Behavioral Foundation for Sustainable Agriculture

Mission LiFE—announced by the Prime Minister at COP26—seeks to transform the dominant "use-and-dispose" culture into a circular economy characterized by "mindful and deliberate utilization" of resources (NITI Aayog, 2026). It is envisaged as an India-led global mass movement to nudge individual and community-level actions that collectively generate significant climate co-benefits (MoEFCC, 2022). The mission aims to mobilize at least one billion Indians and other global citizens to adopt environment-friendly behaviors between 2022 and 2027, with a target of making at least 80 percent of Indian villages and urban local bodies environmentally sustainable by 2028 (India Brand Equity Foundation [IBEF], 2023; MoEFCC, 2022).

Agriculture is central to Mission LiFE because it shapes land use, water and energy consumption, and dietary patterns. Official documents list LiFE actions such as reducing food waste, promoting millets and other climate-resilient crops, composting organic waste, minimizing chemical input use, and encouraging local food systems (MoEFCC, 2022; Prepp, 2024). The Ministry of Agriculture and Farmers' Welfare has linked Mission LiFE to programs promoting natural farming, organic agriculture, and water-efficient technologies, as highlighted in national events on World Environment Day (Government of India, 2023).

By embedding CSA practices within Mission LiFE, India reframes climate action in agriculture as both a technological and behavioral challenge. This integration encourages farmers, consumers, and value-chain actors to choose production and consumption patterns that are simultaneously climate-resilient and resource-efficient (IBEF, 2023).

Digital and Precision Agriculture as Enablers

While CSA identifies what needs to be done, digital and precision agriculture provide powerful tools for how to implement it efficiently and at scale. The **Digital Agriculture Mission (DAM) 2021–2025** aims to transform Indian agriculture through data-driven solutions using artificial intelligence (AI), blockchain, drones, remote sensing, and Internet-of-Things (IoT) devices (NextIAS, 2025). Its core components include a unified farmer database, geo-referenced village maps, a digital crop survey, and a decision-support system that integrates multiple data streams for real-time advisories (Sanskriti IAS, 2025).

The mission envisions an "AgriStack" as a digital public infrastructure for agriculture, enabling precise targeting of schemes, improved crop insurance, and AI-enabled pest and disease forecasting (Sanskriti IAS, 2025). Complementing these public initiatives, numerous agri-tech start-ups provide satellite-based crop monitoring, mobile-phone-based extension, and data analytics services that convert high-resolution information into simple, localized advisories (Economic Times, 2026). Evidence from such platforms indicates that precision recommendations on sowing dates, fertilizer doses, and irrigation scheduling can reduce input use, lower greenhouse gas emissions, and improve yields, thereby directly supporting the three pillars of CSA (ARCC Journals, 2026; World Bank, 2023).

Digital tools can also strengthen value-chain resilience by improving yield forecasting, traceability, price discovery, and access to credit and insurance, which are critical for smallholders facing climate-induced market volatility (Economic Times, 2026; NextIAS, 2025). However, their impact depends on bridging the digital divide across regions, gender, and socio-economic groups, and on ensuring that farmers retain control over their data (Sanskriti IAS, 2025).

Analytical Framework: Measuring Climate-Smart Digital Agriculture

To conceptualize how CSA and digital agriculture jointly contribute to Viksit Bharat 2047, a simple composite indicator can be outlined. Let the **Climate-Smart Digital Agriculture Index** for a given farm or region be expressed as

$$CSA\_D = \alpha \frac{Y}{Y_0} + \beta \frac{R}{R_0} - \gamma \frac{E}{E_0},$$

where Y denotes current yield or income, R denotes a resilience measure (for example, yield stability or probability of loss), E represents greenhouse gas emissions per unit output, and Y_0, R_0, and E_0 are baseline values for a conventional system; α, β, and γ are weights reflecting national priorities.

This formulation reflects FAO's three pillars of CSA—productivity, resilience, and mitigation—while allowing digital technologies to influence the numerator of each component by improving decision making, resource efficiency, and risk management (FAO, 2010; World Bank, 2023). In practice, the resilience term could use indicators such as variance of yields or frequency of crop failure, while the emissions term could be based on life-cycle assessments of input use and land-use change (FAO, 2010).

Water productivity, a key CSA objective in water-stressed regions, can be represented as

$$WP = \frac{Y}{ET},$$

where WP is water productivity, Y is crop yield, and ET is crop evapotranspiration. Precision irrigation systems driven by soil-moisture sensors and weather forecasts aim to maximize WP by increasing yields while maintaining or reducing evapotranspiration (UNFCCC, 2021).

Similarly, the **carbon footprint per unit output** can be approximated as

$$CF = \frac{\sum_{j=1}^{n} E_j}{Y},$$

where E_j denotes emissions from different sources such as fertilizers, fuel, and residue burning. CSA practices like reduced tillage, agroforestry, and residue incorporation seek to minimize CF, and digital monitoring can provide the data needed for carbon accounting and participation in climate-finance mechanisms (FAO, 2010; World Bank, 2023).

These equations do not require primary data in this conceptual article but provide a framework that researchers can operationalize using plot-level or district-level datasets for empirical analysis.

Indian Policy Architecture for Climate-Smart Digital Agriculture

India's policy architecture already contains several elements needed to operationalize climate-smart digital agriculture. Under the **National Action Plan on Climate Change**, the **National Mission for Sustainable Agriculture (NMSA)** promotes soil health management, water-use efficiency, rain-fed area development, and climate-resilient agriculture (Prepp, 2024). The **National Initiative on Climate Resilient Agriculture (NICRA)**, implemented by the Indian Council of Agricultural Research

(ICAR), focuses on strategic research, technology demonstration, and capacity building for climate-resilient technologies across vulnerable districts (CCAFS, 2021; Vajiram & Ravi, 2025).

Press releases from the Ministry of Agriculture indicate that ICAR has developed a large number of climate-resilient crop varieties and management practices, which are being showcased through Kisan Melas and demonstration villages (Government of India, 2023). NMSA, NICRA, Pradhan Mantri Krishi Sinchai Yojana (PMKSY) and other schemes together address climate adaptation, resource conservation, and risk reduction, though their implementation remains uneven across states (DrishtiIAS, 2026).

Parallelly, the **Digital Agriculture Mission** is building digital public infrastructure through farmer registries, geo-referenced village maps, and crop-sown registries, which will enable precise targeting of subsidies, credit, and insurance, as well as AI-based pest forecasting (NextIAS, 2025; Sanskriti IAS, 2025). Private agri-tech firms are partnering with government agencies under public–private partnership models to offer digital advisory, yield mapping, and climate-risk analytics to farmers (Economic Times, 2026).

Mission LiFE, anchored by NITI Aayog and MoEFCC, provides a unifying behavioral framework for these initiatives by emphasizing resource-conserving lifestyles and enumerating 75 actionable LiFE practices, many of which pertain to agriculture and food systems (MoEFCC, 2022; NITI Aayog, 2026). Integrating these missions at the district level through convergence planning and digital monitoring can help mainstream CSA-digital solutions into routine agricultural development.

Smallholders, FPOs, and Inclusive Transformation

Any roadmap toward Viksit Bharat 2047 must be explicitly smallholder-centric, given that holdings below two hectares constitute more than 86 percent of India’s farms (Asia Foundation, 2024; TRIF, 2023). Studies show that most marginal farmers wish to remain in agriculture but require better access to technology, credit, and markets to do so sustainably (TRIF, 2023).

Farmer Producer Organizations (FPOs) and cooperatives can serve as critical institutional vehicles for inclusive climate-smart digital agriculture. They aggregate smallholders, reduce per-unit costs of adopting technologies such as drones and sensors, and enhance bargaining power in input and output markets (Asia Foundation, 2024). Government documents and press releases highlight examples where FPOs collectively manage natural farming clusters, composting units, and micro-irrigation systems, thereby converting LiFE principles into concrete practices (Government of India, 2023).

Digital platforms can be routed through FPOs to provide advisory services, soil testing, crop insurance, and market information, while also ensuring data stewardship and fair benefit-sharing (NextIAS, 2025; Sanskriti IAS, 2025). Women’s self-help groups (SHGs) and youth-led enterprises can further deepen inclusion by acting as local service providers for climate-smart digital solutions, leveraging their relatively higher digital literacy and social networks (ARCC Journals, 2026). This approach directly contributes to SDGs 2 and 5 by enhancing food security and gender equality alongside climate action (UNFCCC, 2021).

Roadmap to 2047: Strategic Priorities

Building on the above analysis, an indicative roadmap for integrating CSA, digital agriculture, and Mission LiFE toward Viksit Bharat 2047 can be structured around five strategic priorities.

1. **Design and dissemination of location-specific CSA-digital packages.** Research organizations and state agricultural universities should formulate agro-ecology-specific “climate-smart packages” that combine climate-resilient varieties, water-saving technologies, diversified cropping patterns, and nutrient-efficient practices, delivered through digital advisory systems linked to the DAM infrastructure (CCAFS, 2021; NextIAS, 2025).
2. **Building climate-ready digital public infrastructure.** Completing the farmer registry, geo-referencing land parcels, and operationalizing the crop-sown registry will enable high-resolution monitoring of adoption and impact, facilitate parametric insurance, and open pathways for smallholders to participate in carbon and ecosystem-services markets (Sanskriti IAS, 2025; World Bank, 2023).
3. **Mainstreaming Mission LiFE practices in agriculture.** State action plans should explicitly integrate LiFE actions such as reduced food waste, millet-based cropping systems, organic waste composting, and plastic-free input management into agricultural extension, with digital tools tracking behavioral change indicators over time (MoEFCC, 2022; IBEF, 2023).
4. **Strengthening FPOs and local governance for climate-smart digital services.** Financial and capacity-building support should enable FPOs to operate as hubs for digital and CSA services—offering drone-based crop monitoring, soil testing laboratories, and community irrigation systems—while ensuring participation of women and youth in leadership roles (Asia Foundation, 2024; Government of India, 2023).
5. **Ensuring ethical and just transitions.** Clear frameworks for data ownership, consent, and benefit-sharing must be established so that farmers remain primary rights-holders over their data and environmental services (Sanskriti IAS, 2025; Economic Times, 2026). Social safeguards, grievance-redress mechanisms, and inclusive design processes are necessary to prevent digital exclusion and unintended concentration of benefits (DrishtiIAS, 2026).

Conclusion

The convergence of climate-smart agriculture, digital and precision technologies, and Mission LiFE offers India a coherent and powerful strategy for transforming agriculture in line with the aspirations of Viksit Bharat 2047. CSA provides a framework for increasing productivity, resilience, and mitigation; digital tools operationalize this framework through data-driven decisions and efficient resource use; and Mission LiFE embeds these changes within a broader behavioral shift toward sustainable lifestyles (FAO, 2010; NITI Aayog, 2026; World Bank, 2023). If implemented through smallholder-centric institutions such as FPOs, supported by robust digital public infrastructure and ethical data governance, this integrated approach can help India achieve SDGs 2, 12, and 13 while raising farm incomes and safeguarding ecosystems. The conceptual equations and policy roadmap outlined in this article provide a basis for further empirical research and programmatic design, aligning closely with the focus areas of climate-smart and resilient agriculture, digital precision farming, agro-ecology, and policy reforms envisaged for the special issue.

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ARTIFICIAL INTELLIGENCE AND SMART PEST MANAGEMENT TECHNOLOGIES: TRANSFORMING INDIAN AGRICULTURE TOWARDS VIKSIT BHARAT 2047

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Abstract

Indian agriculture is undergoing a major technological transformation as the country moves towards the vision of Viksit Bharat 2047. Increasing pest outbreaks, climate variability, pesticide resistance, labour shortages, and environmental concerns are challenging conventional crop protection systems. Artificial Intelligence (AI), remote sensing, drones, Internet of Things (IoT), robotics, and machine learning based smart technologies are emerging as powerful tools for modern pest monitoring and precision pest management. These technologies enable real time surveillance, automated insect detection, predictive analytics, early warning systems, and targeted pesticide application, thereby reducing crop losses and minimizing excessive pesticide use. AI-powered smart traps, computer vision systems, multispectral imaging, and UAV-based surveillance are revolutionizing Integrated Pest Management (IPM) by making pest management more accurate, economical, and environmentally sustainable. India has also accelerated the adoption of digital agriculture through initiatives such as the Digital Agriculture Mission, Drone Didi Scheme, AgriStack, and AI-based advisory platforms. Smart pest management technologies have immense potential to improve productivity, strengthen food security, reduce environmental contamination, and empower Indian farmers with climate resilient crop protection solutions. The integration of AI and precision agriculture will play a pivotal role in transforming Indian agriculture into a sustainable, technology driven, and globally competitive sector under the Viksit Bharat 2047 vision.

Keywords: Artificial Intelligence, Smart Pest Monitoring, Precision Agriculture, Integrated Pest Management, Remote Sensing, Viksit Bharat 2047

Introduction

Agriculture remains the backbone of the Indian economy, supporting the livelihoods of millions of farmers and contributing significantly to national food security. However, Indian agriculture is presently facing multiple challenges, including climate change, declining natural resources, labour scarcity, emerging invasive pests, pesticide resistance, and increasing crop losses due to insect pests and diseases. According to the Food and Agriculture Organization (FAO), insect pests alone are responsible for nearly 20-40% reduction in global crop yields annually (Rahman and Ravi, 2022). Under changing climatic conditions, pest outbreaks are becoming more frequent, unpredictable, and economically damaging.

Traditional pest management approaches mainly depend on manual scouting and indiscriminate pesticide application. Although chemical pesticides have contributed significantly to increased crop production, their excessive and unscientific use has created several ecological and health concerns such as pesticide resistance, resurgence of secondary pests, environmental contamination, destruction of natural enemies, and pesticide residues in food products (Naveed *et al.,* 2023). These concerns have created an urgent need for more sustainable, precise, and intelligent pest management systems.

In recent years, Artificial Intelligence (AI) and smart agricultural technologies have emerged as transformative tools in modern agriculture. AI refers to the ability of computer systems to perform tasks that normally require human intelligence, including learning, reasoning, prediction, and decision-making (Angermueller *et al.,* 2016). The integration of AI with machine learning (ML), deep learning, remote sensing, Internet of Things (IoT), robotics, and unmanned aerial vehicles (UAVs) is revolutionizing agricultural pest monitoring and crop protection systems (Aziz *et al.,* 2025). These technologies provide real time field surveillance, automated pest identification, predictive forecasting, and precision pesticide application, enabling farmers to take timely and informed pest management decisions.

Artificial Intelligence in Modern Agriculture

Artificial Intelligence has rapidly expanded its role in agriculture by enabling data-driven decision making and precision farming practices. AI systems analyse massive datasets collected through sensors, drones, satellite imagery, weather stations, and mobile applications to generate accurate recommendations for farmers (Rahman and Ravi, 2022). Machine learning algorithms can identify patterns in pest population dynamics, crop growth, climatic conditions, and disease occurrence, thereby helping farmers implement preventive management strategies.

The emergence of Agriculture 4.0 has further accelerated digital transformation in farming systems. Technologies such as IoT enabled smart sensors, cloud computing, AI-based advisory systems, and autonomous machinery are making agriculture more efficient and sustainable (Wolfert *et al.,* 2017). AI-powered agriculture can significantly improve resource-use efficiency, reduce production costs, and increase farm profitability.

India is also witnessing rapid growth in digital agriculture innovations through government-supported initiatives such as the Digital Agriculture Mission, National e-Governance Plan in Agriculture (NeGPA), AgriStack, and Kisan Drone programs. These initiatives aim to integrate digital technologies into farming systems and strengthen climate resilient agriculture under the Viksit Bharat framework.

Table 1. Major Smart Technologies Used in Pest Management

Technology	Major Application
Artificial Intelligence (AI)	Pest identification and prediction
Machine Learning	Pest outbreak forecasting
Remote Sensing	Crop stress and pest surveillance
Drones (UAVs)	Precision spraying and scouting
IoT Sensors	Real-time field monitoring
Smart Traps	Automated insect detection
Robotics	Precision pest control

Source: Compiled from Rahman and Ravi (2022), Aziz *et al,.* (2025), and Chakrabarty *et al., (*2026).

Smart Pest Monitoring and Early Detection Systems

Early detection of insect pests is one of the most important components of successful pest management. Conventional pest scouting methods are labour intensive, time consuming, and often inaccurate. AI-based smart pest monitoring systems provide automated, continuous, and highly accurate pest surveillance.

Computer vision technology combined with deep learning models such as YOLO, Faster R-CNN, and Convolutional Neural Networks (CNNs) can automatically identify insect pests from digital images with very high accuracy (Chakrabarty *et al.,* 2026). Smart insect traps integrated with cameras, sensors, and AI software can capture insect images, classify pest species, and transmit real time information to farmers through mobile applications (Passias *et al.,* 2024). Recent studies have demonstrated pest identification accuracies exceeding 90-97% under controlled conditions using AI-based image recognition systems (Buschbacher *et al.,* 2020). Smart pest monitoring systems are now being developed for important agricultural pests such as fall armyworm, brown planthopper, whiteflies, fruit flies, and stem borers.

AI-driven monitoring systems are particularly useful in rice, cotton, maize, sugarcane, and horticultural crops where pest outbreaks can rapidly spread across large areas. Real time pest alerts enable farmers to take timely control measures before economic damage occurs.

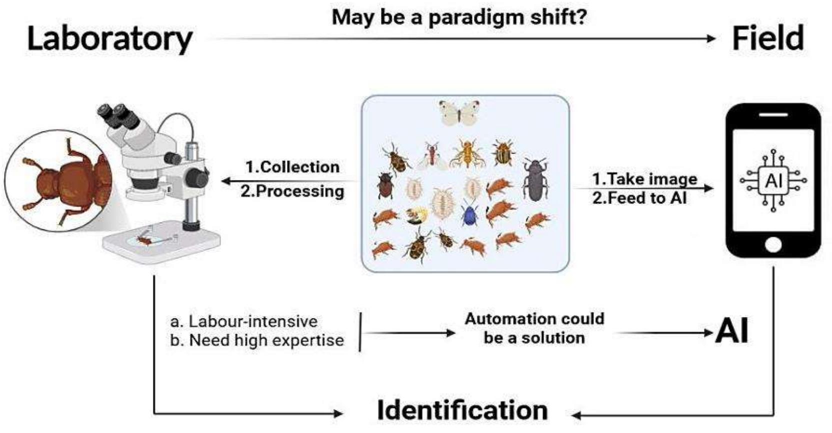

Figure 1. AI-based smart pest monitoring system for automated insect detection and real-time crop surveillance. Source: Adapted from Chakrabarty *et al.,* (2025)

Role of Remote Sensing and Drones in Pest Management

Remote sensing technologies have revolutionized crop monitoring and pest surveillance. Satellite imagery, multispectral sensors, hyperspectral imaging, and drone based remote sensing systems can detect subtle changes in crop health associated with pest infestations (Aziz *et al.,* 2025). Vegetation indices such as the Normalized Difference Vegetation Index (NDVI) help identify crop stress caused by insect feeding.

Drones or Unmanned Aerial Vehicles (UAVs) are increasingly being used for field scouting, pest mapping, crop health monitoring, and precision pesticide spraying. UAVs equipped with thermal cameras and multispectral sensors can quickly scan large agricultural fields and identify pest hotspots with high precision. This technology reduces scouting time and improves pest detection efficiency. Drone based pesticide application has gained significant attention in India because of its ability to reduce labour dependency and optimize pesticide use. Precision spraying through drones ensures uniform droplet distribution and minimizes pesticide drift and environmental contamination (Faiçal *et al.,* 2017). UAV spraying is particularly useful in rice ecosystems, cotton fields, orchards, tea plantations, and inaccessible terrains.

The Government of India has actively promoted drone adoption through the Drone Rules 2021 and subsidy programs under the Sub-Mission on Agricultural Mechanization (SMAM) (Sidharth *et al.,* 2023). Initiatives like the "Namo Drone Didi" scheme are empowering rural women and Farmer Producer Organizations (FPOs) to adopt drone technologies for sustainable agriculture (Kalita *et al.,* 2025).

AI-Based Predictive Analytics and Decision Support Systems

One of the most promising applications of AI in agriculture is predictive pest forecasting. AI algorithms analyse weather parameters, crop stage, humidity, temperature, rainfall, and historical pest incidence data to predict future pest outbreaks (Ibrahim *et al.,* 2022). Such predictive systems help farmers implement preventive control measures rather than reactive pesticide applications.

Machine learning models such as Support Vector Machines (SVM), Random Forest (RF), Deep Belief Networks (DBN), and Long Short-Term Memory (LSTM) networks are increasingly being used for pest population prediction and disease forecasting (Vishnu *et al.,* 2025). These systems support decision making by recommending the appropriate timing, dosage, and method of pest management. AI-enabled mobile applications are also becoming popular among farmers. Platforms such as Plantix, Cotton Ace, and AI-based crop advisory tools help farmers diagnose pest problems through smartphone images and receive instant management recommendations (Rahman and Ravi, 2022). Such digital advisory systems are highly valuable for smallholder farmers who lack access to agricultural experts.

Smart Technologies and Integrated Pest Management (IPM)

Integrated Pest Management (IPM) focuses on sustainable pest suppression using a combination of cultural, biological, mechanical, and chemical methods. AI and smart technologies are strengthening IPM by improving precision, monitoring efficiency, and decision-making capacity (Demirel and Kumral, 2021).

AI-based systems can monitor pest thresholds and recommend pesticide application only when economic threshold levels are reached (Rustia *et al.,* 2022). This reduces unnecessary pesticide use and conserves beneficial organisms such as pollinators and natural enemies. Smart pest management systems also support biological control programs by monitoring pest natural enemy interactions and ecological dynamics (Javed *et al.,* 2025). IoT-enabled smart sensors can continuously monitor field conditions including humidity, temperature, soil moisture, and crop canopy status. Such data driven systems allow farmers to adopt climate-smart pest management strategies. Precision IPM approaches can significantly reduce environmental pollution, pesticide residues, and production costs while improving sustainability.

Role of Robotics and Automation in Crop Protection

Agricultural robotics is another emerging frontier in smart pest management. Autonomous robots equipped with cameras, sensors, and AI systems can detect pest infestations and apply localized pesticide treatments (Fue *et al.,* 2020). These robotic systems minimize chemical usage and improve spraying accuracy. Advanced robotic technologies are also being explored for greenhouse pest management, weed control, and pollinator monitoring. AI-enabled robotic systems can operate continuously and reduce labour dependency in agricultural operations. In developed agricultural systems, autonomous robots are already being used for precision spraying and crop surveillance (Sharma and Shivandu, 2024).

Although large scale robotic adoption in Indian agriculture is still limited due to high costs and infrastructure challenges, rapid technological advancement and government support are expected to accelerate their future integration into farming systems.

AI, Sustainability, and Viksit Bharat 2047

The vision of Viksit Bharat 2047 aims to transform India into a developed, self-reliant, technologically advanced, and sustainable nation. Agriculture will play a central role in achieving this vision. AI and smart pest management technologies directly support several national goals including food security, environmental sustainability, digital agriculture, climate resilience, and farmer welfare (Govindaraj, 2026).

AI-driven pest management systems can significantly reduce pesticide misuse, conserve biodiversity, improve soil and water quality, and enhance farm profitability. Precision agriculture technologies support sustainable intensification by maximizing productivity with minimal environmental damage. These technologies also contribute to Sustainable Development Goals (SDGs), particularly SDG-2 (Zero Hunger), SDG-12 (Responsible Consumption and Production), and SDG-13 (Climate Action).

India’s growing startup ecosystem in agri-tech, expansion of rural internet connectivity, digital infrastructure development, and government policy support are creating a favourable environment for AI-driven agricultural transformation.

Table 2. Government Initiatives Supporting Digital Agriculture in India

Initiative	Objective
Digital Agriculture Mission	Promotion of digital farming
AgriStack	Digital farmer database and advisory
Drone Rules 2021	Simplified drone regulations
Namo Drone Didi	Drone empowerment for rural women
SMAM Scheme	Support for agricultural mechanization
Digital India Mission	Rural digital connectivity

Source: Government of India digital agriculture initiatives and Ministry of Agriculture reports.

Challenges in Adoption of AI Technologies

Despite tremendous potential, several challenges still limit the widespread adoption of AI and smart technologies in Indian agriculture. High initial investment costs, limited digital literacy among farmers, inadequate rural infrastructure, poor internet connectivity, and shortage of quality datasets remain major barriers. AI systems also require large, well-labelled datasets for accurate training and performance. Variability in crop ecosystems, insect morphology, environmental conditions, and field complexity can affect the reliability of AI models (Goodwin *et al.,* 2021). Small and marginal farmers may face difficulties in accessing expensive digital tools and advanced technologies.

To overcome these constraints, stronger collaboration among agricultural scientists, engineers, policymakers, startups, and extension agencies is essential. Capacity building programs, farmer training, affordable digital tools, and public-private partnerships will be critical for scaling AI adoption in Indian agriculture.

Conclusion

Artificial Intelligence and smart pest management technologies are rapidly transforming modern agriculture by making pest monitoring more accurate, timely, and sustainable. AI-driven systems including remote sensing, drones, smart traps, IoT sensors, robotics, and predictive analytics are strengthening Integrated Pest Management and reducing excessive dependence on chemical pesticides. These technologies offer enormous potential for improving crop productivity, environmental sustainability, and climate resilience in Indian agriculture. As India progresses towards the vision of Viksit Bharat 2047, the integration of AI into agricultural systems can play a transformative role in building a technologically advanced, sustainable, and globally competitive agricultural sector. Strengthening digital infrastructure, promoting farmer-centric innovations, and ensuring inclusive access to smart technologies will be essential for realizing the full potential of AI-driven agriculture in the coming decades.

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THE ROLE OF AGRICULTURAL UNIVERSITIES IN ADDRESSING THE UNO'S SUSTAINABLE DEVELOPMENT GOALS (SDGS)

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Introduction

In India, agricultural school education started initially at Saidapet of Chennai (Madras Presidency) in the year 1868, which later shifted to Coimbatore and became the Madras Agricultural College in 1906; similarly, other agricultural colleges were started in Pune (1907), Kanpur (1906), Sabour (1908) and Nagpur (1906) in different regions of country in the pre independence period for the Human Resource development purpose in Agriculture for scientific agricultural extension purpose. Similarly, the first veterinary school was established in 1862 at Babugarh (Uttar Pradesh), followed by the veterinary colleges at Bombay (1886), Calcutta (1893), Madras (1903), and Bihar (1904) to train veterinarians for civil and military services. Also, the Indian Agricultural Research Institute and Indian Veterinary Research Institute kind of premier research institutions also initiated research centric human resource development purposes. The colleges initially offered diploma and degree courses focused on crop cultivation, soil science, and animal husbandry, mainly under provincial governments.

Those days, agriculture sector was the major contributor of economy and food security. So, considering its importance and regulate the agricultural research activities; Imperial Council of Agricultural Research (ICAR) was initiated on 16 July 1929 under the Royal Commission on Agriculture (1926) recommendation then after Independence, the Council was renamed the Indian Council of Agricultural Research in 1947 and its scope was expanded to include education, research, and extension in all agricultural disciplines. At the same time, Agriculture is a state subject and so, considering the vast diversity of agro climatic regions; In 1949, Dr. S. Radhakrishnan, made several landmark recommendations for reforms in university education, with a strong focus on establishment of "Rural Universities" to promote rural reconstruction, agricultural development, and community service and directly influenced the creation of State Agricultural Universities (SAUs) based on the Land-Grant model of the United States during the 1960s. The first SAU, Govind Ballabh Pant University of Agriculture and Technology (GBPUAT), was established in Pantnagar, of Uttarpradesh in present days Uttarakhand in the year 1960; Gradually, the reorganized SAU system was established in many states under the State Agricultural Universities (SAUs).

Decentralized Agricultural University System in India

The reorganized ICAR Agricultural Education Division strengthened the agricultural education system of the country through providing technical, ensuring quality standard maintenance through standard operating procedures for transfer of technology and capacity building in agriculture from the years 1960s' to still date. Because of these efforts, country achieved food security and exporting the agricultural commodities to other countries. Hence, the present need of agricultural university has shifted in broader perspectives as compare to its vast agro ecological land area coverage and population settlement in rural areas and livelihoods. Also, one side the liberalization policy continues to lead innovation in agriculture, animal science, fisheries, and rural development and another side of sustainable development, environmental priorities, inclusiveness and farmer welfare also getting attention under the broader perspectives of Agricultural Universities role in addressing SDGs in India.

At present India have 74 agricultural universities under the National Agricultural Research and Education System. It includes 63 State Agricultural, 3 Central Agricultural Universities 4 Deemed Agricultural Universities and 4 Central Universities that have a faculty of Agriculture. It plays very important role in not only research, education, and extension; it addresses various goals of the United Nation Organization's Sustainable Development Goals. Agriculture is directly and indirectly contributing Fifteen out of seventeen Sustainable Development Goals.

The Agricultural universities' role in Green revolution and other advancements also highly appreciable for Self sustainable food grain production. At the same time in the present context; India, with its large agrarian base, faces multiple challenges: nutritional security, climate change, environmental degradation, uneven rural development, and livelihood insecurity. Hence, to address the system specific issues; the Agricultural Universities mission should be focussed towards the United Nations' Sustainable Development Goals (SDGs) which provide a global framework of (17 goals, 169 targets) to directly and indirectly address the agriculture-related (e.g. SDG 1 — No Poverty; SDG 2 — Zero Hunger; SDG 13 — Climate Action; SDG 15 — Life on Land) issues with better solutions. The agricultural universities work as a knowledge generator, education institution, innovation promotion, extension services, and other supports such as policy, science and farmers' perspective contributions. This article outlines the roles played by agricultural universities in advancing the SDGs, followed by the challenges they face, and how their potential can be better improvement.

UNO Sustainable Development Goals

The UN SDGs are a comprehensive sustainable development which was adopted by UNO in the year 2015 to give focus in the areas to achieve a sustainable, equitable, and prosperous world by 2030; it gives guidelines to various countries for policy-making, infrastructure development, inclusive development planning, natural resource conservation and management and social transformation perspectives. There are 17 SDGs with 169 associated targets and 232 indicators to measure progress. The major goals and its goal numbers mentioned below,

1. No Poverty
2. Zero Hunger
3. Good Health and Well-Being
4. Quality Education
5. Gender Equality
6. Clean Water and Sanitation
7. Affordable and Clean Energy
8. Decent Work and Economic Growth
9. Industry, Innovation, and Infrastructure
10. Reduced Inequality
11. Sustainable Cities and Communities
12. Responsible Consumption and Production
13. Climate Action
14. Life Below Water

15. Life on Land
16. Peace, Justice, and Strong Institutions
17. Partnerships for the Goals

It aims to create a sustainable development with balanced economic growth across the regions of the world with social inclusion, and environmental protection. It also encourages governments, organizations, and individuals to work together to address developmental issues most importantly poverty and inequality, climate issues and biodiversity loss.

Importance of Agricultural Universities in Addressing SDG's

The Agricultural Universities in India responsibilities are shifting over the sixty years' period of time from academic leadership for human resource development to inclusive sustainable development perspectives through implementation of various research and extension programs in broader perspectives. Also, it gives high priority for internationally recognized Academic responsibilities in connection to all seventeen Goals of UNO's Sustainable Development Goals. Also, the sustainable contribution of the institutions continues with merit to showcase their potential and social learning opportunities. The Agricultural universities' contributions to science and society through its valuable education, research and extension and outreach services are highly appreciable from all over the India and globe. Over the years, it is contributing well in the context of developing society. The farmers were adopted high technologies and enhanced their production. The Agricultural Universities are developing improved crop varieties (higher yield, pest/disease resistance) and climate-resilient varieties. It improves the productivity and incomes of smallholder farmers through extension services to address hunger and poverty.

S. No.	SDG	Contribution of Indian Agricultural Universities (AUs)
1.	No Poverty	Promote livelihood-oriented agriculture, skill development, agricultural-entrepreneurship, Farmer Producer Organizations (FPOs), and rural employment generation through extension programs.
2.	Zero Hunger	Develop high-yielding, climate-resilient crop varieties; improve productivity; support food and nutritional security through research and dissemination (key role since Green Revolution).

S. No.	SDG	Contribution of Indian Agricultural Universities (AUs)
3.	Good Health & Well-being	Research on bio fortified crops, safe food systems, nutrition-sensitive agriculture, and zoonotic disease control (veterinary sciences).
4.	Quality Education	Provide specialized higher education in agriculture, fisheries, veterinary, and allied sectors; modern curricula (AI, IoT, precision farming) under initiatives like NAHEP.
5.	Gender Equality	Increased female enrolment, women-centric programs (e.g., Home Science, gender-inclusive extension), and institutions like CIWA promoting women in agriculture.
6.	Clean Water & Sanitation	Develop water-efficient irrigation technologies (drip, sprinkler), watershed management, and water quality research.
7.	Affordable & Clean Energy	Promote renewable energy in agriculture (solar pumps, biomass energy, biofuels) and energy-efficient farm machinery.
8.	Decent Work & Economic Growth	Foster agri-startups, agribusiness incubation, skill-based education, and industry linkages for employment generation.
9.	Industry, Innovation & Infrastructure	Develop agri-technologies (precision farming, drones, AI tools), strengthen agri-infrastructure, and promote innovation ecosystems.
10.	Reduced Inequality	Outreach programs for smallholders, tribal farmers, and marginalized communities via Krishi Vigyan Kendras (KVKs) and extension services.
11.	Sustainable Cities & Communities	Promote urban agriculture, peri-urban farming, waste recycling, and sustainable food systems for cities.
12.	Responsible Consumption & Production	Work on post-harvest management, food processing, value addition, and reduction of food losses.
13.	Climate Action	Develop climate-resilient agriculture practices, carbon sequestration, climate-smart agriculture, and adaptation strategies.
14.	Life Below Water	Fisheries universities and institutes promote sustainable aquaculture, marine biodiversity conservation, and blue economy.
15.	Life on Land	Research on soil health, biodiversity conservation, agroforestry, and sustainable land management practices.
16.	Peace, Justice & Strong Institutions	Strengthen institutional governance, policy research, and transparent agricultural systems supporting food security and stability.
17.	Partnerships for the Goals	Collaborate with international bodies (e.g., FAO, World Bank), industry, and government through projects like NAHEP and global knowledge platform

Agricultural Universities’ Human Resource Development

Agricultural universities provide formal higher education as well as short-course/training programs. They have been modernizing curricula (e.g. introducing climate change, sustainability, digital agriculture). Projects like the National Agricultural Higher Education Project (NAHEP) have enhanced quality and relevance of teaching process. Thus, maintaining a **high-quality teaching and**

training environment within higher education institutions is fundamental to their sustainable success and long-term institutional excellence. It ensures quality teaching and supports a long-term, impact-oriented human resource development process—both for contributing to globally competitive job markets and for fostering a new generation of critical thinkers. It is also possible by development of Human Resource through Graduate and Post-Graduation programmes in agriculture and allied sciences in a decentralized manner in across the country. The University led training institutes and research institutions, agricultural start-up incubators support to students and farmers through Skill development, vocational training, and entrepreneurship programmes. The agricultural university also reducing inequalities through Inclusive education opportunities for rural youth, women, farmers and marginalized sections of the mainstreams. Also, various other public and private sector human resource development programs also supports in the process. The academic infrastructure such as class rooms, laboratories, libraries, Information and Communication Technology infrastructures, field observation based research fields, playgrounds, hostel facilities, accessible various remote locations, connection with National and international institutions support to enrich the quality of education with extracurricular activities in a sustainable basis. Though, as a developing society; we face lot of financial issues in both public and private sectors to build the appropriate infrastructures to the institutions, effective utilization and its impact to the society. Hence, it addresses the UNO's SDG Goal numbers of 4 Quality Education, 5 Gender Equality, 8 Decent Work and Economic Growth, 9 Industry, Innovation, and Infrastructure and 10 Reduced Inequality.

Need based Research & Innovation for Sustainable Agriculture

The agricultural universities play very important role in promotion of precision farming technologies, resource use efficient Integrated Farming System, natural farming, resource –efficient and climate resilient technologies, adoption of climate stress tolerant varieties and animal breeds and organic agriculture for sustainable Agriculture. These activities also play very important role to provide an evidence based policy suggestions to implement various sustainable development oriented missions and programs to strengthen sustainable agriculture and rural livelihoods. Hence, it addresses the UNO's SDG Goals numbers of 2 Zero Hunger through sustainable food production for addressing the food and nutrition security issues, Goal number 9 to provide inputs to Industry and Infrastructure. It also provides Decent Work and Economic Growth in connection with Goal number 12 and the goal number 13 of Climate Action and finally it addresses the goal number 15 of Life on Land through the natural resources conservation and management process.

Frontline Agricultural Extension & Outreach activities

Several globally recognized and highly ranked universities are performing well in **extension and outreach activities.** In recent years, many universities aligned with the **UN Sustainable Development Goals (SDGs)** have also grown significantly across the world. Particularly in developing economies, the role of **"lab-to-land" technology diffusion and adoption** is crucial in narrowing development gaps and supporting sustainable growth. The Government of India has implemented initiatives such as **"My village, My pride (*Mera Gaon Mera Gaurav)*"** and various **entrepreneurship incubation programmes** in collaboration with leading academic institutions to ensure meaningful impact at the grassroots level. Many universities are actively contributing to these efforts and demonstrating strong performance in this domain.

Also, the Agricultural Universities in India operates Farm Science centre's popularly called as a *Krishi Vigyan Kendras (KVKs)* plays very important role in transfer of Universities' technologies in to the farmers' field. The directorates of extensions also provide various training programmes to farmers such as promotion of commercial agricultural activities, nutrition gardens, crop diversification, etc. for food and nutrition security. It also facilitates capacity building programs to Gender-sensitive women farmers' training program, Self Help Group based capacity building activities and drudgery reduction activities. It also provides research and policy guidelines for promotion of Farmer Producer Organizations, effective market linkage based effective models and value-chain development process. Hence, it addresses the UNO's SDG Goal numbers of 1 through poverty reduction and reduces the hunger issues which was mentioned in the goal number 2. It also supports good health and well-being, Gender Equality, supports Responsible Consumption and Production. It also connects partnerships with various other sustainable Goals. Agricultural Universities also help in training women farmers, promoting gender-sensitive agricultural technologies, supporting women's participation in extension and leadership roles. All together it addresses the following SDG numbers of 1, 2, 3, 5, 12 and 17.

Natural Resource Management activities

The agricultural activities mostly concerned with the effective utilization of natural resources; most importantly the soil and water conservation is very important and the agricultural universities research, front line extension and academic programs such as workshop and conferences provide lot of regulatory mechanism to the development stakeholders. The studies on soil & water conservation, effective watershed management, micro-irrigation, based activities impact in the society. Also the studies on circular economy based climate-resilient agricultural practices, carbon sequestration, and agroforestry models also support the effectively utilize the natural resources. The marine biodiversity and coastal conservation, sustainable fisheries for livelihood to fishermen also mostly depends of fisheries research and academic institutions across the coastal regions. These activities directly address the UNO's SDGs of water conservation, climate resilience and sustainable livelihood on life on land. Hence, these Natural Resource Management activities addresses the SDGs of 6, 13, 14 and 15.

Agricultural Universities responsibilities in Policy Formulation Support & sustainable Governance

Agriculture is the backbone of economy and around 50% of people of the country still depends on agriculture. The rural development and other activities mostly depends on agricultural sector only. Also, the recent emergence of data science has given plat form to form a need based policies for formulation of the development programs. So, the Agricultural universities role in policy formulation with evidence based data bases and the impact studies of the public sector based scheme assessments support to various development stakeholders such as extension organizations, NGOs and private sectors. It also acts as a knowledge hub for agriculture and sustainable development centric policy formulations. The higher learning institutions are contributing in quality research with high impact publication, parents and transfer of the laboratory findings in to the real world practical requirements. The unbiased research problem selection to find out the solution with available educational infrastructures and financial support is really very tough task as compare to the developed countries' works. But, even though finding good opportunities to find out the real need based problem to get solutions with available resources with the support of innovative research methods may plays very important role for better research findings and its outscaleing the technology adoption process for sustainable development of the country and global recognition. Here, the dedicated researchers and scholars' role plays very important role. So, the institution which one is doing good research may rule the academics in any competitive institution development process. The DST, DBT, ICAR and Ministry of science and development, various foreign institution collaboration, students exchange programs, resources sharing opportunities also support well for effective research led science for better social contributions. Hence, it can strengthen the effectiveness of various agriculture and allied Institutions to build partnerships with various stakeholders for addressing the UNO's Sustainable development goals.

Role of Agricultural Universities in promotion of Nutrition security, health and community wellbeing of the country

The agricultural universities played very important role in food security of the developing economics; most importantly the world highest populated country; Now, issues have raised in balance diet and nutrition security specific health issues. The agricultural universities are addressing the issues through nutri- rich fortified crops for addressing the malnutrition issues. The agriculture-nutrition intensive community models such as agri-nutri village, community kitchen garden and other nutrition sensitive extension initiatives enhancing awareness and capacities to effectively integrates Agriculture -nutrition - health to address the UNO's SDG's of hunger reduction for good health and well-being. It also majorly benefits the women for their nutrition enhancement and address the SDG of 16 and 17.

Agricultural Universities for promotion of Agricultural Entrepreneurship and Start-up Ecosystem

Technology is changing in major science and technology disciplines in India. Particularly, after liberalization, lot of changes happened in innovative technology development, information and communication Technologies adoption process. It requires appropriate human resources through providing appropriate capacity building programs and need based technology tie-ups with the existing human resources. The agricultural Universities plays very important role in agribusiness and start-ups promotion through establishment of Agri-incubation centres, Agri-business management initiatives and Technology Business Incubators (TBIs) and other technology enabled activities to the need can support the sustainable management of the institutions with global standards. It addresses the UNO's SDGs of 8, 9 and 1 for promotion of innovation oriented industry connection, support to economic growth and development process.

Clean Energy Affordability and Sustainable Cities

Indian Agricultural Universities contribute to both clean energy transitions and sustainable community development by promoting resource-efficient, climate-smart agricultural systems. They advance renewable energy solutions such as solar-powered irrigation, biogas, and biomass-based energy, while also improving energy efficiency in farm operations and agro-processing. At the same time, they support sustainable urban and peri-urban agriculture through innovations like rooftop gardening, vertical farming, and protected cultivation, enhancing local food security in cities. Their work on waste recycling, composting, and circular bioeconomy approaches helps convert urban organic waste into valuable inputs, reducing environmental pollution. Through research, education, and extension services, these universities strengthen resilient food systems, sustainable infrastructure, and low-carbon rural–urban linkages, contributing holistically to both SDG 7 and SDG 11.

Challenges Facing Agricultural Universities

Despite their potential and some notable progress, agricultural universities in India face several bottlenecks in more fully contributing to SDGs:

1. The infrastructure plays very important role in the high quality institution building process. Many SAUs have outdated labs, insufficient funding, lack of modern equipment, limited digital infrastructure. This limit research, teaching and outreach.

2. The Agricultural University curricula in some universities are still not fully aligned with emerging challenges (climate-smart agriculture, precision farming, sustainability, ICT, agri-business).
3. The Agricultural University's recruitment process is slow, there is non-replacement of retiring faculty and insufficient incentives for the activities
4. There is **limited agricultural extension and farmer outreach capacity** within the Krishi Vigyan Kendras (KVKs), coupled with a **lack of effective integration between research institutions/universities and farmers or field-level agencies**. This gap weakens the flow of knowledge, technologies, and field-level feedback, thereby affecting the overall efficiency of agricultural development programmes.
5. Funding / Financial Constraints: The education institutions are not a business corporate. It is majorly giving non profitable services to the society and its impact also Measurable in long-term perspectives only. So, mobilizing adequate financial facilities form funding partners are very essential to the successful management of the institutions. Because, more than 50% of the less recognized universities and academic institutions are facing huge financial crisis to provide a quality services to produce a quality human resources, innovation and science led research and extension Service for impacting the society. Hence, mobilizing appropriate, appreciable finance may be the appropriate sustainable management solution to upscale the institutions to address the upcoming social needs centric development process.
6. Agriculture is often seen as less prestigious, less lucrative. Students may prefer other disciplines. This reduces intake and innovation in the sector.

Conclusion

Agricultural universities in India plays very important role to address the SDGs through Human resource development, need based Research & Innovation development process**,** Frontline Agricultural Extension & Outreach activities, Natural Resource Management activities, responsibilities in Policy Formulation Support & sustainable Governance, promotion of Nutrition security, health and community wellbeing of the country, promotion of Agricultural Entrepreneurship and Start-up ecosystems. Also to maximize the agricultural universities potential requires sustained investment, institutional reforms, and stronger linkages between academia, government, industry, civil society, and farming communities and to address the SDGs in India

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FARM MANURE AS AN EMERGING RESERVOIR OF ANTIBIOTIC RESISTANCE: THREAT TO SUSTAINABLE AGRICULTURE AND FOOD SAFETY

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Abstract

Antimicrobial resistance (AMR) is an increasing international issue that impacts agriculture, the ecosystem, and human health. In agriculture, the accumulation of antibiotic resistance is rapidly growing because of overuse of antibiotics in animals, which results in the overpopulation of antibiotic-resistant bacteria and resistance genes within the agricultural environment, which is known as the antibiotic resistome. Farm manure is a significant distributor, and it aids in spreading resistance via soil and crops. This interferes with soil microbial equilibrium, lowers productivity and brings about resistant pathogens into the food chain. The solution to solving this problem lies in prudent use of antibiotics, treatment of manure and sustainable agricultural practices in a co-ordinated, One Health strategy.

Introduction

Antimicrobial resistance (AMR) is nowadays considered one of the gravest health issues in the world. It causes almost 700, 000 deaths each year across the world and this figure may increase to 10 million by 2050 unless it is checked. The widespread use of antibiotics in the production of livestock in agriculture has also played a role in this crisis. One of the largest consumers of antibiotics in animal production is India, and this trend is likely to continue in the next few years.The overall collection of antibiotic resistance-genes and resistant microorganisms in an environment is referred to as antibiotic resistome. Although resistance occurs naturally, it has increased with the growth of human activities, particularly the overuse of antibiotics. Farm manure has become a significant reservoir, it is a linkage between livestock, soil, crops, and finally humans.

Resistance to Spread

Antibiotics are also extensively used in livestock as a treatment, disease prevention, and growth promotion. A huge percentage of these antibiotics are released as unmetabolized and in combination with the resistant bacteria.

In applying manure to farmlands, it introduces:

- Antibiotic residues
- Antibiotic resistant bacteria
- Antibiotic resistance genes (ARGs): The resistance genes to antibiotics in bacteria are called antibiotic resistance genes (ARGs).

Horizontal gene transfer (HGT) also promotes the spread of resistance, in which bacteria exchange genetic material through:

- Conjugation - by cell-to-cell contact.
- Change - acquisition of free DNA in the environment.

- Transduction - through bacteriophages (viruses)

Impact on Agricultural Systems

The build-up of the resistome in agricultural soils has dire consequences:

1. **Soil Health Degradation**
   Nutrient cycling, soil fertility and beneficial microbes are disturbed, causing soil health to be impaired in the long term.
2. **Reduced Crop Productivity**
   Distorted interactions between plants and microbes undermine the nutrition and resistance to diseases in plants, which ultimately impact yield**.**
3. **Food Safety Risks**
   The food chain can be impacted by crops cultivated in polluted soils that contain antibiotic resistant bacteria which can be harmful to humans.

Examples of Antibiotic Resistome in Agriculture

In agriculture, the antibiotic resistome is a well-known feature in farm manure and soil systems that harbours a number of resistant bacteria and genes. An example is *Escherichia coli* present in cattle manure which is frequently harbouring resistance genes, such as blaTEM and tetA that confer resistance to commonly used antibiotics. Likewise, *Enterococcus faecalis* in poultry waste might harbour genes like *vanA* and *ermB* which result in resistance to some of the key medications like vancomycin. Others are *Salmonella* species in pig manure that have *sul1* and *aadA* genes, *Staphylococcus aureus* in dairy farms with *mecA* gene that causes high-level resistance to antibiotics and *Klebsiella pneumoniae* with *blaNDM* and *blaCTX-M* genes, which are linked to high-level resistance to antibiotics. These illustrations underscore the role of agricultural practices in the perpetuation and dissemination of clinically important resistance characteristics (Table1).

Table 1: Common antibiotic-resistant bacteria and genes present in farm manure

Bacteria	**Resistance Genes**	**Source**	**Implication**
Escherichia coli	*blaTEM, tetA*	Cattle manure	Antibiotic-resistant infections
Enterococcus faecalis	*vanA, ermB*	Poultry litter	Vancomycin resistance
Salmonella spp.	*sul1, aadA*	Pig manure	Foodborne illness
Staphylococcus aureus	*mecA*	Dairy farms	Methicillin-resistant *Staphylococcus aureus* (MRSA infections)
Pseudomonas aeruginosa	*mex genes*	Soil/manure mix	Multi-drug resistance
Klebsiella pneumoniae	*blaNDM, blaCTX-M*	Mixed livestock waste	Carbapenem resistance

Management and Control Strategies.

To deal with the resistome, combined strategies are needed:

- Prudent use of antibiotics when under the supervision of veterinarian
- Treatment of manure (composting, anaerobic digestion, biochar application)
- Environmentally friendly (crop rotation, organic inputs) farming practices.
- Frequent surveillance with molecular tools

- Education on responsible practices to farmers

Ongoing surveillance and observation of resistance genes using the latest molecular technologies are also important in the understanding and management of the issue (Fig.1).

Fig.1: Graphical illustration of the spread of antibiotic resistome to the soil environment via farm manure, other soil bacteria and the anticipated solution.

Future Perspectives

Future plans need to be directed to:

- Creation of alternatives including probiotics and vegetarian antimicrobials.
- Genomic surveillance of resistance genes.
- Enhancing policies to control the use of antibiotics.

Promoting a One Health approach that incorporates the health of humans, animals, and the environment.

Conclusion

The antibiotic resistome of farm manure is an insidious yet pernicious risk to agriculture, environmental sustainability and human health. It facilitates transfer of resistance among soil, crops and food systems. To prevent future food security and ecosystem health, a proactive strategy of responsible use of antibiotics, better waste management, and sustainable farming is necessary.

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DIGITAL DIVIDE IN INDIAN AGRICULTURE: CHALLENGES AND PATHWAYS FOR INCLUSIVE GROWTH

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Abstract

Digital technologies are increasingly reshaping Indian agriculture through mobile applications, online marketplaces, artificial intelligence-based advisories, digital payments, and weather forecasting systems. These innovations have the potential to improve productivity, strengthen market participation, and enhance farmers' livelihoods. However, the benefits of digital agriculture remain unevenly distributed, particularly among small and marginal farmers in rural India. Poor internet connectivity, weak digital infrastructure, irregular electricity supply, and limited access to smartphones continue to hinder effective digital participation. The digital divide is further intensified by low literacy levels, lack of technical awareness, economic constraints, and language barriers, as many digital platforms are not designed for rural users. Women farmers face additional challenges due to restricted access to technology, financial limitations, and inadequate training opportunities. Consequently, many farmers remain excluded from timely agricultural information and government services. Bridging this divide requires affordable digital access, stronger rural infrastructure, localized platforms, farmer-oriented training, and inclusive policies to ensure equitable and sustainable agricultural development in India. As a consequence, a large number of farmers remain excluded from timely information related to weather forecasting, market prices, crop management, insurance services, and government welfare schemes. Bridging this divide requires a holistic and inclusive approach involving stronger rural digital infrastructure, affordable internet access, localized digital platforms, farmer-oriented training programs, and responsive extension support systems. Sustainable agricultural transformation in India depends not only on technological advancement but also on ensuring equitable digital participation for every farmer.

Keywords: Digital Divide, Indian Agriculture, Digital Literacy, ICT in Agriculture, Farmer Empowerment, Agricultural Extension

Introduction

The rapid expansion of digital technologies has introduced a new phase of transformation in Indian agriculture. Mobile-based advisory services, digital marketplaces, precision farming tools, artificial intelligence applications, and online financial platforms are increasingly influencing agricultural production and marketing systems. These technologies promise better decision-making, improved efficiency, and enhanced income opportunities for farmers. Yet, the reach of digital agriculture remains highly unequal.

A substantial proportion of India's farming population, particularly small and marginal farmers, continues to face difficulties in accessing and utilizing digital technologies effectively. This inequality is commonly described as the "digital divide," which refers not merely to the absence of internet access but also to disparities in affordability, digital literacy, infrastructure, awareness, and technological confidence. Rural India continues to lag significantly behind urban regions in digital penetration, creating structural disadvantages for agricultural communities.

For smallholders, the digital divide compounds existing vulnerabilities such as fragmented landholdings, unstable income, dependence on traditional farming practices, and limited institutional support. Farmers who cannot access digital information often remain dependent on middlemen for market intelligence and advisory services, reducing their bargaining power and economic resilience. Moreover, the digital transition in agriculture has revealed strong educational and generational disparities. Younger and better-educated farmers adapt more easily to digital platforms, whereas elderly and less-educated farmers frequently struggle with technological adoption.

The issue also possesses a significant gender dimension. Women farmers contribute extensively to agricultural labour and household food security, yet they remain digitally marginalized due to restricted device ownership, social barriers, and limited participation in training programs. Consequently, the benefits of digital agriculture often bypass a large section of rural women.

In this context, understanding the nature and consequences of the digital divide is essential for developing inclusive agricultural policies. Bridging this gap is not simply a technological necessity but a social and economic imperative for ensuring equitable rural development.

Digital Divide in Indian Agriculture

The digital divide in agriculture reflects unequal access to information and communication technologies among farming communities. In India, this divide is closely associated with income inequality, educational disparities, regional imbalance, and social exclusion. Since agriculture remains the primary livelihood source for millions of rural households, unequal access to digital resources directly affects productivity, market participation, and livelihood security. Following are some key components of digital divide in Indian agriculture.

1. Digital Exclusion Among Small Farmers

Small and marginal farmers constitute the majority of India's agricultural population. Their limited financial capacity, low educational attainment, and dependence on uncertain agricultural income make digital adoption particularly difficult. Farmers without digital access often experience delayed information regarding weather conditions, crop diseases, market prices, and government support schemes.

This exclusion reinforces rural inequality. Farmers with digital connectivity gain access to real-time information and broader market opportunities, while digitally excluded farmers remain dependent on conventional networks that are often slower, less reliable, and exploitative.

Importantly, digital exclusion is not limited to the ownership of smartphones or internet availability. It also involves the ability to interpret digital information, trust online systems, navigate applications, and apply technological knowledge in practical farming situations. Many small farmers remain disconnected from agricultural advisories, e-commerce platforms, digital banking systems, and government portals because multiple barriers operate simultaneously.

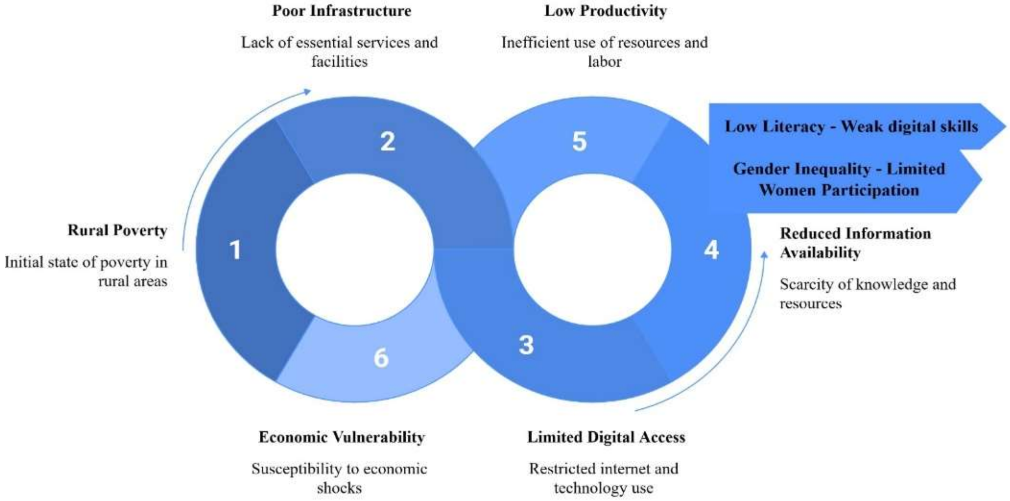

Figure1: Components of the Digital Divide in Indian Agriculture

2. Infrastructural Constraints

Weak rural infrastructure remains one of the most critical barriers to digital agriculture. Many villages continue to experience unstable electricity supply, poor mobile network coverage, and inadequate internet speed. Even where connectivity exists, interruptions and low bandwidth limit the effective use of mobile applications and online advisory systems.

The infrastructural divide is particularly visible in remote regions where technological investments remain insufficient. Consequently, farmers located near urban centres benefit more from digital innovations than those living in isolated rural areas, thereby widening regional disparities within agriculture.

3. Economic Barriers and Affordability

The affordability of digital technologies significantly influences adoption patterns among farmers. For economically vulnerable households, purchasing smartphones, maintaining internet subscriptions, and repairing devices represent additional financial burdens. Farmers often prioritize essential agricultural inputs such as seeds, fertilizers, and irrigation over technological expenditure.

As a result, many households share a single device among several family members, limiting regular and independent access to digital services. Irregular usage reduces familiarity and confidence, ultimately weakening the effectiveness of digital agricultural interventions.

4. Digital Literacy and Awareness Gap

Digital literacy is fundamental for meaningful technological participation. A considerable number of farmers remain unaware of available digital platforms or lack the skills necessary to use them efficiently. Many depend on younger family members or local intermediaries to operate mobile applications and online services.

Low educational attainment further restricts digital confidence. Farmers frequently perceive digital technologies as complex, unreliable, or inaccessible. Without adequate awareness and practical exposure, the adoption of digital agriculture remains superficial and unsustainable.

5. Gender Dimension of the Digital Divide

The digital divide is particularly severe among women farmers. Although women play a substantial role in agricultural production, their access to technology remains disproportionately low. Social norms, restricted ownership of mobile devices, financial dependence, and limited participation in training programs collectively reduce women's digital inclusion.

This exclusion affects not only women's access to agricultural information but also household welfare and farm productivity. When women are excluded from digital systems, families lose opportunities related to market information, financial services, and climate-related advisories.

6. Importance of Digital Training

Digital training has emerged as a crucial strategy for reducing technological exclusion in agriculture. Farmer-oriented training programs enhance confidence, improve awareness, and encourage practical application of digital tools. Training enables farmers to access weather forecasts, market prices, crop management advisories, and online government services more effectively.

However, one-time training programs often produce limited long-term impact. Continuous learning, practical demonstrations, and localized support systems are necessary for sustained digital engagement.

7. Institutional and Community Support

Agricultural extension agencies, rural institutions, self-help groups, and community organizations play a decisive role in strengthening digital inclusion. Farmers are more likely to adopt digital technologies when local support systems are available to guide and assist them.

Community-based digital centres, trained rural youth, and farmer groups can function as local facilitators, reducing fear and uncertainty associated with technology use. Human support remains essential because technological adoption in rural areas is deeply influenced by trust, social interaction, and collective learning.

MAJOR CHALLENGES FACED BY SMALL FARMERS

The digital divide creates several practical and economic difficulties for small farmers, including:

- Limited access to timely agricultural information
- Dependence on intermediaries for market intelligence
- Reduced participation in online marketplaces
- Inability to utilize digital advisory services effectively
- Exclusion from government schemes and digital financial systems
- Lack of confidence in technology-driven platforms
- Gender-based inequality in access to information and resources

Collectively, these challenges reduce farmers' capacity for informed decision-making and sustainable agricultural growth.

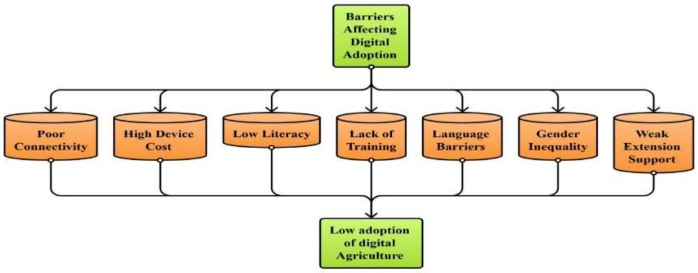

Figure 2: Barriers Affecting Digital Adoption Among Farmers

STRATEGIES FOR BRIDGING THE DIGITAL DIVIDE

Bridging the digital divide requires a comprehensive and farmer-centred approach that addresses both technological and social inequalities.

1) **Government Policies:** Government policies play a crucial role in promoting digital agriculture by investing in rural connectivity, supporting innovation, and creating schemes that encourage farmers to adopt digital technologies. Strong policy frameworks can help ensure that technological benefits reach even remote farming communities.
2) **Strengthening Rural Infrastructure:** Reliable electricity, high-speed internet connectivity, and stable mobile networks must be prioritized in rural development policies. Digital agriculture cannot succeed without strong infrastructural foundations.
3) **Ensuring Affordable Digital Access:** Subsidized smartphones, affordable data plans, and community digital centres can reduce financial barriers for small farmers and encourage regular technology use.

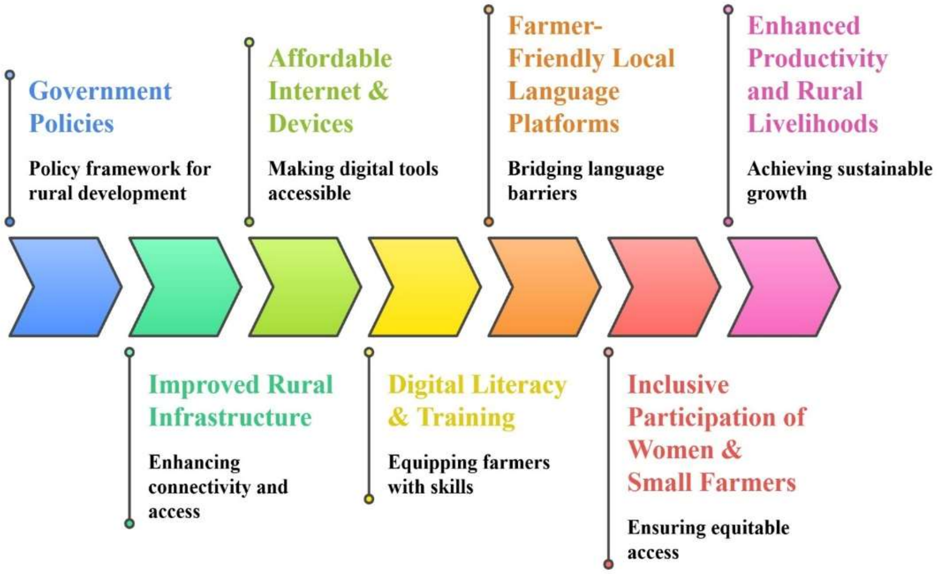

Figure 3: Strategies for Bridging the Digital Divide

4) **Promoting Practical Digital Literacy:** Training programs should focus on practical applications rather than technical complexity. Demonstration-based learning in local languages can significantly improve confidence and participation.
5) **Developing Localized Digital Platforms:** Farmer-friendly applications with regional language support, voice-based interfaces, and simplified navigation systems are essential for improving usability among rural populations and encourages community-based support systems. Village-level digital resource centres and peer-learning groups can create collective support mechanisms that encourage sustained digital participation.
6) **Inclusive participation of women and small farmers:** Extension personnel should function as digital facilitators who guide farmers in using online platforms, accessing government schemes, and interpreting digital advisories. Special training initiatives and inclusive policies are needed to improve women's access to digital technologies and agricultural information systems.

7) **Enhanced productivity and livelihoods:** In the Indian context, where a large proportion of the population depends on agriculture, linking digital technologies directly with income generation and livelihood improvement is one of the most effective ways to reduce the digital divide. When farmers see technology as a tool for economic progress rather than an additional burden, adoption becomes more inclusive and sustainable.

Conclusion

The digital divide has emerged as a significant obstacle to inclusive agricultural development in India. While digital technologies possess immense potential to transform farming systems, their benefits remain unevenly distributed among rural communities, particularly small and marginal farmers. Weak infrastructure, affordability constraints, limited digital literacy, language barriers, and gender inequality collectively restrict meaningful participation in digital agriculture. Bridging this divide requires more than technological expansion; it demands a socially inclusive and farmer-oriented development framework. Investments in rural connectivity, affordable digital access, continuous training, localized platforms, and strengthened extension systems are essential for ensuring equitable agricultural transformation. Digital inclusion must be recognized not merely as a technological objective but as a pathway toward rural empowerment, livelihood security, and sustainable agricultural growth.

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TRANSFORMING BLUE GROWTH IN INDIA: ROADMAP TO VIKSIT BHARAT 2047

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Abstract

Aquaculture has emerged as one of the most rapidly expanding sectors in global food production, significantly contributing to food security, employment creation, and export revenues. In India, aquaculture plays a vital role in the vision of Viksit Bharat 2047, aiming to transform the nation into a developed economy. Nevertheless, challenges such as disease outbreaks, environmental degradation, and rising input costs impede sustainable growth. The prospects and obstacles related to the aquaculture growth in India, emphasizing technological innovations, sustainability, climate adaptability, and regulatory frameworks. This provides a comprehensive roadmap for achieving a robust and globally competitive aquaculture sector by 2047.

Keywords: Aquaculture, Blue Economy, Sustainability, Technology, Viksit Bharat 2047

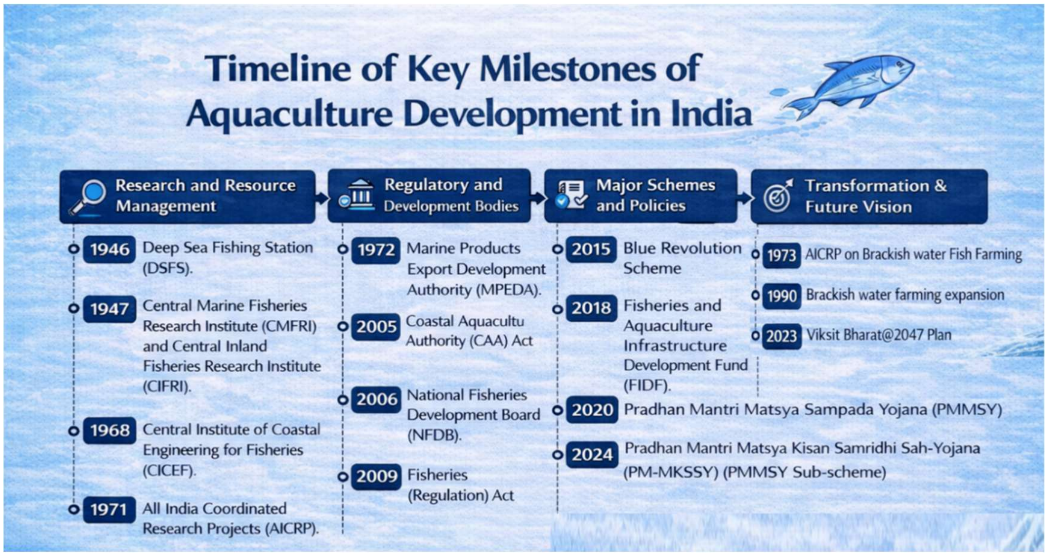
Introduction

Aquaculture in India has undergone a significant transformative journey transformation over the past eight decades evolving from a gradual transition from traditional capture fisheries to a scientifically managed and economically vital sector. This progression reflects the dynamic interplay of research, institutional growth, policy interventions, technological advancements, and substantial investments, which together have redefined the sector as key driver of food security, livelihoods, and national economic development.

Production Growth and Structural Transformation

India's aquaculture development can be divided into four key phases (Figure 1). The foundation phase (1946–1973) focused building a strong scientific and institutional framework. The establishment of pioneering institutions like the Deep-Sea Fishing Station (DSFS), Central Marine Fisheries Research Institute (CMFRI), and Central Inland Fisheries Research Institute (CIFRI) facilitated systematic resource assessment and the development of marine and inland fisheries. This period represented a significant transition from subsistence fishing practices to knowledge-driven management, supported by initial progress in coastal engineering and brackishwater research. The subsequent phase of expansion and specialization set the stage for commercialization which became evident during the expansion phase from 1990 to 2009. This period witnessed swift development in shrimp farming and significant expansion of brackishwater aquaculture. However, the intensification of production also brought about environmental and sustainability concerns, prompting the implementation of essential regulatory frameworks such as the Coastal Aquaculture Authority (CAA) Act (2005) and the Fisheries Regulation Act (2009). These initiatives ensured governance, resource conservation, and long-term sustainability of the sector. The current growth phase (2015–2024) of India’s fisheries sector is evident through ascendent production trends and global positioning (Figure 2) is marked by unprecedented policy support, increasing financial investments, and swift technological advancements. Key initiatives such as the Blue Revolution, the Fisheries and Aquaculture Infrastructure Development Fund (FIDF), and the Pradhan Mantri Matsya

Sampada Yojana (PMMSY) have facilitated infrastructure development, boosted productivity, and fostered sustainable aquaculture practices. In general, fisheries policy has transitioned from the production-centric Blue Revolution (2015) to a more sustainable, mission-oriented framework under PMMSY (2020), shifting its focus from merely increasing output to enhancing efficiency, resilience, and an integrated value chain development.



Timeline of Key Milestones of Aquaculture Development in India

Research and Resource Management

- **1946** Deep Sea Fishing Station (DSFS).
- **1947** Central Marine Fisheries Research Institute (CMFRI) and Central Inland Fisheries Research Institute (CIFRI).
- **1968** Central Institute of Coastal Engineering for Fisheries (CICEF).
- **1971** All India Coordinated Research Projects (AICRP).

Regulatory and Development Bodies

- **1972** Marine Products Export Development Authority (MPEDA).
- **2005** Coastal Aquacultu Authority (CAA) Act
- **2006** National Fisheries Development Board (NFDB).
- **2009** Fisheries (Regulation) Act

Major Schemes and Policies

- **2015** Blue Revolution Scheme
- **2018** Fisheries and Aquaculture Infrastructure Development Fund (FIDF).
- **2020** Pradhan Mantri Matsya Sampada Yojana (PMMSY)
- **2024** Pradhan Mantri Matsya Kisan Samridhi Sah-Yojana (PM-MKSSY) (PMMSY Sub-scheme)

Transformation & Future Vision

- **1973** AICRP on Brackish water Fish Farming
- **1990** Brackish water farming expansion
- **2023** Viksit Bharat@2047 Plan

Figure 1: Key Milestones of Aquaculture Development in India

Economic Contribution and Market Dynamics

India is the world's second-largest fish-producing nation, contributing nearly 8% of global production, and has emerged as a key player in the global fisheries sector. The, fish production has more than tripled from 5.66 MMT in 2000–01 to 19.77 MMT in in 2024–25, with inland aquaculture accounting for nearly 75% of total output. This reflects a clear structural shift toward aquaculture-led growth. India is the world's third-largest producer of whiteleg shrimp next to China and Ecuador. Shrimp production witnessed remarkable expansion, increasing, from 32,634 tons in 2000–2001 to over 1.16 million tons in 2023–24, reflecting significant gains in productivity and global competitiveness. In particular, *Penaeus vannamei* has driven this transformation, with production rising from 1,731 tons in 2009–10 to over 1.07 million tons in 2023–24, indicating rapid commercialization and technological adoption. The shrimp sector now forms the backbone of India's seafood exports, contributing nearly 70% of total export value. In FY 2023–24, India exported 1.78 million tons of seafood valued at US$ 7.38 billion (₹60,523.89 crore). Frozen shrimp dominated exports, accounting for 7,16,004 tons worth US$ 4.88 billion, specifically the cultivation of whiteleg shrimp, which serves as the primary driver of seafood exports as vannamei shrimp alone contributed 6,25,475 tons valued at US$ 4.25 billion. The sector has demonstrated consistent growth, with an average annual growth rate of 6.30% over the past five years and 7.58% year-on-year growth in recent periods. Fisheries play a vital role in India's agri-food economy, supporting 28 million livelihoods, contributing approximately ₹1,65,075 crore to Gross Value Added (GVA), accounting for 1.12% of total GVA and around 7% of agricultural GVA. Serves as fundamental support by providing subsistence, social security, and economic empowerment to over 30 million people reliant on aquaculture. The period represents sectoral transition toward technology-driven and export-oriented growth within India's expanding blue economy, characterized by rising productivity, strong value chain integration, and increasing global competitiveness forming a key pillar of India's evolving blue economy (Figure 2).

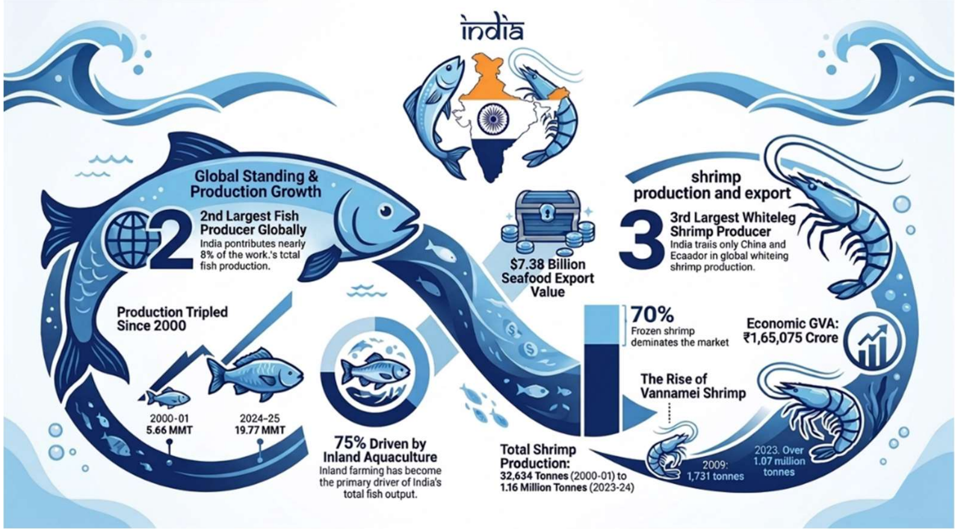


Figure 2: Current status of fisheries sector in India

Transitioning the Blue Revolution toward Sustainable Blue Growth

The Viksit Bharat 2047 vision intent to position the blue economy as a key engine of national prosperity by doubling farmers' incomes and enhancing global competitiveness. It envisages increasing fish production to over 40 million tons by 2047, boosting seafood exports to ₹1,00,000 crore, and creating around 55 lakh new employment opportunities within the sector. Beyond economic contributions, the sector is vital for food security, nutrition, and livelihoods, particularly in rural and coastal regions. Accordingly, under the Viksit Bharat 2047 vision, India's fisheries sector is transitioning toward a Blue Economy framework, emphasizing quality-driven, technology-enabled, and resource-efficient growth. In due course, it establishes fisheries sector as a high-value, globally competitive that fosters economic growth, food security, and environmental sustainability. This strategy prioritizes value addition, sustainability, innovation, biodiversity conservation and economic diversification, including inland aquaculture and emerging ocean-based sectors in addressing food security challenges, improving rural livelihoods. Hence addressing these issues through a balanced and strategic approach is crucial to fully realize the fisheries sector's potential as a key driver in achieving the vision of Viksit Bharat 2047.

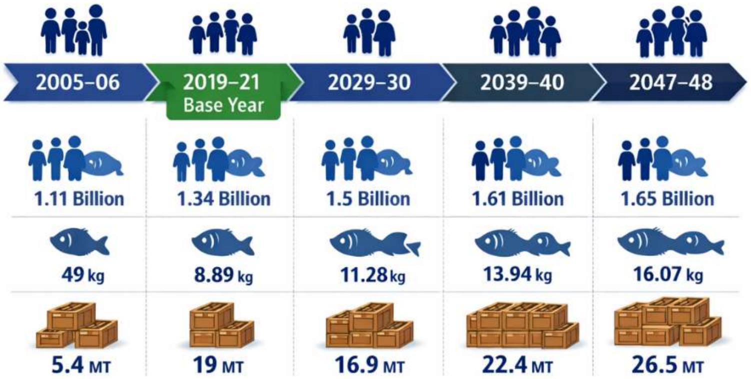


Figure 3 : Future fish consumption and demand in India

Assessing Opportunities Amidst Sectoral Constraints

Opportunities in Fisheries and Aquaculture sector

India's fisheries and aquaculture sector presents substantial scope for expansion, modernization, and value creation, driven by increasing demand, technological progress, and changing market dynamics. These factors collectively position the sector positioning the sector as a key pillar in achieving the vision of Viksit Bharat 2047.

Demand Expansion and Nutritional Security

India's aspiration toward Viksit Bharat 2047 is closely aligned with the need to build a sustainable and resilient food system capable of meeting the demands of a rapidly expanding population. India's per capita fish consumption, currently around 10 kg annually, is considerably lower than the global average of about 20.4 kg, underscoring a substantial untapped domestic market. This disparity in consumption, when viewed alongside rapid population growth, increasing urbanization, and rising income levels, suggests a fundamental shift towards a greater demand for affordable, protein-rich aquatic foods. Projections indicate that total fish demand may increase from approximately 13 million tons in 2022 to about 26.5 million tons by 2050, with per capita consumption expected to rise to 16.07 kg. At the same time, production is projected to reach nearly 51 million tons, highlighting the dual challenge of meeting domestic nutritional needs while sustaining export growth. These trends not only reflect changing dietary preferences but also emphasize the expanding role of fisheries in addressing nutritional security. As a result, the growing demand–supply gap necessitates a compelling need for scaling up production, strengthening supply chains, and strategically promoting fish as a vital component of a balanced and nutritious diet.

Technological Innovation and Digital Aquaculture

A major opportunity for advancing aquaculture within the Viksit Bharat framework lies in the integration of emerging digital and precision technologies, marking a clear shift from traditional, input-intensive practices to data-driven production systems. The implementation of Artificial Intelligence (AI), Internet of Things (IoT), and big data analytics is facilitating real-time monitoring and informed decision-making, which in turn boosts productivity and resource efficiency. Ongoing monitoring of essential water quality indicators—like dissolved oxygen, temperature, ammonia, and pH—via sensor-based systems enables early identification of stress conditions and disease threats, while machine learning tools facilitate predictive management and optimization of farming operations. Specifically, the introduction of automated and AI-driven feeding systems signifies a critical efficiency gain, given that feed accounts for nearly 60–70% of total production costs. By synchronizing feed input with animal behavior and environmental factors, these systems improve feed conversion ratios (FCR), reduce input wastage, and minimize environmental impacts. Moreover, digital platforms and mobile applications are revolutionizing farm management by allowing remote monitoring, access to real-time advisory services, market insights, and financial inclusion—an especially crucial advancement in the context of India's fragmented aquaculture systems dominated by smallholders.

Sustainable Intensification and Productivity Enhancement

Meeting the rising demand for aquatic food necessitates substantial gains in productivity, as traditional aquaculture systems—characterized by low stocking densities and minimal input use—are inadequate to achieve the targets envisioned under Viksit Bharat 2047. The adoption of intensive and super-intensive production models is essential to meet the ambitious targets of Viksit

Bharat 2047. In this context, the transition toward intensive and super-intensive production systems, such as biofloc technology and recirculating aquaculture systems (RAS)offer a strategic viable pathway for scaling up productivity while minimizing environmental impacts. Biofloc systems enhance efficiency by converting waste nutrients into microbial protein, thereby reducing feed costs and improving water quality, while RAS enables near-complete water reuse through advanced filtration, making it particularly suitable for water-limited regions. By enabling efficient resource use, reduced water consumption, and nutrient recycling, these systems support sustainable intensification, these technologies support higher stocking densities, faster growth rates, and significantly greater productivity per unit area compared to conventional pond-based systems.

Diversification of Species and Farming Systems

Indian aquaculture is predominantly focused on a limited number of species, particularly carps and shrimp, exposing producers to market and ecological risks. Another important opportunity lies in the diversification of cultured species and farming systems to enhance resilience and economic returns. Expanding the range into high-value alternatives species such as tilapia, pangasius, seabass, and mud crab can improve income stability and cater to evolving domestic and export market demands. Additionally, niche markets like ornamental fish farming offer high export potential with relatively low investment requirements. At the systems level, integrated and ecosystem-based farming approaches such as aquaponics and integrated multi-trophic aquaculture (IMTA) offer promising efficient pathways for sustainable production. These systems are designed to mimic natural ecological processes, where waste from one component is efficiently utilized as an input for another, thereby optimize resource use, enhance nutrient recycling, and reduce environmental impacts. For instance, aquaponics integrates fish culture with hydroponic plant production, enabling nutrient recycling, reduced water use, and enhanced productivity. Such models are particularly relevant for urban and peri-urban areas, contributing to localized food production, resource efficiency, and improved nutritional security and sustainable intensification.

Climate-Resilient and Sustainable Aquaculture

Climate change presents a dual dynamic for aquaculture, serving as both a source of risk and a driver for innovation. While rising temperatures, unpredictable rainfall, and extreme weather events jeopardize production stability, they also prompt the shift towards climate-resilient and adaptive farming systems. A significant opportunity lies in the development of climate-resilient species and strains through selective breeding and genetic enhancement, especially those capable of withstanding temperature fluctuations, changes in salinity, and low levels of dissolved oxygen conditions. Concurrently, the implementation of sustainable farming practices— minimizing water exchange, optimizing energy use, and adopting environmentally friendly feed formulations can mitigate ecological impacts while enhancing system resilience. Integrating circular economy principles, where waste is efficiently recycled and reused within production systems, further strengthens sustainability. Additionally, the promotion of low-carbon or carbon-neutral aquaculture—through interventions such as solar-powered aeration and energy-efficient infrastructure can aid in achieving emission reduction goals while improving long-term viability. Together, these strategies establish climate-responsive aquaculture as a critical component of sustainable sectoral growth in the sector.

Rural Development and Employment Generation

Aquaculture presents considerable opportunities for rural development and employment generation, supporting millions of livelihoods across the value chain—from hatcheries and feed production to farming, processing, and marketing. Under the Viksit Bharat 2047 initiative, this sector is crucial for poverty alleviation and income diversification, especially by enabling smallholder farmers to integrate aquaculture as a reliable and supplementary income source alongside conventional agriculture. The sector presents significant opportunities for enhancing social inclusion. Greater involvement of women in activities like seed production, feed preparation, and post-harvest processing can foster gender equity and strengthen household incomes. Moreover, community-oriented approaches, such as cooperatives and producer organizations, can improve collective contribution, facilitate better market access, and lower transaction costs.

Advances in Genetics, Breeding, and Nutrition

Advancements in genetics, selective breeding, and nutrition offers substantial opportunities to enhance productivity, resilience, and sustainability in aquaculture. Selective breeding programs have already delivered quantifiable gains in growth rates, feed efficiency, and disease resistance among various cultured species, while the development of Specific Pathogen Free (SPF) shrimp and genetically improved fish strains has contributed to reduced disease risks and more stable production systems. The use of genomic tools and marker-assisted selection further expedites genetic enhancement, facilitating robust, high-performing stocks suited to a diverse range of farming conditions.

Integration with Global Food Systems

Aquaculture is emerging as an essential part of global food systems, offering a more resource-efficient and scalable source of animal protein compared to terrestrial livestock. In the light of increasing global demand, this sector offers a strategic opportunity for India to enhance its position as a reliable supplier of high-quality, sustainably produced seafood to international markets. Positioning India as a global hub for sustainable aquaculture will necessitates profound integration with global value chains. This can be achieved through partnerships with international research institutions, active involvement in trade frameworks, and strict adherence to quality, safety, and sustainability standards. Such alignment has the potential to improve export competitiveness while ensuring compliance with the changing demands of the market. Furthermore, aligning aquaculture development with the Sustainable Development Goals (SDGs) especially those related to food security, poverty alleviation, and environmental sustainability enhances its strategic significance on a global scale. This integration not only supports national economic growth but also aids in broader global initiatives toward resilient and sustainable food systems.

Policy Support, Investment, and Institutional Strengthening

The trajectory of aquaculture in fulfilling the goals of Viksit Bharat 2047 is heavily dependent on strong policy backing and efficient institutional structures. Government initiatives like the Pradhan Mantri Matsya Sampada Yojana (PMMSY) have already accelerated sectoral growth by providing focused financial support, infrastructure, development and fostering capacity-building efforts. Moving ahead, policy priorities should focus on simplifying regulations, encouraging sustainable and responsible aquaculture practices, fostering private sector involvement, and strengthened investment in research and development. Collaborations between the public and private sectors will be vital for scaling innovations, improving technology adoption, and broadening infrastructure throughout the value chain. Strategic investments in hatcheries, feed production facilities, cold chain logistics, and processing plants are essential for enhancing efficiency, minimizing post-harvest losses, and increasing value addition. Simultaneously, the implementation of digital governance mechanisms can significantly enhance transparency and operational efficiency. Online licensing systems, digital monitoring platforms, and integrated service portals can streamline regulatory processes, reduce administrative delays, and facilitate easier access to institutional support, thereby enabling a added supportive and responsive environment for aquaculture development.

Innovation Ecosystem and Start-up Opportunities

The emergence of start-ups and innovation- driven ecosystems is opening new avenues for the transformation of the aquaculture industry. Agri-tech and aqua-tech enterprises are providing solutions in critical areas such as real-time water quality monitoring, swift disease diagnostics, precision feeding, and efficient supply chain management, thereby enhancing productivity and operational efficiency. The expansion of incubation centers, innovation hubs, and access to venture capital is essential to nurture these enterprises and enhancing their impact. Strengthening collaboration among academia, industry, and government can further accelerate the translation of research into commercially viable technologies and practices. Engaging youth in aquaculture entrepreneurship is particularly essential for promoting innovation and advancing sectoral modernization. By establishing a supportive environment that encourages experimentation, investment, and technology adoption, India can cultivate a dynamic, competitive, and future-oriented aquaculture sector.

Challenges in Fisheries and Aquaculture sector

Disease Outbreaks and Biosecurity Constraints

Infectious diseases continue to pose one of the most critical challenges in aquaculture, frequently resulting in substantial economic losses and instability in production. The emergence of new and re-emerging pathogens further intensifies the vulnerability of the sector. The growing intensification of aquaculture marked by high stocking densities and increased input use has amplified disease risks. Overcrowded culture conditions facilitate swift pathogen spread, while environmental stressors such as deteriorating water quality compromise the immune defences of cultured species, rendering them more susceptible to infections. Effective management of diseases is further obstructed by inadequate biosecurity measures at the farm level. Many small-scale operations lack uniform protocols for disinfection, quarantine, and regular health monitoring. Limited access to rapid diagnostic tools and aquatic animal health services, particularly in rural areas, delays early detection and timely intervention. Furthermore, the absence of effective vaccines for the majority of aquatic pathogens remains a critical gap. While alternative methods like immunostimulants and probiotics are being explored, their efficacy frequently varies among different species and culture settings. Addressing these issues necessitates a holistic strategy that combines better farm management, reinforced biosecurity protocols, advanced diagnostic tools, and ongoing research in the field of aquatic animal health.

Environmental Impacts and Sustainability Concerns

The rapid expansion of aquaculture has intensified concerns about its environmental impacts. Effluents from aquaculture farms generally contain leftover feed, fecal waste, and chemical residues, leftover feed nutrient loading and eutrophication in nearby water bodies. Consequently, this frequently results in detrimental algal blooms, diminished dissolved oxygen concentrations, and a decrease in aquatic biodiversity. Coastal aquaculture, particularly shrimp farming, has been associated with the deterioration of ecologically sensitive habitats such as mangrove ecosystems. The conversion of mangrove areas into aquaculture ponds interferes with natural ecological processes and reduces coastal resilience, increasing vulnerability to storms, flooding, and shoreline erosion. Another significant concern is soil salinization, especially in coastal areas where the intrusion of saline water impacts nearby agricultural lands. This phenomenon not only reduces soil productivity but also leads to conflicts between aquaculture and traditional farming practices, complicating land-use management. Although sustainable technologies like biofloc systems and recirculating aquaculture systems (RAS) present promising solutions to minimize environmental impacts, their widespread adoption is constrained by high capital investment and technical challenges. Ensuring environmental sustainability in aquaculture therefore requires a balanced strategy that combines responsible intensification with ecosystem conservation, supported by effective regulatory policies and incentives to promote environmentally friendly practices.

Climate Change and Environmental Variability

Climate change represents a long-term challenge for aquaculture. Rising global temperatures, shifting rainfall patterns and increased frequency of extreme weather events such as cyclones and floods directly affect aquaculture productivity. Variations in temperature can significantly affect the metabolism, growth, and reproductive cycles of cultured species. Higher temperatures often lead to reduced dissolved oxygen levels, increasing stress and susceptibility to diseases. In addition, fluctuations in salinity due to erratic rainfall or seawater intrusion can negatively impact species that have narrow tolerance ranges. Extreme weather events further exacerbate risks by damaging aquaculture infrastructure, resulting in stock losses and economic disruptions. Coastal aquaculture systems are particularly at risk due to sea-level rise, storm surges, and coastal flooding. Extreme weather events can cause physical damage to aquaculture infrastructure, leading to stock losses and economic setbacks. Coastal aquaculture systems are particularly vulnerable to sea-level rise and storm surges. Addressing these challenges requires the climate-resilient aquaculture systems, including the use of tolerant species, improved farm design, and the implementation of early warning and monitoring systems. However, the implementation of such measures is constrained by limited awareness, and financial constraints.

Rising Input Costs and Economic Pressures

Economic sustainability poses a significant concern for aquaculture farmers, particularly in the context of rising input costs. Feed, which accounts for 50–70% of overall production expenses, has seen a notable rise in price due to the escalating costs of fishmeal, fish oil, and various other ingredients. Seed quality and availability significantly affect production outcomes. The reliance on high-quality seed, such as Specific Pathogen Free (SPF) shrimp, raises operational expenses. Additionally, energy costs associated with aeration, pumping, and various farm activities add to the overall expenditure. Small-scale farmers are particularly vulnerable to these cost pressures, due to their limited access to credit and financial assistance. Price volatility in both domestic and international markets further intensify economic uncertainty, making it difficult for farmers to plan and invest. Confronting these challenges calls for the formulation of budget-friendly feed alternatives, increased supply chain efficiency, and access to affordable financing options.

Limited Access to Technology and the Digital disparity

Although technological innovations have the potential to significantly improve aquaculture productivity, their implementation is inconsistent across the sector. Many small and marginal farmers face challenges in accessing advanced tools such as AI-based monitoring systems, automated feeding solutions, and digital management platforms. A major constraint is the digital disparity particularly in rural areas where internet access and technical proficiency are often inadequate. Even when these technologies are available, their high costs and operational intricacies may deter widespread adoption. Additionally, extension services and capacity-building initiatives often fall short in facilitating effective technology transfer. As a result, the benefits of innovation tend to be concentrated among larger, better-resourced farms, widening inequalities within the sector. Addressing this issue requires inclusive and scalable approaches for technology dissemination, including the development of affordable solutions, offering targeted training programs, and enhancing public–private partnerships to ensure wider accessibility and adoption.

Market Volatility and Export Dependency

India’s aquaculture sector, particularly shrimp farming, relies heavily on export markets. Although this provides substantial revenue opportunities, it also exposes the sector to global market fluctuations, trade restrictions, and geopolitical uncertainties. Changes in consumer preferences, food safety regulations, and trade policies in importing nations can have immediate impacts on export volumes and prices. For example, rigorous quality standards and certification requirements can pose challenges for small-scale producers. Although domestic markets for aquaculture products are expanding, they have not yet fully developed to accommodate production surpluses. This imbalance increases vulnerability to external shocks. Diversification of markets, development of domestic value chains, and promotion of value-added products are crucial to enhance resilience against market volatility.

Infrastructure Deficiencies and Supply Chain Gaps

Infrastructure constraints continue to pose a major obstacle to the efficient functioning of the aquaculture sector. Limited availability of cold storage, inadequate processing facilities, and fragile transportation networks contribute to significant post-harvest losses and deterioration in product quality. Inefficiencies within the supply chain further impede both domestic distribution and export performance. Transportation delays and disruptions can compromise the freshness, safety, and overall market value of seafood products, ultimately impacting competitiveness in both local and global markets. Strengthening infrastructure particularly cold chain systems, modern processing units, and reliable logistics is critical for sustainable sectoral growth. Strategic investments, supported by public–private partnerships, can play a vital role in bridging these gaps and improving overall supply chain efficiency.

Skill Gaps and Human Resource Constraints

Human resource development is a vital yet often overlooked component of aquaculture development. Many farmers lack the technical expertise necessary for contemporary aquaculture practices, such as managing water quality, controlling diseases, and optimizing feed. Training and extension services are often limited in scope and reach. Consequently, this leads to suboptimal farm management practices and reduced productivity. The involvement of youth in aquaculture is also limited, partly due to the perception of aquaculture as a traditional and less appealing occupation. It is crucial to promote youth involvement through education, training, and entrepreneurial opportunities for the future of the sector.

Research Gaps and Innovation Constraints

Although India has a strong network of research institutions, there are gaps in translating research outcomes into practical applications. Despite India's extensive network of research institutions, there exist gaps in translating research outcomes into practical applications. Limited collaboration between academia, industry, and farmers restricts the dissemination of innovations. Research efforts in fields like disease management, climate resilience, and feed development must be enhanced. Furthermore, the commercialization of novel technologies and products necessitates supportive policies and investment. Establishing a robust innovation ecosystem that integrates research, industry, and policy is essential for promoting sustainable aquaculture development.

Policy, Governance, and Institutional Strengthening

Aquaculture development is increasingly supported by evolving governance frameworks and government initiatives such as the Pradhan Mantri Matsya Sampada Yojana, which are driving sectoral growth. Streamlining regulatory processes, harmonizing standards across regions, and improving coordination among agencies present strong opportunities to enhance efficiency and ease of operations. The adoption of digital governance tools and data-driven decision-making can further improve transparency, monitoring, and policy implementation. Strengthening institutional capacity and fostering better collaboration will enable more responsive, efficient, and sustainable management of the aquaculture sector.

A proactive and coordinated approach to addressing these challenges can empower India to strengthen its position as a global leader in sustainable aquaculture, while also making substantial progress towards the goals of Viksit Bharat 2047.

Future Prospects under Viksit Bharat 2047

India’s fisheries and aquaculture sector is poised for demand- driven expansion, underpinned by low per capita fish consumption in conjunction with rising population, urbanization, and incomes. Future development will rely on technology-enabled intensification, where AI, IoT, and precision aquaculture systems improve productivity, resource efficiency, and real-time facilitate decision-making at the farm level. Sustainability will continue to be a focal point, with climate-resilient production systems, stress-tolerant species, and adaptive management practices ensuring production stability amid environmental variability. At the same time, circular economy approaches such as waste recycling and efficient feed utilization will reinforce ecological sustainability. From an economic standpoint, the sector holds significant scope for value addition, diversifying exports, and expanding the domestic market, supported by advancements in cold chain logistics, processing facilities, and traceability systems to enhance global competitiveness. On the institutional front, coherent policies, digital governance frameworks, and inclusive support systems (credit, insurance, extension) will be key drivers. Strengthened public–private partnerships and sustained investment in research and innovation will further expand technology dissemination and sectoral transformation. Overall, the sector is expected to transition into a high-value, technology-oriented, and climate-resilient industry, playing a strategic role in achieving the goals of Viksit Bharat 2047.

Conclusion

India’s fisheries and aquaculture sector has evolved into a vital component of the agri-food economy, driven by aquaculture-led growth and rising economic importance, yet constrained by challenges related to disease, environmental sustainability, climate variability, and governance. Achieving the vision of Viksit Bharat 2047 necessitates a strategic shift toward sustainable, technology-driven, and inclusive development, with emphasis on biosecurity, climate resilience, value chain enhancement, and policy coherence. In summary, the alignment of technological innovation with responsible environmental management and effective governance can empower India to become a globally competitive, resilient, and sustainable leader in aquaculture by 2047.

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CLIMATE-SMART AND RESILIENT AGRICULTURE: REIMAGINING INDIA'S FARMS THROUGH PMKSY 2.0

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Abstract

Climate change poses significant challenges to Indian agriculture, particularly in terms of water scarcity, soil degradation, and production instability. The *Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) 2.0* represents a strategic shift from conventional irrigation development toward climate-resilient resource management. This paper examines the role of PMKSY 2.0 in promoting climate-smart agriculture through efficient water use, watershed development, and sustainable soil management. It highlights how integrated approaches under the scheme enhance agricultural productivity, strengthen resilience, and support long-term sustainability. The study underscores the importance of technological innovation, community participation, and policy support in achieving climate-resilient farming systems in India.

Keywords: Climate-smart agriculture, PMKSY 2.0, water management, soil health, watershed development, resilience

Introduction

Agriculture remains a cornerstone of India's economy, employing a large proportion of the population and ensuring food security. However, increasing climate variability—manifested through erratic rainfall, rising temperatures, and frequent droughts—has intensified pressure on agricultural systems. Traditional irrigation practices and unsustainable land use have further aggravated water scarcity and soil degradation.

In response, the Government of India introduced the *Pradhan Mantri Krishi Sinchayee Yojana (PMKSY)*, with PMKSY 2.0 representing an advanced phase focused on sustainability and resilience. The program emphasizes the principles of *"Har Khet Ko Pani"* and *"Per Drop More Crop,"* integrating irrigation efficiency with climate adaptation strategies.

Conceptual Framework: Climate-Smart Agriculture

Climate-smart agriculture (CSA) is built on three fundamental pillars:

1. Enhancing agricultural productivity
2. Strengthening resilience to climate change
3. Reducing greenhouse gas emissions

CSA promotes resource-efficient and environmentally sustainable practices. Within this framework, water and soil management are central components, as they directly influence crop productivity and ecosystem stability. PMKSY 2.0 aligns closely with CSA principles by integrating irrigation efficiency with conservation-based approaches.

PMKSY 2.0: A Paradigm Shift in Water Management

PMKSY 2.0 moves beyond conventional irrigation expansion to focus on integrated water resource management. Its major components include:

- **Micro-irrigation (Per Drop More Crop):** Promotes drip and sprinkler systems to optimize water use efficiency.
- **Har Khet Ko Pani:** Expands irrigation access to underserved and rain-fed areas.
- **Watershed Development:** Encourages rainwater harvesting, groundwater recharge, and soil conservation.
- **Infrastructure Development:** Strengthens irrigation networks and water storage systems.

This integrated approach ensures both supply-side and demand-side management of water resources.

Soil and Water Synergy in Climate Resilience

Soil and water are interdependent resources that determine agricultural sustainability. PMKSY 2.0 enhances this synergy through:

- **Improved Soil Moisture Retention:** Efficient irrigation ensures optimal water availability for crops.
- **Reduced Soil Erosion:** Watershed interventions such as contour bunding and check dams prevent topsoil loss.
- **Enhanced Soil Fertility:** Balanced water application minimizes nutrient leaching and salinity.

Healthy soils improve water infiltration and storage, thereby increasing resilience to droughts and extreme weather events.

Technological Interventions and Innovation

PMKSY 2.0 incorporates modern technologies to enhance decision-making and resource efficiency. These include:

- Geographic Information Systems (GIS) for planning watershed activities
- Remote sensing for monitoring land and water resources
- Mobile-based advisory services for farmers
- Emerging tools such as artificial intelligence and climate forecasting

Such innovations enable precision agriculture and adaptive management under changing climatic conditions.

Socio-Economic Impacts

The implementation of PMKSY 2.0 has significant socio-economic implications:

- **Increased Agricultural Productivity:** Reliable irrigation supports multiple cropping and higher yields.
- **Income Enhancement:** Efficient resource use reduces costs and increases profitability.
- **Risk Mitigation:** Reduced dependence on monsoons lowers vulnerability to climate shocks.
- **Employment Generation:** Watershed and irrigation projects create rural job opportunities.

These outcomes contribute to rural development and poverty reduction.

7. Challenges and Constraints

Despite its potential, PMKSY 2.0 faces several challenges:

- Uneven adoption of micro-irrigation technologies
- Limited awareness and technical knowledge among farmers
- Regional disparities in implementation
- Financial and institutional constraints

Addressing these issues requires coordinated efforts, policy support, and capacity-building initiatives.

Way Forward

To strengthen the impact of PMKSY 2.0, the following measures are recommended:

- Scaling up awareness and training programs for farmers
- Integrating traditional knowledge with modern practices
- Enhancing financial support and incentives for micro-irrigation
- Strengthening institutional coordination and monitoring mechanisms
- Promoting community-based water governance systems

A holistic approach combining technology, policy, and community engagement is essential for long-term sustainability.

Conclusion

PMKSY 2.0 represents a transformative step toward climate-smart and resilient agriculture in India. By integrating efficient water management with soil conservation and technological innovation, it addresses the critical challenges posed by climate change.

The success of the initiative lies in its ability to balance productivity with sustainability while empowering farmers and communities. As India moves toward a more resilient agricultural future, PMKSY 2.0 will play a crucial role in ensuring that every field has access to water and every farmer has the opportunity to prosper.

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INDIAN AGRICULTURE: FROM A GLORIOUS HERITAGE TO A DEVELOPED INDIA 2047

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Background

India, since ancient times, has been a land of sages and prosperous agriculture. In the present era, when the entire world is caught in the race of industrialization, India remains a country whose soul resides in its villages and fields. The soil here not only produces food grains but also nourishes culture, tradition, and consciousness. The true strength of India lies neither in industries nor in markets, but in the fertility of its fields and in the seeds sown by farmers with devotion, ensuring the nation's food security.

Indian agriculture has traversed centuries of evolution from the Vedic period to modern science. Despite adversities such as foreign invasions, natural calamities, and policy failures, it continues to sustain millions of lives. As we envision a "Developed India," it is essential to understand, respect, and modernize our agricultural heritage.

Agricultural Traditions in Ancient India

In the Vedic era, agriculture was regarded as a divine activity. The Earth was revered as a mother, and farmers as her sons. Agricultural prosperity was linked with religious rituals and yajnas. References in the Rigveda highlight the harmonious relationship between agriculture and nature, emphasizing balance with natural elements such as rain, sun, air, and soil.

Ancient rulers established observatories to predict climatic patterns and guide agricultural practices. Folk scholars like Ghagh and Bhaddari composed agricultural wisdom blending science and experience, which remains relevant in rural India even today. Archaeological findings from Mohenjo-daro and Harappa reveal granaries, ploughs, and irrigation systems, indicating a well-organized agricultural system. The Saraswati region practiced double cropping, bullock-driven ploughing, and advanced water management techniques. Kautilya's *Arthashastra* outlined clear policies on agricultural taxation, irrigation, seed storage, and price regulation. Texts like the *Charaka Samhita* and *Sushruta Samhita* provided valuable insights into soil quality, farming practices, and medicinal plants. Agriculture was largely organic and cattle-based, integrating food production with cultural and ecological sustainability. Crop selection was based on soil suitability, as mentioned in ancient texts "*Subeejam Sukshetre Jayate Sampadyate*".

Agriculture in Medieval India

During the Bhakti movement, land, food, and farmers were revered as sacred. Poets like Kabir, Tulsidas, Rahim, and Surdas depicted both the struggles and dignity of farmers. Under Mughal rule, Raja Todar Mal introduced a structured land revenue system. While administratively efficient, it gradually increased the burden on farmers. During colonial rule, the forced cultivation of cash crops like indigo, opium, and cotton led to famines and agrarian distress. Literary works such as Dinabandhu Mitra's *Nil Darpan* and Munshi Premchand's *Godaan* portrayed the exploitation of farmers. Zamindari practices, moneylenders' debts, and exploitative taxation led to several agrarian revolts, including the Santhal and Indigo rebellions.

Challenges in Contemporary Indian Agriculture

Despite technological advancements, Indian agriculture faces complex challenges. Climate change has disrupted traditional stability, causing erratic monsoons, prolonged droughts, and sudden floods. Approximately 85% of farmers belong to small and marginal categories, lacking access to land, resources, technology, and capital. Farmers sow seeds with hope, but inadequate irrigation, fertilizers, and technical knowledge limit productivity and profitability. Market inefficiencies further worsen their condition, as farmers have little control over price determination and remain trapped in middlemen networks. These socio-economic pressures often lead to mental stress, depression, and, tragically, farmer suicides, reflecting a deep national concern.

Reconstruction of Agriculture in Independent India

Post-independence, agricultural practices evolved with changing needs. Rising population and shrinking cultivable land necessitated modernization. Agricultural education was strengthened, beginning with initiatives like postgraduate programs at Pusa in 1923. The Green Revolution, driven by improved crop varieties, chemical fertilizers, and irrigation, made India self-sufficient in food production. Subsequent revolutions: White, Blue, Yellow, and others diversified agriculture. However, these advancements also led to ecological challenges such as declining groundwater levels, soil degradation, and environmental pollution, along with regional disparities in benefits.

Opportunities for Agriculture in a Developed India

Modern agricultural education and practices have enhanced productivity through soil management, climate-resilient farming, crop diversification, and integrated pest management. Yet, population pressure demands further innovation. Efforts have been made to preserve indigenous knowledge and traditional seeds through gene banks. Initiatives like Soil Health Cards and precision farming promote efficient resource use. Advanced technologies such as gene editing have enabled the development of improved crop varieties, including India's first genome-edited rice varieties (DRR Dhan-100 and Pusa DST Rice-1). Climate-resilient strategies such as crop diversification, hydroponics, aeroponics, and the revival of millets have been adopted to address environmental and nutritional challenges. Geographical Indication (GI) tagging of region-specific agricultural products enhances farmers' income and recognition. Legal frameworks like the Protection of Plant Varieties and Farmers' Rights (PPV&FR) Act safeguard innovations.

Today, Indian agriculture is undergoing a digital transformation through remote sensing, artificial intelligence, robotics, and drone-based technologies. The future may even witness remote farming and agricultural expansion beyond Earth. India has also initiated space agriculture experiments under ISRO's Axiom-4 mission, studying the germination and growth of crops like moong, fenugreek, beans, sesame, tomato, brinjal, and rice under microgravity. Research on microalgae such as spirulina and chlorella explores their potential for oxygen production, waste recycling, and nutrition in space environments.

Conclusion

Indian agriculture is poised to reclaim its historic glory and emerge as a global leader by 2047. However, it is crucial to remember that the foundation of all agricultural progress lies in India's rich traditional heritage. By integrating ancient wisdom with modern innovation, India can truly achieve sustainable agricultural development and global leadership.

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BREWING CHANGE: REVIVING LIVELIHOODS IN DARJEELING’S CLOSED PLANTATIONS THROUGH WOMEN-LED SELF HELP GROUPS AND NATURAL FARMING

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Abstract

The tea gardens of Darjeeling and the Dooars lowlands of North Bengal share a common wound: the sudden collapse of a plantation economy that once defined every dimension of workers’ lives. Tens of thousands of families, mostly Adivasi, mostly women have been left on land they cannot legally call their own, without wages, rations or any meaningful fallback. Clinical research now documents the consequences: one in four tea garden workers in Darjeeling is undernourished; morbidity in Dooars communities tracks directly to food insecurity and poverty. Yet the women in these communities have not been passive. Self Help Groups (SHGs) formed by women from closed garden households are the most resilient institution still standing in this landscape. This article argues that federating these SHGs, connecting them to natural farming on abandoned plantation land, and linking them to markets and institutional credit can offer a realistic, affordable and scalable path toward revival, one that aligns squarely with the goals of Viksit Bharat 2047, SDG 2, SDG 12, SDG 13 and Mission LiFE.

Keywords: Closed tea gardens, Adivasi women workers, SHGs, Viksit Bharat 2047, Mission LiFE

Introduction

Every cup of Darjeeling tea carries a geography, mist-covered ridges, altitude-cooled air, and a flavour so particular that no other place on earth can replicate it. What it rarely carries is the story of the people who made it. For generations, tea plantation workers in the Darjeeling hills and the Dooars plains of North Bengal lived and worked entirely within the plantation system. The garden was not just a workplace; it was a world which provided wages, rations, housing, schools and hospitals, all within its boundaries.

When that world collapsed, there was nothing waiting on the other side. North Bengal has approximately 450 tea gardens spread across Darjeeling Hills, Terai and Dooars (Sonar, 2024). The closure crisis has accelerated sharply in the past decade. In 2022 alone, DOTEPL (Darjeeling Organic Tea Estates Pvt. Ltd.) abandoned ten estates including Happy Valley, Ambootia and Rangaroon, leaving their workers without wages, statutory benefits or clear legal recourse. The Darjeeling Tea Association has publicly stated that nearly 30 per cent of gardens are defaulters on provident fund and gratuity obligations (Singh, 2023).

The Human Cost of a Closed Garden

A tea garden closure is unlike a factory shutdown in one critical way: workers do not just lose a job, they lose an entire ecosystem of survival. The plantation system historically provided housing, weekly rations of rice and wheat, access to a garden hospital, and schools for children, all of which cease the moment management abandons a garden. Research in the closed gardens of Dooteriah, Kalej Valley and Peshok in the Darjeeling hills found that workers absorbed into MGNREGS after closure earned an average of just Rs 8,000-12,000 per year which is a fraction of their previous income and depended on multiple casual sources to survive (Hannan and Golay, 2022).

Fig. 1: Cascading Impact of Tea Garden Closure on Communities

The health consequences of this collapse are now clinically documented. A 2023 investigation of tea garden laborers in the Darjeeling district revealed that a quarter of the population experienced undernutrition, with household food insecurity identified as a key contributing factor (Mandal *et al.,* 2023). Furthermore, a 2022 study conducted in Alipurduar, located in the Dooars region, corroborated the interconnectedness of poverty, undernutrition, and morbidity within plantation communities, with women disproportionately affected (Yasmin *et al.,* 2022). These findings are not isolated instances; rather, they signify a systemic crisis that has been developing over the past twenty years.

Women have borne the heaviest burden of this collapse. In the Dooars tea belt, women, primarily Adivasi from the Oraon, Munda, Kharia, and Santhal communities, who were brought in as indentured laborers in the late 1800s, make up almost 60% of the workforce (Bhattacharya, 2024). Gurung and Mukherjee's (2018) research showed that the limited education and skills of tea workers, along with the isolated nature of plantation life, significantly restrict their ability to move up in their jobs, especially for women. The land itself pays a cost too. Decades of tea monoculture have left plantation soils acidic and low in organic matter. Abandoned slopes on Darjeeling's steep terrain erode rapidly without root cover. What was once among the most biologically productive hillside terrain in the subcontinent deteriorates quietly alongside the communities that depended on it.

What Women's SHGs Are Already Doing

In the middle of this crisis, Self Help Groups have emerged as the most resilient institution still functioning in closed tea garden communities. Formed primarily by women from affected households, these groups save small amounts every week, extend interest-free emergency loans to members, and serve as informal social security for communities whose formal welfare systems have disappeared. In West Bengal, which has some of the highest SHG coverage under the National Rural Livelihoods Mission (NRLM) in the country their reach is substantial (Bhattacharjee *et al.,* 2024). Research across the state has consistently shown that SHG membership improves women's socio-economic conditions, strengthens their confidence and increases their ability to access government entitlements (Cheek and Corbett, 2024).

In the tea belt, SHGs have done more than save. Members have taken up kitchen gardening on whatever land they could access, producing vegetables that reduce household food expenditure and, in some cases, generate small local income. Groups have moved into food value addition, dried herbs, forest honey, pickles, fermented bamboo shoots, finding buyers in town markets. Where SHGs are active, families are demonstrably more likely to have accessed PM-KISAN, MGNREGS and PMAY entitlements, because the group acts as a bridge into a bureaucratic system that otherwise feels inaccessible.

India's Economic Survey 2022-23 described SHGs as a little-known but high-impact institution, noting that India's 12 million SHGs cover 142 million families with savings of over Rs 47,000 crore and a loan repayment rate exceeding 96 per cent, figures that reflect an institutional trust built entirely from below (GoI, 2023). In the tea belt of North Bengal, this trust already exists. What is missing is the infrastructure to convert it into agricultural and economic productivity at scale.

A Practical Framework for Revival

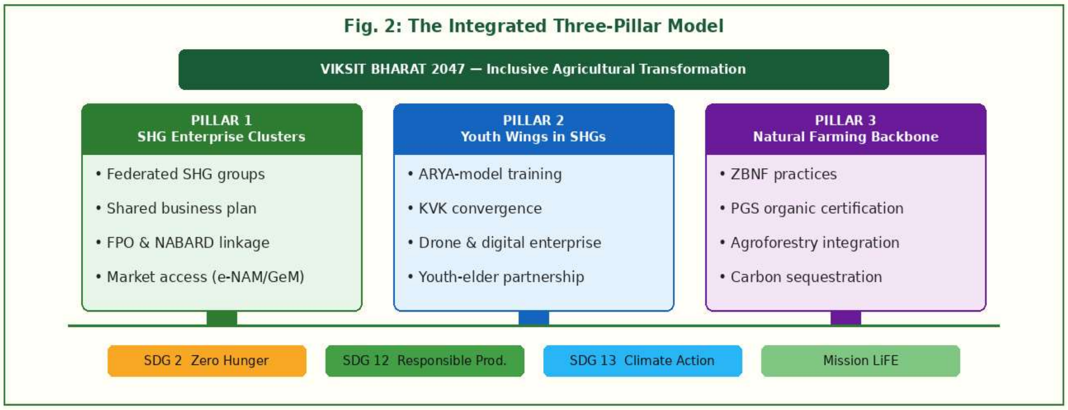

Fig. 2: An Integrated Framework for SHG-Led Agricultural Revival in Closed Tea Garden Communities

Federated SHG Clusters: Individual SHGs are effective at saving and mutual support. They are less equipped, alone, to negotiate prices, access institutional credit or apply for collective certification. When five to eight groups in the same locality come together around a shared business plan, forming an Agri-Enterprise Cluster, they gain the scale to do all these things. Formal linkage with Farmer Producer Organisations (FPOs) gives clusters access to e-NAM and GeM portals, enabling direct institutional sales. NABARD's dedicated credit windows for federated SHG structures are already in place; the critical gap is ensuring that groups in closed tea garden areas are actively connected to them (NABARD, 2022).

Bringing Youth into the Cluster Economy: Youth outmigration from the tea hills is not a cultural inevitability; it is a rational response to the absence of economic opportunity. Evidence from Andhra Pradesh's natural farming programme shows that when SHGs are given real productive activity and youth are embedded within that economy with defined roles in processing, digital sales and account management intergenerational participation in local agriculture becomes viable (Bharucha *et al.,* 2020). The same principle applies to North Bengal: creating an SHG cluster economy gives young people from closed garden households a reason to stay and a productive role within it.

Natural Farming on Abandoned Plantation Land: The abandoned slopes of Darjeeling's closed estates are not dead land. Research from the ICAR Research Complex for NEH Region, Meghalaya demonstrates that an Integrated Organic Farming System (IOFS) which incorporates crops, horticulture, livestock, rainwater harvesting and local nutrient recycling, significantly improves farm income and livelihood security for hill farmers in precisely this kind of terrain (Ansari *et al.,* 2023). The NEH region shares Darjeeling's altitude gradient, rainfall patterns and soil characteristics, making this model directly transferable. Natural farming inputs like cow dung, jaggery, gram flour, leaf mulch cost almost nothing, build soil health over successive seasons and prevent the erosion that unchecked abandonment accelerates. Collective PGS organic certification gives clusters premium market access without the cost burden of individual certification. The Darjeeling geographical indication tag which is globally recognised and legally protected positions these products for both domestic premium and export markets. Agroforestry layers of fruit trees, large cardamom and medicinal plants add further income streams while sequestering carbon and stabilising fragile slopes.

Why This Goes Beyond Darjeeling

The framework described above maps directly onto the national priorities of Viksit Bharat 2047 and the Sustainable Development Goals. SDG 2 (Zero Hunger) is addressed when SHG kitchen gardens and federated cluster farms restore food production in communities that lost subsidised rations overnight. A 2022 peer-reviewed study found that women farmers in hilly areas who used traditional agroecological methods had a more varied diet than those who only bought food from the market. This is especially relevant for natural farming in closed tea garden areas (Layek *et al.,* 2023). Natural farming supports SDG 12 (Responsible Production) through composting, water conservation, the elimination of chemicals, and the efficient recycling of organic materials on the farm, creating truly circular systems. In addition, SDG 13 (Climate Action) is supported by the agroforestry and carbon capture potential of restored plantation slopes.

Mission LiFE which is India's national call for a lifestyle in harmony with nature finds perhaps its most authentic expression in this context. The women of Darjeeling's tea belt did not adopt natural farming as a philosophical preference. They turned to low-input, locally sourced methods because they had no other option. Their practice is already what Mission LiFE calls for. What is needed is not a change in behaviour, but institutional recognition of, and sustained support for, the behaviour that already exists.

This model is also replicable. The plantation closure crisis is not confined to Darjeeling. Assam, the Nilgiris, and parts of Kerala face similar trajectories of estate abandonment, indigenous worker displacement and the deterioration of captive agricultural communities. A tested, evidence-backed revival model from North Bengal would have national and potentially regional significance.

What Needs to Happen

- Secure land access: Workers living on closed garden land must be given the legal right to cultivate it through long-term lease, cooperative tenure or community land titles. Without this, every other recommendation in this article remains aspirational. This is the precondition for everything else.
- Dedicated credit for SHG clusters: NABARD and state cooperative banks should create a targeted credit window for federated SHG clusters in closed tea garden areas, treating group savings history as collateral. Existing NRLM infrastructure should be used to identify and register eligible groups.
- Subsidised PGS organic certification: Group certification under the Participatory Guarantee System should be facilitated through KVKs and State Agriculture Departments, with first-cycle

costs fully subsidised. This single intervention unlocks premium market access for natural produce under the Darjeeling brand.

- Youth integration through applied skilling: Short, hands-on training in natural farming, food processing and digital market access which is designed for youth from closed tea garden households should be delivered through KVKs and State Agricultural Universities in Darjeeling, Jalpaiguri and Alipurduar districts. The IOFS models demonstrated in Meghalaya and Sikkim by ICAR provide ready-to-adapt templates.

Conclusion

The communities living inside Darjeeling's closed tea gardens did not simply wait for policy to find them. Without wages, without rations and without land titles, the women of these communities built what they could: savings groups that met weekly, kitchen plots on whatever ground they could access, networks of mutual support that kept the most vulnerable households from complete collapse. That this happened at all — in conditions of near-total institutional abandonment — is both remarkable and instructive. Viksit Bharat 2047 is a national vision of a developed, equitable India. Its credibility will not rest on rising GDP figures or export milestones alone. It will rest on whether the Adivasi woman who spent her working years plucking leaves for a garden that then abandoned her is part of the story of 2047. The path forward is not complicated: connect her SHG to land, credit and markets, support natural farming on slopes that are already hers in practice if not in law, and create a real reason for her children to stay. No new institution is required. No untested model is needed. What is required is the political will to recognise and invest in what already exists. That is achievable. It is also long overdue.

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FARMER-PRODUCER ORGANIZATION (FPOS) EMPHASIZING EASTERN INDIA

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Abstract

Farmer Producer Organizations (FPOs) have emerged as a pivotal institutional mechanism for improving the socio-economic status of small and marginal farmers in India. This is particularly critical in Eastern India, notably West Bengal, where extreme land fragmentation and restricted market access hinder agricultural growth. Utilizing secondary data, this study evaluates the operational performance and systemic hurdles faced by FPOs in the region. The findings indicate that while FPOs successfully achieve economies of scale as evidenced by reduced input costs and enhanced technical literacy—significant constraints remain. Persistent challenges such as inconsistent procurement, inadequate post-harvest infrastructure and credit constraints undermine long-term sustainability. The study concludes that for FPOs to transition from survival to scalability, targeted interventions in credit accessibility, professionalized management, and robust market linkages are essential.

Introduction

Agriculture plays a crucial role in the economy of Eastern India, which includes states such as West Bengal, Bihar, Odisha, Jharkhand and Assam. The region is characterized by a large number of small and marginal farmers who depend on agriculture as their key income stream for livelihood despite having favorable agro-climatic conditions and rich natural resources. The farmers of eastern regions face several structural challenges like small landholdings, high input costs, limited access to quality input, inadequate market linkages, good source of knowledgeable support and weak bargaining power.

In recent years, a cluster of institutions such as Farmer-Producer Organizations (FPOs) have been promoted as an effective strategy to address these challenges to mitigate the burning situation of Indian farmers. FPOs aim to organize them into groups so that they collectively purchase agricultural inputs, adopt improved technologies and market their production more efficiently. FPOs as farmer-owned enterprises help to strengthen their bargaining power and improve access to markets, financial services, and technical knowledge. As a result, FPOs are increasingly recognized as an important institutional mechanism for enhancing farmer’s income and promoting sustainable agricultural development in Eastern India.

Concept

A Farmer Producer Organization (FPO) is a coalition of farmers formed to promote the common economic and social interests of its members. It has a formal structure, defined membership, and established rules and regulations for its functioning. Primarily farmers are organized at the village level into small groups of about 15–20 members, commonly known as Farmer Interest Groups

(FIGs), Mishra *et al.,* (2022). These groups are then aggregated to form a larger organization called Farmer Producer Organization (FPO). The main objective of FPO is to boost the farmers income through combined action, improve access to resources, technology, and markets and hence elevate their incomes (FAO, 1990). Various institutions play a crucial role in promoting and developing FPOs in India. Small Farmers' Agribusiness Consortium (SFAC) and the National Bank for Agriculture and Rural Development (NABARD) are key agencies supporting FPOs. These organizations assist in the form of capacity building, training and skill development of members, financial support and access to credit. Such support significantly contributes to enhancing the performance and sustainability of FPOs in India.

Benefits of FPOs

Farmer Producer Organizations (FPOs) play a vital role to ameliorate the economic condition of farmers, especially small and marginal farmers. One of the major benefits of FPOs is to deliver agricultural resources at lower costs. FPOs obtain licenses for supplying seeds, fertilizers and pesticides, which allows FPOs to provide raw materials to their members at relatively lower rates than the open market. This helps in reducing the cost of cultivation.

The primary objective of the Farmer Producer Organization (FPO) model is to enable the transition from individual subsistence farming to collective commercialization. By aggregating agricultural produce, FPOs attain the scale required to bypass traditional, multi-layered intermediaries, thereby allowing farmers to capture a greater share of the consumer rupee. This structural transformation significantly improves price realization and strengthens the collective bargaining power of small and marginal farmers.

Moreover, FPOs serve as vital institutional mechanisms for human capital development. Through structured extension services and targeted technical training, they promote the adoption of efficient farming practices and modern agricultural technologies. In doing so, FPOs help bridge the productivity gap associated with fragmented landholdings, enhancing both farm-level efficiency and overall rural livelihoods.

Field observations from Northern West Bengal reveal that several FPOs provides seeds, fertilizers and pesticides to their members at relatively lower prices. Some organizations also assist with training and information on improved agricultural practices, hence highlighting the practical role of FPOs in supporting farmers at the grassroots level.

Status of FPOs in Eastern India

Table: Distribution of Farmer-Producer Organizations (FPOs) and their membership across selected states of Eastern India.

State	No. of FPOs	Total Shareholders	Average Members per FPOs	Rank (Based on No. of FPOs)
Odisha	1899	480146	253	1
Bihar	1840	756029	411	2
West Bengal	1806	223807	124	3
Assam	1198	70238	59	4
Jharkhand	776	142760	184	5

Source: TCI, 2026

Among the major states in Eastern India, Odisha ranks first in terms of the number of FPOs (1899) followed by Bihar (1840) and West Bengal (1806). Assam and Jharkhand occupy the fourth and fifth positions, respectively, representing comparatively lower numbers of FPOs in these states. In terms of membership strength, Bihar shows the highest average number of members per FPO (411), suggesting stronger farmer aggregation and participation. Odisha and Jharkhand also demonstrate moderate membership levels, while West Bengal shows a relatively lower average membership (124). Assam accounts the lowest average (59) signifying a smaller FPO size in the state.

Challenges of FPOs in Eastern India

Despite the growing importance of Farmer Producer Organizations (FPOs), they face several challenges that limit their effectiveness, particularly in Eastern India. One of the major constraints is the lack of professional management. Many FPOs are managed by farmers who have limited resources and technical expertise, which affects decision making and business activities. Poor infrastructure including lack of warehouse facilities, transportation and processing units are major issues that limits the operational capacity of FPOs in the region. Another significant challenge is the meagre amount of capital which further accelerates financial constraints and limited access to institutional credits. Therefore, this major restriction creates huge hurdles in their ability to expand business activities such as procurement, storage and value addition throughout the areas. In addition, fragile market linkages further reduce their competence as many FPOs struggle to connect directly with larger markets and often depend on local traders.

Field survey evidence from Dakshin Dinajpur district of West Bengal describes that irregular procurement of production; post-harvest management facilities, low price realization and insufficient finance are huge constraints which the FPOs members are finding it hard to come up with on daily basis. (Gupta & Dutta,2026).

Way Forward

To improve the performance and sustainability of Farmer-Producer Organizations (FPOs) in Eastern India, several policies including capacity building and collaborative thinking of the members are need to be reinforced. Government initiatives under the “Formation and Promotion of 10,000 FPOs” scheme provides training and handholding support for five years which enhances in developing managerial and entrepreneurial skills among farmers (Government of India, 2025). Another important aspect is to bolster the economic connections of the farmers through many new networks. Therefore, platforms such as the electronic National of Agriculture Market (e-NAM) can help FPOs to access wider markets and ensure better price discovery for farmers (SFAC, 2025). Regulations in the form of equity grants, credit guarantee schemes and financial assistance up to ₹18 lakh per FPO have been introduced to encourage the financial base of these organizations (Government of India, 2021).

After achieving the target of forming 10,000 FPOs, the Government of India is now focusing on strengthening and supporting of existing FPOs. Hence, recently the government has adopted regulations highlighting the need to develop FPO federations, promoting value addition and improving institutional support to ensure long-term sustainability of FPOs.

Conclusion

Farmer Producer Organizations (FPOs) have emerged as an important institutional mechanism for improving the economic sustenance of small and marginal farmers in Eastern India. The analysis highlights in reducing input costs, improving market connections and strengthening the bargaining power of farmers and management of crop yields along with mitigating post-harvest losses. Field-based evidence from West Bengal further reflects that FPOs are actively involved in providing resources and technical guidance to their members, contributing to better farm practices and the enhancement of income. However, depending on the field supported data of the states under study the performance of FPOs is not uniform across the areas as several challenges emerged out such as limited capital framework, fragile market linkages, lack of professional management in coaching and inadequate infrastructures continue to affect their effectiveness creating obstacles which can be attenuated through proper institutional governance for long term success in the eastern region of India.

In this context, the focus of policy should move beyond increasing the number of FPOs towards consolidating their operational capacities and financial sustainability by promoting value addition and developing marketing abilities. Overall, FPOs hold significant potential to transform the agricultural sector in Eastern India, provided that adequate support mechanisms are in place to ensure their growth and efficiency.

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RESEARCH VS. INNOVATION: AMBIGUITY AND EXPECTATIONS IN SCIENTIFIC INSTITUTIONS

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The scientific community, particularly within government research institutions such as the Indian Council of Agricultural Research (ICAR), is currently experiencing a growing shift in expectations. Scientists and technical personnel are increasingly expected not only to conduct research but also to generate innovative technologies, patents, and practical solutions that can directly contribute to agricultural and livestock development. While this objective is important for national growth and institutional reputation, the framework under which scientists are functioning often creates confusion and contradiction between the concepts of “research” and “innovation.” Traditionally, research refers to the systematic investigation of a scientific problem through experimentation, validation, and analysis. The primary objective of research is to generate reliable knowledge supported by scientific evidence and previously published literature. Most projects in ICAR institutes are funded under research budget heads, where scientists are required to formulate hypotheses, conduct trials, validate results, and publish findings in peer-reviewed journals. Scientific publications also demand strong literature support, proper citations, and references from earlier studies. In this process, researchers often revisit, repeat, or refine previously studied concepts. In many ways, the term “research” itself implies “re-searching” or investigating existing knowledge further to improve scientific understanding.

However, alongside these conventional expectations, scientists are simultaneously encouraged to develop entirely new technologies, innovations, and inventions. Institutes are often evaluated based on the number of technologies released, patents filed, or innovative products developed. Higher authorities expect institutions to contribute novel technologies that can strengthen institutional reputation, improve extension outreach, and support farmers and industries. While such expectations are understandable and beneficial, they also create a contradiction within the existing scientific system.

The contradiction arises because innovation and invention require freedom of thought, experimentation beyond existing literature, and practical problem-solving approaches. At the same time, the current research framework places heavy emphasis on references, prior publications, and established methodologies. When every scientific observation must be justified using earlier literature, the possibility of producing completely original ideas becomes restricted. A scientist attempting to introduce a novel field-based innovation may face criticism if supporting references are unavailable, even though originality itself implies limited prior documentation.

This challenge becomes more significant in agricultural and livestock sciences, where practical field innovations are often developed through experience, observation, and localized problem-solving rather than through conventional laboratory research alone. Farmers, field technicians, and scientists working closely with rural communities frequently identify unique practices or technologies that may not yet be scientifically documented. However, due to the rigid structure of research evaluation, such innovations may struggle to gain institutional recognition unless they are converted into formal research publications supported by references and repeated trials.

Therefore, there is a need to reconsider the terminology and framework under which innovation-oriented scientific work is carried out in government institutions. One possible approach is to distinguish between “research” and “search” or exploratory innovation activities. Research may continue to focus on hypothesis testing, scientific validation, and academic investigation, while “search” could represent exploratory, innovation-driven activities aimed at solving practical problems and developing new technologies.

Under such a framework, scientists and technical staff could be encouraged to pursue creative ideas, indigenous technologies, field-based innovations, and practical engineering solutions without excessive dependence on existing references. Instead of solely relying on literature review as the primary measure of scientific value, institutions could establish robust technical evaluation committees comprising subject experts, engineers, extension specialists, and policymakers. These committees could evaluate innovations based on originality, applicability, scientific soundness, economic feasibility, and farmer benefit.

Such an approach would create a more supportive environment for creativity and innovation within government institutions. Scientists would have greater intellectual freedom to experiment with unconventional ideas and practical technologies. Technical staff, who often possess valuable field-level experience, would also gain opportunities to contribute meaningfully to innovation processes. This may ultimately lead to the development of low-cost, location-specific, and farmer-friendly technologies that directly address real-world agricultural challenges.

Furthermore, differentiating research from innovation-oriented “search” activities could help reduce the psychological pressure currently experienced by many scientists and technical staffs. At present, scientists and technical staffs are expected to simultaneously publish high-impact research papers, secure external funding, develop technologies, file patents, and achieve extension outcomes. Balancing all these expectations within a single framework can become difficult and may discourage risk-taking or creative experimentation. A dual framework recognizing both academic research and exploratory innovation could provide a more balanced and productive scientific ecosystem.

Research in its traditional form may remain particularly relevant within academic programs such as Master’s and PhD studies. Students pursuing postgraduate education work within limited time periods and are primarily trained in scientific methodology, experimentation, literature review, and evidence-based analysis. Their work naturally emphasizes validation and scholarly publication. In contrast, scientists and technical staffs working in long-term institutional service roles often engage directly with field problems, farmer needs, and technological applications. Therefore, their contributions may extend beyond conventional academic research toward innovation, adaptation, and technology development.

Conclusion

In conclusion, the growing expectations placed upon scientists and technical staffs in institutions such as the Indian Council of Agricultural Research reveal an important ambiguity between the concepts of research and innovation. While research remains essential for scientific advancement and academic credibility, innovation requires flexibility, originality, and freedom from excessive procedural limitations. The present system often places scientists and technical staffs in a contradictory position where they are expected to produce entirely new technologies while simultaneously remaining confined within conventional research frameworks heavily dependent on previous references and validations.

Therefore, there is a need to rethink the terminology and operational framework used in government scientific institutions. The term “research” may gradually be replaced or supplemented by the concept of “SEARCH” — representing Scientific Exploration, Application, Resourcefulness, Creativity, and Human-centerd innovation. Such a framework would encourage scientists and technical personnel to focus more on discovery, practical problem-solving, indigenous innovation, and technology development rather than only re-validating previously established knowledge.

Adopting the concept of “SEARCH” could provide greater intellectual freedom, promote creativity, and create a more innovation-friendly scientific ecosystem. Instead of emphasizing only publication-oriented outputs, institutions could encourage real-world solutions, field-based technologies, and farmer-centred innovations evaluated through strong technical committees and practical applicability. This transition may ultimately help government institutions achieve both scientific excellence and meaningful technological advancement for society.

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POLICY REFORMS AND AGRICULTURAL TRANSFORMATION IN INDIA: TRENDS, CHALLENGES AND THE WAY FORWARD

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Abstract

Agriculture is still important to the Indian economy, despite the decreasing role in GDP, providing food security and livelihoods. The paper will discuss how policy reforms have spurred agricultural transformation in the form of subsistence based to market based and technology intensive production. It examines the important stages such as the Green Revolution, liberalization since 1991, and recent income support, risk reduction, and market integration initiatives. Empirical data shows that there is an ongoing structural imbalance whereby agriculture has a huge proportion of the workforce in comparison to its GDP contribution implying low labour productivity. The production patterns indicate that the food-grains are replaced by horticulture which exceeded the level of food-grains production since 2012-13. Nonetheless, there are still problems like small landholdings, fluctuation in prices, infrastructure gaps and risk associated with climatic changes. The paper points out the necessity of extensive sustainable policy changes.

Keywords: Agricultural transformation, policy reforms, structural imbalance, horticulture diversification

Introduction

Agriculture is still an element of the Indian economy, providing a large share of the population and contributing to food and nutritional security (Satyasai and Shukla, 2016). The sector has structural imbalances as it still has a significant number of workers even though its share in Gross Domestic Product (GDP) has been decreasing (Patel *et al.,* 2022). Agricultural transformation is the process of the transition of traditional, subsistence-based agriculture to a more productive, market-based and technologically-intensive one (Barrett *et al.,* 2023). This has been influenced in India by several policy interventions, institutional developments and the technological advancements and it is important to understand how policy reforms can contribute to this transition in order to design future strategies to enhance the income of farms and make them sustainable (Gulati and Juneja, 2018).

Evolution of agricultural policy reforms

The policies of agriculture in India have changed drastically over time as the focus has changed to income growth and to sustainability instead of food security.

Early phase: Productivity Enhancement: The Green Revolution was a time of change that brought in high yielding varieties, the extension of irrigation, and the use of chemicals. This resulted in a significant food grain production and contributed to self-sufficiency.

Liberalization and market reforms: The economic reforms of the post-1991 period were focused on market orientation, decreased state intervention, and promotion of participation of the private sector. These reforms enabled superior integration of agriculture to national and global markets.

Recent policy initiatives: Recent reforms are aimed at income support, risk management, and market efficiency:

- Price assurance minimum support price (MSP).
- PM-KISAN as direct income transfers.
- Pradhan Mantri Fasal Bima Yojana (PMFBY) to reduce risks.
- e-NAM to integrate the digital market.

All these policies are meant to enhance income of farmers, minimize vulnerability and efficiency.

Trends in agricultural transformation

Structural changes: The transformation of Indian agriculture has been the gradual change in subsistence farming to commercialization. There is a noticeable decline in the share of agriculture in GDP, accompanied by continued dependence of the population on the sector.

Diversification: Farmers are also moving out of the traditional cereals to high-value crops like fruits, vegetables, livestock and fisheries. This transformation is facilitated by the evolving consumption patterns, urbanization and improvement in market opportunities.

Technological advancement: The embrace of better seeds, mechanization and irrigation technologies and online platforms have resulted in a high level of productivity. New technologies, like precision farming and data-driven agriculture are only increasing the pace of transformation.

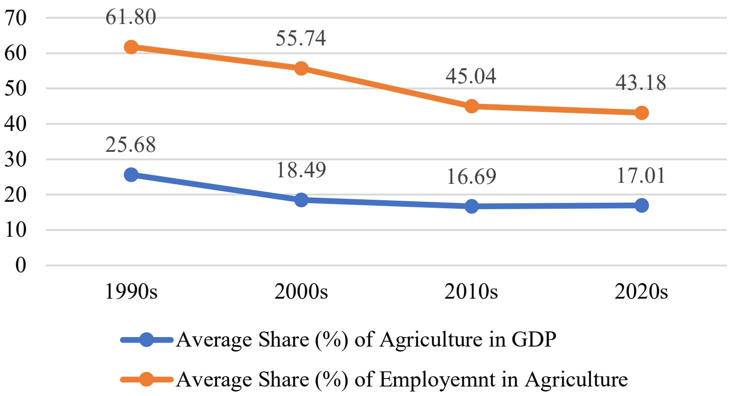
Market Integration: There has been increased connectivity, infrastructural development and digital platforms, which have enhanced the relationship between farmers and markets. Nevertheless, there exists regional differences in access to markets.

Empirical trends

Structural transformation in Indian agriculture:

This (Figure 1.) demonstrates how an economy has changed structurally in four decades with a gradual decrease in the proportion of agriculture both in terms of GDP (25.68 % to 17.0 %) and its share of employment (61.80 % to 43.18 %). The fact that the employment share has always been higher than the GDP contribution by a factor of about 2.5x indicates low agricultural labour productivity compared to other sectors and inadequate structural transformation, and the fact that the agricultural GDP share has increased significantly in the 2020s, could indicate opportunities to increase agricultural labor productivity or sector shocks.

Figure 1. Decadal share (%) of agriculture in GDP Vs employment



(Source: www.data.worldbank.org)

Growth in agricultural output

The table (Table 1.) sheds light on the structural change of agricultural production in India by comparing the food-grain and horticultural production in the selected years. During the initial years (1991-92), food-grain production (168.38 million tonnes) was much more than horticultural production (97 million tonnes) and therefore the difference between them was enormous. This shows that there was domination in traditional cereal-based agriculture.

Table 1. Shift from food-grains to horticulture production in India

Year	Food grains (million tonnes)	Horticulture (million tonnes)	Difference (H–F)
1991–92	168.38	97	–71.38
2010–11	244.49	241	–3.49
2012–13	257.13	269	+11.87
2024–25	357.73	370.74	+13.01

(Source: www.indiastat.com)

Both industries grew over time but horticulture grew at a higher rate. By 2010-11, foodgrain production was nearly close to horticulture production 244.49 and 241 million tonnes respectively. The biggest shift was made in 2012-13, when the horticultural production (269 million tonnes) overtook foodgrain production (257.13 million tonnes). This negative to positive difference change is a structural change to high-value agriculture. By 2024-25, production of horticulture (370.74 million tonnes) surpassed food production (357.73 million tonnes), further supporting the long-term leadership of horticulture in terms of output.

Challenges in agricultural transformation

Regardless of this progress, there are still a number of limitations to agricultural transformation:

- Limited economies of scale due to small and fragmented landholdings.
- Market uncertainty and volatility of prices.
- Poor infrastructure such as storage and transportation.
- Inequality in development in regions.
- Poor institutional credit and extension facilities.

Such obstacles limit the success of the policy interventions and restrict income growth of farmers.

Policy implications and way forward

In order to realize sustainable agricultural transformation that is inclusive, the following policy actions are necessary:

- Enhancing market reforms to guarantee improved price realization.
- Increasing infrastructure investment such as cold chains and logistics.
- Moving towards climate-resilient agriculture.
- Using digital technologies to realize precision farming and market intelligence.
- Ensuring better agricultural extension systems.

The government, the private sector and the farmer institutions need to work in a coordinated manner to bring about long-term change.

Conclusion

Agricultural transformation in India has been shaped by a series of policy reforms aimed at improving productivity, ensuring food security, and enhancing farmers' income. While significant progress has been made, the sector continues to face structural and institutional challenges. Future policy efforts must focus on bridging regional disparities, strengthening market linkages, and promoting sustainable practices. A holistic and inclusive approach will be key to achieving resilient and prosperous agricultural systems.

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KISAN CREDIT CARD AS A CATALYST FOR VIKSIT BHARAT 2047: LINKING FINANCIAL INCLUSION WITH SUSTAINABLE AGRICULTURE

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Abstract

India's vision of becoming a fully developed nation by 2047 known as Viksit Bharat 2047 rests significantly on transforming its agriculture sector, which employs nearly 46 percent of the national workforce and contributes around 18 percent of GDP. The Kisan Credit Card (KCC), launched in 1998 on the recommendation of the R.V. Gupta Committee and implemented by NABARD in partnership with commercial banks, regional rural banks, and cooperative banks, is one of India's most far-reaching instruments for delivering institutional credit to farming households. Despite its scale, with over 7.4 crore active accounts with an aggregate credit limit exceeding Rs. 8.9 lakh crore as of 2023. Significant gaps remain in awareness, digital access, and equity of coverage. This article examines how the KCC scheme can be strategically repositioned not merely as a credit delivery tool but as a catalyst for financial inclusion and sustainable agricultural development, thereby contributing to the aspirations of Viksit Bharat 2047. The article also identifies persistent barriers and offers actionable policy recommendations.

Keywords: Kisan Credit Card, Financial Inclusion, Viksit Bharat 2047, Sustainable Agriculture, Rural Credit, Agricultural Finance, India

Introduction

Agriculture remains the backbone of India's rural economy, yet the very people who sustain the nation's food security are among its most financially vulnerable. Access to affordable institutional credit is widely recognised as a decisive factor in determining whether a farmer can invest in quality inputs, modern machinery, irrigation infrastructure, and crop insurance. Without formal credit channels, small and marginal farmers routinely turn to moneylenders who charge exorbitant interest rates, perpetuating debt cycles that erode farm incomes across generations. The Kisan Credit Card scheme was conceived precisely to break this cycle. After the R.V. Gupta Committee's 1998 recommendation, NABARD and the banking sector jointly rolled out a revolving credit facility that allowed farmers to meet their seasonal production needs without repeatedly applying for fresh loans. Over the following two decades, the scheme was progressively expanded to cover allied activities, household consumption needs, and medium-term farm investments. The Government of India's articulation of Viksit Bharat 2047 as a centenary development goal calls for inclusive and sustainable growth across all sectors of the economy. For agriculture, this translates into a dual mandate: improving farmer incomes through institutional support, and transitioning toward ecologically responsible production systems. The KCC, when reimagined and fully leveraged, can serve both objectives simultaneously. This article explores that convergence in detail.

Evolution and Coverage of the Kisan Credit Card Scheme

From its inception as a crop loan instrument, the KCC underwent substantial restructuring in 2004 to include long-term credit components and farm maintenance expenses, and again in 2012 when a simplified application process, a smart card facility, and an ATM-enabled RuPay card were introduced. These revisions made the scheme far more practical, enabling farmers to access credit at their convenience rather than making repeated bank visits during peak agricultural seasons. A landmark expansion came in 2020 under the Pradhan Mantri Kisan Samman Nidhi (PM-KISAN) framework, which launched a saturation drive linking all eligible PM-KISAN beneficiaries to the KCC. By 2023, active KCC accounts exceeded 7.4 crore with an aggregate credit limit crossing Rs. 8.9 lakh crore. This expansion was particularly notable in historically underserved states such as Uttar Pradesh, Bihar, Jharkhand, and West Bengal, where institutional credit penetration had remained low for decades. The interest subvention scheme associated with KCC ensures that prompt-repaying farmers receive credit at an effective rate as low as 4 percent per annum.

KCC as a Vehicle for Financial Inclusion

The Kisan Credit Card (KCC) has become a cornerstone of financial inclusion in India, bridging the gap between simply owning a bank account and actively utilizing formal credit. While initiatives like Jan Dhan Yojana achieved high account ownership, the KCC ensures these accounts remain functional and productive for the rural workforce.

Key Impacts of the KCC Scheme

- **Boosting Agricultural Productivity:** KCC holders show higher confidence in managing operational costs. Access to credit encourages investments in high-quality seeds, micro-irrigation, and modern storage, directly improving farm yields and income stability.
- **Empowering Women Farmers:** Recent government efforts have successfully linked women to the KCC network. Research indicates that female beneficiaries are more likely to reinvest their earnings into their farms than those relying on high-interest informal lenders, fostering greater gender equity in agriculture.
- **Building Creditworthiness:** Beyond immediate loans, the KCC helps unbanked households establish a formal financial footprint. Long-term cardholders find it significantly easier to secure additional institutional loans for diversifying their businesses or purchasing assets.

Linking KCC with Sustainable Agriculture

The integration of the Kisan Credit Card (KCC) with sustainable farming practices is a critical shift toward long-term agricultural health. By providing reliable credit, the KCC reduces the pressure on farmers to prioritize immediate, high-yield results that often degrade soil and water resources.

How KCC Supports Sustainable Farming:

- **Eliminating Distress Sales:** Reliable institutional credit prevents farmers from selling their produce prematurely at low prices. This financial stability allows them to invest in soil health, crop rotation, and organic composting rather than relying on quick-fix chemical inputs.
- **Green Investment Incentives:** Recent NABARD guidelines encourage banks to offer specific KCC sub-limits for eco-friendly infrastructure, such as drip irrigation, farm mechanization, and organic inputs.

- **Integrated Digital Ecosystem:** By linking credit with insurance (PMFBY), infrastructure funds (AIF), and digital markets (e-NAM), farmers gain a streamlined support system. Evidence from pilot projects in Gujarat and Punjab shows that this integrated approach can boost farmer income by **15% to 25%** over two seasons.
- **Higher Net Returns:** Farmers utilizing "green credit" instruments are statistically more likely to adopt sustainable methods, leading to better net returns per hectare compared to those using traditional informal borrowing.

Challenges in Realizing the Full Potential of KCC

Despite its transformative reach, the KCC scheme continues to face structural and operational challenges that must be squarely acknowledged. A NABARD survey conducted in 2023 found that over 35 percent of eligible farmers in Bihar and Uttar Pradesh were unaware of the scheme or its revised benefits. Extension workers and bank officials often struggle to communicate updated terms, especially in remote and tribal areas where literacy rates remain lower and banking infrastructure is sparse. The digitisation of KCC processes, while broadly beneficial, has created an unintended exclusion of farmers who lack smartphones, stable internet connectivity, or digital literacy. Patel and Chauhan (2023) documented that the shift toward online application portals, while reducing turnaround time in peri-urban areas, paradoxically disadvantaged the most marginalised farmers in interior villages who cannot navigate digital interfaces independently. Collateral and documentation requirements continue to deter small and marginal farmers, particularly tenant cultivators and sharecroppers who lack formal land ownership records. Despite RBI and NABARD guidelines relaxing norms for small borrowers, branch-level implementation remains inconsistent, with many bank officials continuing to demand land documents or guarantors that vulnerable groups cannot easily furnish. Repayment distress during adverse seasons caused by floods, droughts, or pest outbreaks results in KCC accounts turning non-performing, after which affected farmers are effectively excluded from formal credit. While PMFBY crop insurance is designed to address seasonal losses, protracted claim settlement delays and basis risk frequently leave farmers without timely relief, undermining the credit discipline that the KCC system is built to encourage.

Source: AI-generated illustration (created using OpenAI image generation tools) based on the concepts and policy recommendations presented in this article.

Policy Recommendations for Aligning KCC with Viksit Bharat 2047

To align the Kisan Credit Card (KCC) with the **Viksit Bharat 2047** vision, the program must evolve from a basic loan scheme into a strategic tool for sustainable development. Experts suggest a shift toward "smarter" and more equitable credit to drive rural prosperity.

Policy Framework for Future-Ready Agricultural Credit:

- **Hyper-Local Outreach and Literacy:** Enrolment should be decentralized to the panchayat level, utilizing Gram Sabhas and Krishi Vigyan Kendras. Training extension officers in financial counseling and establishing peer-learning networks can bridge the awareness gap effectively.
- **Digital Accessibility:** To reach the most marginalized, KCC services must be available via USSD on feature phones. Streamlining the e-KYC process to ensure a seven-day disbursement window will build trust among first-time borrowers.
- **Introduction of "Green KCC":** A new sub-category should offer lower interest rates and higher credit limits for farmers practicing ecological stewardship. Rewarding organic farming, soil health adherence, and watershed management aligns credit with India’s climate goals.
- **Inclusivity for Landless Cultivators:** Barriers for tenant farmers, women, and sharecroppers must be removed. Leveraging Joint Liability Groups (JLGs) and Farmer Producer Organisations (FPOs) allows for credit access based on collective trust rather than individual land titles.

Key Recommendations at a Glance

Strategy	Primary Objective
Financial Counseling	Integrated agronomy and financial literacy at the village level.
Green Incentives	Preferential rates for verified sustainable agricultural practices.
Institutional Buffers	Using FPOs and JLGs to vouch for those without formal land records.

Conclusion

The Kisan Credit Card scheme, now in its third decade, stands at a critical juncture. It has already achieved remarkable scale reaching over 7.4 crore farming households and channeling trillions of rupees into agricultural production across India. Yet the full arc of its potential as a connector between financial systems and sustainable land use, between rural households and national development goals, remains substantially unrealised. The vision of Viksit Bharat 2047 demands that no farmer be left behind not by poverty, not by geography, not by gender, and not by ignorance. The KCC, when implemented with equity, innovation, and ecological consciousness, is more than a credit card. It is an institutional commitment that India’s farmers matter that their labour deserves structured support, and that sustainable agriculture is the foundation, not the footnote, of a developed India. Sharma and Mishra (2023) concluded that KCC-linked households in Eastern India showed not only higher agricultural productivity but also greater household resilience against climate shocks. That finding captures the dual promise of this scheme: it is simultaneously a poverty-alleviation instrument and a climate-adaptation tool. As India charts its course toward 2047, the Kisan Credit Card must be at the centre of that journey expanded, deepened, and aligned with the sustainable future the nation aspires to build.

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BRIDGING THE GAP: ACCELERATING INDIA'S SELF-RELIANCE IN PULSES

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Abstract

India currently stands as the global leader in pulse production, yet the sector faces significant hurdles, with 85–87% of cultivation remaining rain-fed and highly susceptible to erratic monsoons and climate stress. Despite a rising national demand projected to reach 32 million tonnes by 2030, productivity is often hampered by the use of nutrient-deficient marginal lands, low irrigation coverage, and the slow adoption of high-yielding varieties (HYVs). To address these challenges, the Mission for Aatmanirbharta in Pulses (2025–31) has been launched as a strategic framework to achieve self-sufficiency by boosting domestic output and reducing import dependency. Furthermore, self-reliance empowers the nation's small and marginal farmers—who constitute the bulk of the agricultural workforce—by providing them with stable income through guaranteed procurement schemes like PM-AASHA and higher Minimum Support Prices (MSP). Beyond the economic benefits, increasing pulse cultivation naturally enhances soil health through nitrogen fixation, promoting more sustainable farming cycles and reducing the need for chemical fertilizers. Ultimately, a self-sufficient pulses sector strengthens rural prosperity, drives employment in new post-harvest processing hubs, and aligns with the broader national vision of a resilient and independent "Viksit Bharat."

Keywords: Pulses production, pulses demand, Mission for Aatmanirbharta in Pulses, and food security.

Introduction

Pulses are more than just a basic agricultural product in India; they are essential to rural economy, soil health, and national well-being. Even though India is the world's leading producer, importer, and consumer of pulses. The development of sustainable, independent domestic production is still the India’s top priority. The increased demand for pulses, which has fueled by rising wages and a growing emphasis on balanced diets, offers a crucial chance for agricultural expansion. Pulses are a nutritional powerhouse that goes beyond economics. Pulses are affordable, high-protein (20–30% protein) staples, providing essential nutrients like iron, zinc, and folate that complement cereal-based diets. They are vital for combating protein-energy malnutrition. According to the National Institute of Nutrition, they make up around 25% of India's dietary protein. However, the average daily intake is still less than the suggested 85 grams, which directly contributes to the country's persistent protein-energy malnutrition. Significant geopolitical and economic disruptions are being caused by the continuous confrontation in West Asia between Israel, the United States, and Iran.

These disruptions have far-reaching effects on global agriculture and India's food security. Energy and nutrient supply chains have been interrupted by the near closure of the Strait of Hormuz, a critical chokepoint that handles 20% of the world's oil shipments and roughly 30% of the fertilizer trade. This has increased costs and threatened crop yield globally. India, the world's largest consumer and producer of pulses, imported approximately 5.6–5.7 million tonnes (mt) of pulses in FY26, valued at $3.57 billion. While imports were historically high in 2024-25, they reduced in 2025-26 due to higher domestic production and a 35% decline in import value. Key imports include yellow peas, lentils, and urad.To bridge the demand-supply gap, the Government of India is focusing on increasing productivity, aiming to reach 350 lakh tonnes by 2030-31 through initiatives like the Mission for Aatmanirbharta in Pulses.

India's Pulse Production

Twelve different pulse crops can be grown in India's varied agroclimatic conditions during the summer, rabi, and kharif seasons. Madhya Pradesh, Maharashtra, and Rajasthan account for roughly 55% of the country's production, with the top ten states producing more than 91% of the total. The pulse production of different states is given in the fig.1. Closing these gaps is essential to lowering reliance on imports, guaranteeing nutritional security, and moving the nation closer to Atmanirbharta in the pulses sector.

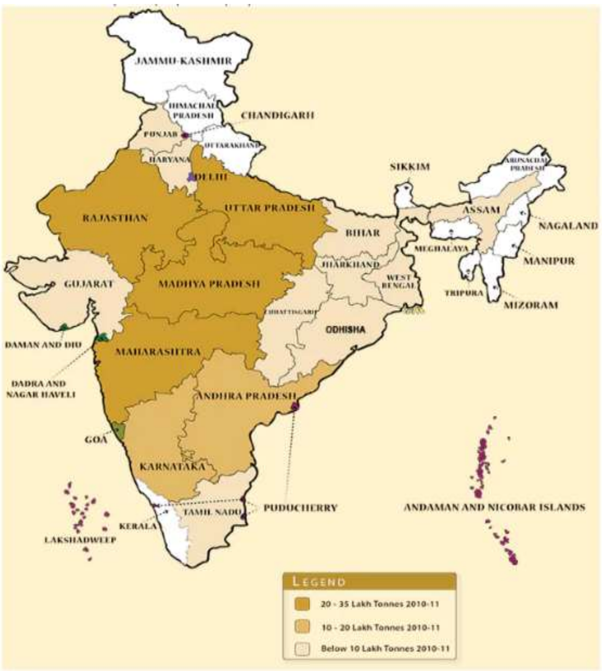

Fig.1. Pulse production by India states

The projected pulse production to rise steadily, with domestic supply estimated to reach 30.59 MT by 2030 and 45.79 MT by 2047. Gram (chickpea) is dominant ((40%) of total) pulse crop cultivated in India, followed by tur (arhar). Rabi pulses dominate with over 60 % of total pulse production, where average productivity is around 764 – 851 kg/ha.

Pulse demand trends in India

Annual consumption is around 28 million tons, with forecasts suggesting a need for 30.59 MT by 2030. Domestic production, often affected by monsoons, averages 25–26 MT, falling short of total demand. To bridge the gap, India imports significant quantities. In FY24, imports hit a 6-year high of 4.65 MT. Increasing population and improving dietary standards are pushing up demand for protein-rich foods. About 80% of pulse production depends on rainfed areas, leading to volatility. To stabilize prices, the government frequently adjusts duty-free import policies for yellow peas, tur, and urad. The projected pulse demand forecast is shown in the fig.2. The current per capita availability is roughly 45-50 grams per day, though nutritionists often recommend higher levels for balanced diets. India's pulse demand is increasing at an average annual rate of roughly 2-3%. By 2030, the projected requirement is expected to reach approximately 32 million tonnes. The current per capita availability is roughly 45-50 grams per day, though nutritionists often recommend higher levels for balanced diets. While India has significantly boosted production through the National Food Security Mission, the country still relies on imports (primarily from Canada, Australia, and African nations) to bridge the gap during years of erratic monsoon rainfall.

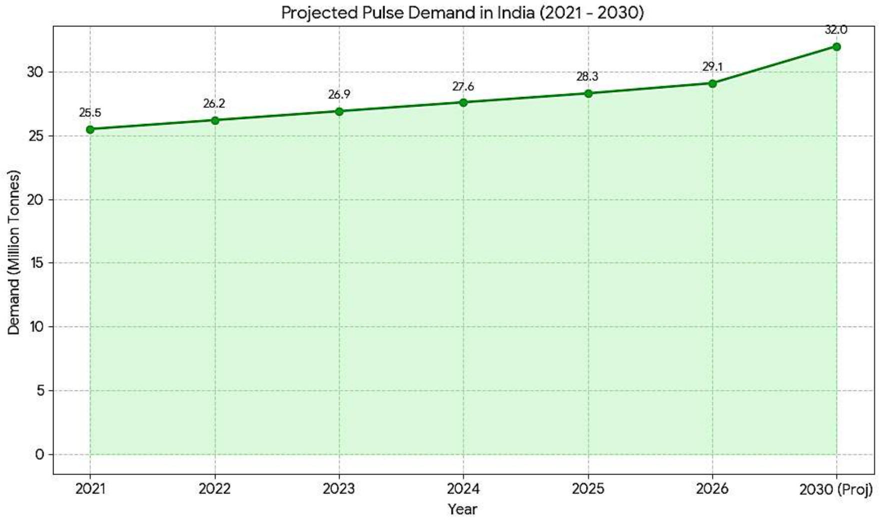

Fig.2. Project Pulse Demand in India

Mission for Aatmanirbharta in Pulses

The Mission for Aatmanirbharta in Pulses (2025–31) is a strategic initiative designed to achieve national self-sufficiency by significantly boosting domestic production, reducing import dependency, and enhancing farmer livelihoods. To expand the cultivation footprint, the Mission targets an additional 35 lakh hectares by utilizing rice fallows and promoting intercropping and crop diversification. A central pillar of this strategy is the modernization of seed infrastructure, focusing on the development and distribution of climate-resilient, high-yielding, and pest-resistant varieties. This effort includes the production of 126 lakh quintals of certified seeds and the free distribution of 88 lakh seed kits to farmers. To ensure quality and consistency, the ICAR will oversee breeder seed production while the SATHI portal manages quality assurance, supported by state-level five-year rolling production plans. Furthermore, the Mission adopts a holistic approach to agricultural productivity by integrating soil health management, balanced fertilization, mechanization, and large-scale technical demonstrations facilitated by ICAR, Krishi Vigyan Kendras (KVKs), and state agencies. Together, these measures aim to build a resilient and independent pulse production ecosystem capable of meeting India’s rising domestic demand.

Through the Pradhan Mantri Annadata Aay SanraksHan Abhiyan (PM-AASHA), the government is strengthening financial security for farmers by guaranteeing the procurement of essential pulses such as Tur (Arhar), Urad, and Masoor. Over the next four years, the National Agricultural Cooperative Marketing Federation of India (NAFED) and the National Cooperative Consumers' Federation (NCCF) will ensure 100% procurement in participating states, providing fair pricing and reducing market volatility. This initiative is complemented by a major investment in the post-harvest value chain, which includes subsidizing 1,000 processing and packaging units at up to ₹25 lakh each to minimize losses and create rural employment. Following NITI Aayog's recommendations, a cluster-based strategy will be employed to optimize resource use and diversify cultivation geographically. By the 2030–31 season, the Mission aims to reach a production target of 350 lakh tons and a yield of 1,130 kg/ha across 310 lakh hectares. Ultimately, these efforts seek to eliminate import dependence and ensure long-term nutritional security through climate-resilient and soil-friendly farming practices.

Challenges in India's Pulse Production

The challenges facing pulse production in India are primarily rooted in environmental and structural constraints. Approximately 85–87% of pulse cultivation remains rain-fed, leaving crops in key producing regions like Madhya Pradesh and Maharashtra highly vulnerable to erratic monsoons, drought, and terminal heat stress. Because pulses are often relegated to marginal, nutrient-deficient lands with less than 15% irrigation coverage, their yields are significantly lower than those of major cereals. This productivity gap is further widened by a low seed replacement rate and the slow adoption of high-yielding varieties (HYVs). Furthermore, the high protein content of these crops makes them a prime target for pests such as the gram pod borer and pod fly, as well as diseases like Fusarium wilt. The sector is also dominated by small-scale farmers with less than two hectares of land, who lack the financial capacity to invest in modern technologies or manage market volatility. Finally, inadequate storage infrastructure leads to substantial post-harvest losses, ultimately diminishing the marketable surplus available to consumers.

Way forward

The advancement of India's pulse sector relies on a multifaceted strategy that integrates cutting-edge science with expanded land use. By leveraging modern breeding tools such as genomics, genome editing, and speed breeding, researchers aim to develop and deploy high-yielding varieties with enhanced resistance to biotic stress. A significant portion of production growth is expected to come from expanding cultivation into non-traditional areas—specifically targeting rice fallows—to increase the total acreage by 3.5 million hectares. To support this expansion, the seed chain will be strengthened from the breeder to the certified level through 150 dedicated seed hubs. On the field, productivity per hectare will be optimized, particularly in rain-fed regions, by promoting line-sowing, integrated pest management (IPM), and micro-irrigation. Finally, to provide the necessary economic incentive for farmers to transition from cereals to pulses, the government is committed to ensuring competitive Minimum Support Prices (MSP) alongside robust procurement systems.

Conclusion

The "Mission for Aatmanirbharta in Pulses" represents a pivotal advancement in securing India's nutritional and economic future. By emphasizing self-reliance, the initiative empowers the agricultural community through the adoption of modern technology, guaranteed procurement, and improved access to high-quality seeds, all while championing climate-resilient and sustainable farming techniques. This comprehensive strategy integrates scientific innovation with cluster-based interventions and enhanced value chains, aiming to satisfy domestic demand, eliminate reliance on imports, and establish India as a global frontrunner in sustainable production. Beyond basic food security, the Mission's broader impact encompasses improved soil health, the expansion of rural employment, and the development of robust post-harvest infrastructure. Ultimately, these efforts establish a resilient and productive foundation for the pulses sector, driving rural prosperity and contributing significantly to the vision of a Viksit Bharat**.**

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MAXIMUM RESIDUE LIMITS IN AQUACULTURE: A KEY TO SUSTAINABLE FISH FARMING IN INDIA

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Abstract

India has emerged as one of the world's leading aquaculture producers, contributing both to domestic nutrition and international seafood markets. However, the extensive use of antibiotics, pesticides, and veterinary/fishery drugs to manage disease and enhance production presents significant risks of chemical residues in aquaculture products. Maximum Residue Limits (MRLs) play a crucial role in safeguarding public health, protecting market access, and promoting sustainable aquaculture practices. This article discusses the scientific basis of MRLs, the regulatory frameworks governing residue management in India, farm-level challenges, monitoring mechanisms, and strategic recommendations to align Indian aquaculture with global food safety and sustainability standards.

Keywords: Maximum residue limit (MRL), Aquaculture, risk, Withdrawal Period, Sustainable fishing, regulatory

Introduction

Aquaculture has become a critical contributor to India's food production system, livelihood security, and export industry. India ranks second globally in aquaculture output, with farmed fish and shrimp accounting for substantial income, particularly in coastal and rural areas (FAO, 2020). However, intensive farming systems are vulnerable to disease outbreaks, prompting the use of antibiotics, disinfectants, and pesticides to maintain productivity. When these substances are improperly administered—whether through overdosing, poor-quality drugs, or premature harvesting—chemical residues can persist in edible tissues. These residues may exceed permissible limits, posing risks such as toxicity, allergenic reactions, and antimicrobial resistance (AMR). Moreover, non-compliance with residue standards can result in international trade rejections, harming the national economy and reputation. In this context, Maximum Residue Limits (MRLs) form the backbone of seafood safety assurance. MRLs specify the highest allowable concentration of a residue resulting from legally approved drug use, ensuring products are safe for consumption.

The Scientific and Toxicological Basis of MRLs

MRLs are derived from scientific toxicological assessments. Regulatory authorities evaluate the pharmacokinetics of drugs in aquatic species, the rate of residue depletion, and the Acceptable Daily Intake (ADI) for humans. The MRL is then set at a level that ensures consumer exposure remains well below the ADI throughout life (Codex Alimentarius, 2024).

The principle is simple: *proper drug use and correct withdrawal periods prevent harmful residues.*

Determining the NOAEL: Regulatory toxicologists first establish the *No Observed Adverse Effect Level* (NOAEL) through long-term animal in-vivo studies.

Calculating the ADI: The NOAEL is divided by uncertainty factors (typically 100-fold or greater to account for inter-species and intra-species variability) to determine the Acceptable Daily Intake (ADI) for humans.

Mapping Depletion Kinetics: In target species like shrimp or fish, scientists map out how a drug metabolizes and clears the body over time. The MRL is set at a tissue concentration that guarantees an individual's total dietary exposure will remain safely below the ADI over a lifetime.

Permissible and Prohibited Residue Thresholds in Indian Aquaculture

The following table outlines the current statutory Maximum Residue Limits (MRLs) and Extraneous Maximum Residue Limits (EMRLs) established by Indian regulatory bodies (FSSAI/CAA) for commercial fish and shellfish tissue:

Category	Drug / Substance Name	Established MRL / Threshold (mg/kg or ppm)	Regulatory Status & Context
Permitted Therapeutics *(Strict MRLs Apply)*	Oxytetracycline	0.1 mg/kg	Broad-spectrum antibiotic; requires careful withdrawal tracking.
	Tetracycline	0.1 mg/kg	Monitored carefully to prevent cross-resistance.
	Oxolinic Acid	0.3 mg/kg	Quinolone class; clearing times vary by water temperature.
	Trimethoprim	0.05 mg/kg	Often used in combination with sulfonamides.
Prohibited Substances *(Zero-Tolerance / MRPL)*	Chloramphenicol	0.0003 mg/kg (0.3 ppb)	Strictly banned; linked to bone marrow suppression in humans.
	Nitrofurans *(Furazolidone, Nitrofurazone, etc.)*	Nil / BDL	Carcinogenic risk; zero-tolerance enforcement in export markets.
	Malachite Green	Nil / BDL	Highly toxic industrial dye historically used as an antifungal agent.
	Fluroquinolones	Nil / BDL	Completely banned in coastal aquaculture to protect human health.
Environmental Contaminants & Heavy Metals	Lead (Pb)	1.5 mg/kg	Monitored to evaluate pond soil quality and industrial runoff.
	Mercury (Hg)	1.0 mg/kg	Bioaccumulative heavy metal; key metric for wild and farmed finfish.
	Cadmium (Cd)	3.0 mg/kg	Monitored to detect feed contamination and environmental exposure.

Indian Regulatory Framework for MRLs in Aquaculture

India utilizes a specialized, multi-agency framework designed to separate domestic oversight from export-oriented compliance.

Domestic Oversight

- Food Safety and Standards Authority of India (FSSAI): Operates under the Ministry of Health and Family Welfare. FSSAI codifies statutory MRL allocations for aquaculture products sold within domestic markets, aligning primarily with international Codex Alimentarius standards.
- Coastal Aquaculture Authority (CAA): Mandated to regulate environmental impacts and inputs in coastal zones. The CAA maintains a strict registry of approved aquaculture inputs, explicitly banning hazardous antibiotics and heavy-metal-based compounds in shrimp farming.

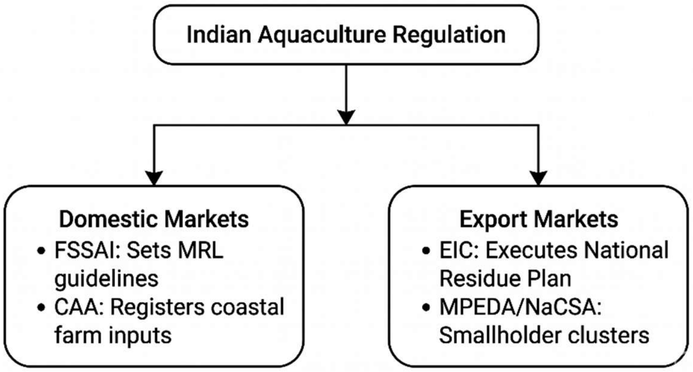
Export Enforcement

- Export Inspection Council (EIC): Acting as the official certifying body for outbound food commodities, the EIC administers the statutory *National Residue Control Plan (NRCP)*. It ensures all processing establishments undergo strict batch testing prior to export.
- Marine Products Export Development Authority (MPEDA) & NaCSA: MPEDA facilitates international trade compliance, manages farm registration networks, and issues diagnostic health cards. Its sister society, the National Centre for Sustainable Aquaculture (NaCSA), organizes small-scale farmers into structured clusters to enforce uniform biosecurity standards.

Global Market Alignment

Indian exporters must dynamically align operations with strict, evolving international standards:

- European Union (EU): Enforces highly sensitive performance limits and utilizes uniform food safety criteria across all member states.
- US Food and Drug Administration (FDA): Deploys import alerts and operates on a strict approved-drug registry for food-producing animals.
- Japan: Utilizes a comprehensive positive list system alongside specialized zero-tolerance protocols for unlisted veterinary drugs.



Strategic Benefits of Comprehensive MRL Compliance

Protecting Public Health: Mitigates immediate toxicological risks like bone marrow suppression linked to chloramphenicol exposure, prevents antibiotic hypersensitivity, and breaks the transmission pathway of drug-resistant bacteria from farms to human communities.

Sustaining Global Market Share: Minimizes costly border rejections at international ports of entry. This sustains high foreign exchange earnings and preserves the reputation of Indian seafood.

Fostering Ecosystem Integrity: Restricts the discharge of bioactive chemical compounds into surrounding coastal and freshwater ecosystems. This helps protect wild aquatic biodiversity and prevents soil microflora imbalances.

Driving Farm Profitability: Shifting focus from reactionary chemical interventions to proactive farm management directly lowers operational overhead, lowers disease-related mortality, and yields premium-quality harvests.

Systemic Farm-Level Challenges in India

Despite robust regulatory architectures, several operational vulnerabilities remain at the primary production level:

- **Fragmented Smallholder Demographics:** The Indian aquaculture landscape is dominated by small, non-contiguous homestead ponds. This fragmentation makes uniform biosecurity training difficult and encourages a reliance on informal peer networks rather than certified aquaculture pathologists.
- **Ad-Hoc Withdrawal Tracking:** Driven by fluctuating market prices or sudden disease scares, farmers occasionally harvest crops prematurely, cutting short the mandatory withdrawal period.
- **Counterfeit and Unlabeled Inputs:** The market contains mislabeled commercial preparations or "aqua-shop" blends that conceal banned antimicrobials under generic labels like "growth promoters" or "feed supplements."
- **Decoupled Laboratory Access:** While export-oriented facilities utilize advanced analytical equipment like Liquid Chromatography-Mass Spectrometry (LC-MS/MS), regional farming hubs often lack rapid, cost-effective diagnostic tools for real-time testing.
- **Dual-Standard Market Economics:** The domestic market rarely enforces the same strict residue testing applied to exports, reducing the incentive for farmers who do not sell to export supply chains to adopt rigorous compliance measures.

Monitoring, Testing, and Certification Procedures

The Residue Control Plan overseen by the EIC involves:

- Farm registration and traceability tagging
- Sampling of water, feed, and animal tissue
- Use of LC-MS/MS and HPLC for residue quantification
- Certification based on compliance documentation
- MPEDA provides farm health cards and farmer training
- State fisheries departments assist in capacity building

However, ongoing investment in rapid field diagnostic kits and mobile analytical labs is essential.

Actionable Recommendations for a Sustainable Future

To secure the future of Indian aquaculture, the industry should focus on five strategic pillars:

I. Transition to Preventive Biosecurity

Farms must shift from chemical treatments to preventive health management. This includes maintaining optimized stocking densities, implementing strict water filtration, and deploying scientifically verified probiotics (competitive exclusion bacteria) and natural immunostimulants to support animal health.

II. Standardize Input Supply Chains

Implement mandatory batch-traceability and QR-code labeling for all commercial feeds, supplements, and water conditioners to ensure transparency from manufacturer to farm.

III. Expand Decentralized Diagnostics
Deploy affordable, field-ready rapid diagnostic kits (such as ELISA or lateral flow strips) at the district level. This allows farmers to verify residue clearance before planning a harvest.

IV. Launch Targeted Extension Campaigns
Conduct practical training programs through local extension networks to teach smallholders how to read drug labels, calculate accurate biomass dosages, and track precise withdrawal timelines.

V. Integrate Food Safety and AMR Policies
Align FSSAI domestic monitoring with the *National Action Plan on Antimicrobial Resistance*. Establishing uniform residue standards for both domestic and export streams ensures that all consumers receive the same high standard of food safety.

Conclusion

Maximum Residue Limits are far more than bureaucratic hurdles; they are essential tools for public health safety and international trade. For India to retain its position as a global aquaculture leader, the industry must continue to bridge the gap between regulatory policy and farm-level execution. By investing in diagnostic infrastructure, enforcing input transparency, and championing preventive health management, India can ensure its aquaculture growth is both economically robust and environmentally sustainable.

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PROSPECT OF SOYBEAN CULTIVATION IN INDIA

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Abstract

Soybean is the ‘Wonder Seed ‘of the world. It’s use is of many fold. It provides both protein and fat to the malnutrition population. Soybean is cultivated in India in a large portion of dry climate area as well as hilly tract of Himalayas from Punjab to Manipur as Kharif crop. Proper cultural practices including varieties can influence the best productivity of the crop. Farmers should be provided with quality inputs and nearby infrastructures in processing the produce. It is expected in this way productivity at farmer’s level and area of cultivation both can be increased. Thus farmer’s income may increase appreciably.

Keywords: Soybean, cultivation regions, fat-oil, proteins, farmer’s income

Introduction

Soybean had been originated in China (North Eastern Provinces) and domesticated as early as 11 century B.C. However it spreads to other countries of world possibly during 18 century A.D. In recent time the spreading of soybean is mainly in countries viz. China, U.S.A., Brazil and Argentina. It is noted that the production per unit land area is much higher in U.S.A. than that of China. Brazil has almost equivalent production per unit land area. In India Soybean production per unit land area is almost one-fourth of U.S.A. productivity. Whereas productivity south asian countries are better than India (almost double). It is interesting to note that area of cultivation under soybean 11million hectares and placed under fourth position after U.S.A. Brazil and Argentina but more than that of China. However, total production of soybean is about 12 million metric tonnes less than that of China i.e. 16 million metric tonnes. Therefore ample scope for increasing productivity of soybean is in India. These can be achieved by genetic improvement for yield, incorporation of disease and lodging varieties, incorporation of planting of seeds, weed control and harvesting machinery.

Introduction of soybean to Indian subcontinent dates back to 1000AD through silk route from northern India and Himalayan mountains. Soybean cultivation got momentum during the 1970s as the vast monsoon fallow lands of Madhya Pradesh provided appropriate niche for its cultivation. Soybean as food plant is being grown in the country since last century under various names in different parts of country as Bhat, Bhatman, Bhatmas ,Ramkulthi, Bhut, Kalitur, Teliakulth and Garryakalay (Singh and Saxena,1979). The versatile adoption of soybean was adjusted and conceived that it can be grown successfully in areas wherever the rainfall does not exceed 35 inches. Hence the extensive growing of soybean was feasible throughout India, chiefly in the North Indian tract extending from Punjab to Khasi and Manipur hills and in Sindh. It was also grown on the slope of the Himalayas (Dupare *et al.,* 2008).

Uses

The crop is known for its high food value from centuries and it was used for food purposes (milk, douche, hamanatto, miso, sheyu, doufu, natto, tempeh, soya flour, green beans, roasted soynuts, and soybean sprouts) with the dawn of civilization. Major use of soybean is its oil and meal. Oil extracted from soybean into shortening, margarine, cooking oil and salad dressings. Soy oil is also used in industrial paint, varnishes, caulking compounds, linoleum, printing inks, and products. In recent years soy based lubricant and fuel products are replacing non-renewable petroleum products. Lechithin extracted from soy oil is a natural emulsifier and lubricant used in many food, commercial and industrial applications. For example, it helps keep the chocolate and cocoa butter in a candy bar from separating. It is also used in pharmaceuticals and protective coatings. Soy meal is a very good component of animal feed mixture because of high protein content. Soy flour, grits, chunks and tofu are made from grinding whole soybeans are used as food items. Soy sauce is also used in salad and cooking and even industrial derivatives such as biofuels, bio plastics, inks, lubricants, and adhesives. Historically dominated by soy meal, India's soybean exports now require diversification toward premium products to stabilize performance and enhance competitiveness.

Productivity

Production genetics increased yield of soybean cultivars developed from 10 to 30kg ha^{-1}yr^{-1}. Desirable lines are selected as future cultivars based on high and stable yields across years and locations.

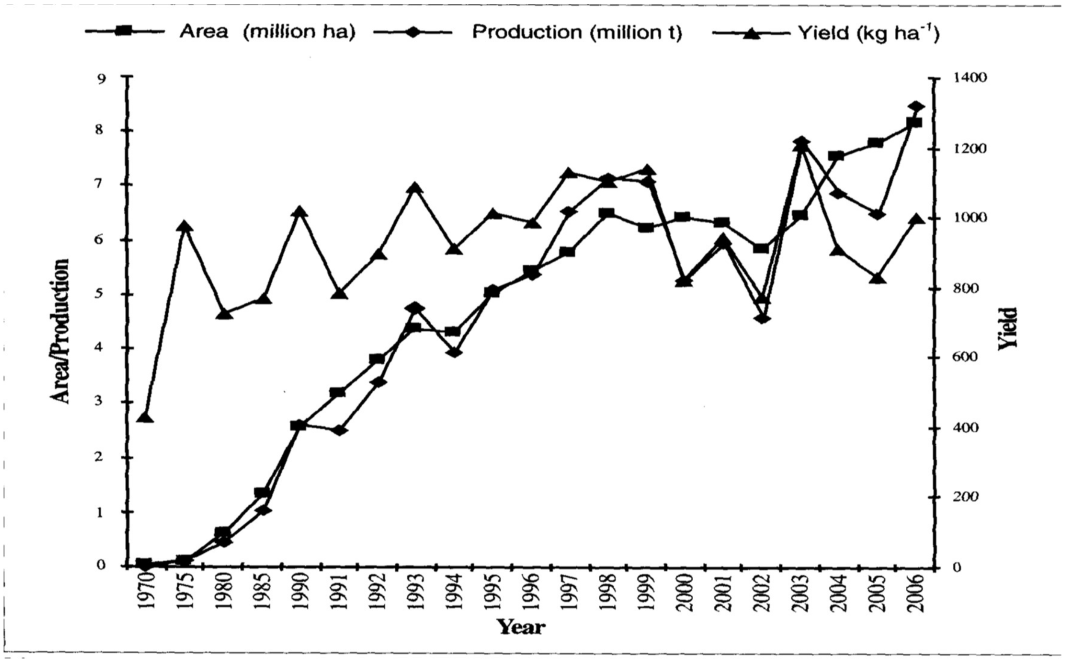

Fig. 1. Area, Production and Yield in India (Yearwise) (after Dupare et al., 2008)

Yield, whether affected by genetic and/or environment factors is controlled by growth of the soybean plant and seed numbers and growth of seeds. Major 5 states of soybean production are:

Area (Lakh ha.)	Production (Lakh MT.)	Productivity (Kg/ha)	
Madhya Pradesh	59.74	57.89	969
Maharashtra	49.26	66.16	1343
Rajasthan	11.80	12.07	1023
Karnataka	4.60	5.45	1184
Gujarat	2.22	3.73	1682

It is noted that soybean production per unit land area is more in Gujarat than that of Madhya Pradesh and Maharashtra. Again Chhattisgarh has higher yield per hectare than Gujarat.

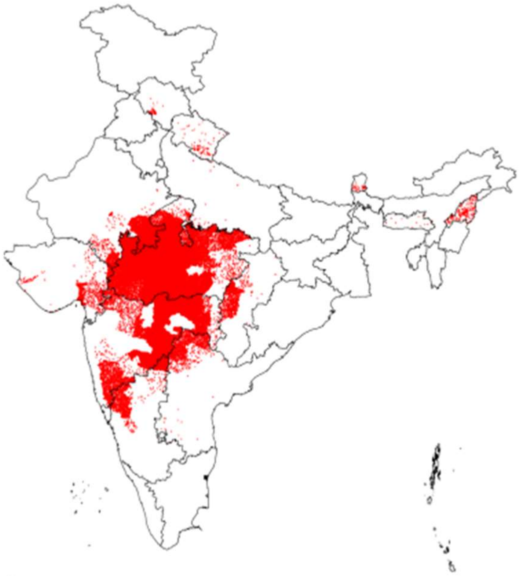

Fig.2. Soybean growing geographical map of India

Cultivation

Little improvements have been made to the quality of soybean seed available in the market. Seed quality in soybeans is only moderately good, and periodically poor. Moderately good quality, however, are not now satisfying the expectations of farmers, who are becoming increasingly aware of the importance of high quality seed for efficient maximal production. The most chronic seed quality problems in soybeans relate to germinability and vigor. Substantial losses in germinability and vigor are caused by hot-dry weather during seed maturation, weathering from rainfall and warm temperatures during the harvest period, and mechanical abuse during harvesting and handling operations. Production of high quality soybean seed requires timely harvest followed by aeration and/or drying as necessary to reduce seed moisture content to 12%or less and careful combining and handling to minimize mechanical damage. Seeds are usually put in farrows 1ft distance in the field.

Soybean maturity selection is an important management decision. Maturity group (GM) zones represent regions where a cultivar is best adopted without implying that MG-specific cultivars cannot be grown elsewhere.

Climate: Soybean, originally adapted to temperate–subtropical regions of China, is grown in India under subtropical to tropical conditions, primarily during the kharif season. The ideal growing conditions for cultivation are between 20 and 30 °C (70 and 85 °F), with temperatures below 20 °C (70 °F) and above 40 °C (105 °F) severely stunting growth.

Varieties: Improved soybean varieties for India States are evolved considering yield, biotic and abiotic constrains with prevalent agroclimate of the regions. Modern crop varieties typically require 80 to 120 days from planting to harvest and grow to a height of about 1 m (3 ft).

Andhra Pradesh	LSB-3, NRC-77, MACS-1188
Assam	PS 1347, JS 97-52, SL 688
Bihar	PS 1347, SL 688
Chhattishgarh	
Delhi	PS 1347, SL 688
Gujarat	NRC-86 (ahilya-6)
Haryana	PS 1347, SL 688
Jharkhand	Birsa Safed Soybean-2
Karnataka	NRC-77, GC-00209-4-1-1 (Karune), DSb-1, MACS-1188, MAUS-2(Pooja), Dsb-21, KPS-344
Madhya Pradesh	RVS 2001-4, JS-20-29, JS-20-34, NRC-86 (ahilya-6), Raj Soya-18, Raj Soya-24
Marathwada & Vidarbha region of Maharashtra	MAUS-158, NRC-77, MACS-1188, JS-20-29, JS-20-34, Dsb-21, NRC-86 (ahilya-6), KPS-344, Raj Soya-24
Punjab	PS 1347, SL 688, SL 744
Rajasthan	RKS-24, RKS-45 Pratap Soya 45), JS-20-29, JS-20-34, NRC-86 (ahilya-6), Raj Soya-24
Tamil Nadu	NRC-77, MACS-1188, KPS-344
Uttrakhand	VL Soya 59, VL Soya 65, Pusa 97-12, PS-19, VL Soya 77, VL Bhat 201, Pant Soy-24, Pant Soya-21, Pant Soya-23
Uttar Pradesh	PS 1347, SL 688, JS-20-29, JS-20-34, NRC-86 (ahilya-6), Pant Soy-24, Raj Soya-24
West Bengal	PS 1347, SL 688
North Eastern Hill States	JS 97-52, VL Soya 59, Pusa 97-12 (Directorate of Oil Seed Development)

Fertilization: A more comprehensive requirements may be realized through the season –long nutrient uptake, partitioning and remobilization pattern in soybean.

Nutrient accumulation for producing 60bu/A of soybean grain

Parameter	Total uptake (lbs/A)	Grain removal (lbs/A)	Harvest Index (%)	Nutrient removal coefficient(lbs/bu)
Macronutrients				
N	245	179	73	2.98
P	19	15	81	0.25

Parameter	Total uptake (lbs/A)	Grain removal (lbs/A)	Harvest Index (%)	Nutrient removal coefficient(lbs/bu)
K	141	57	41	0.95
S	17	10	59	0.17
Mg	45	8	18	0.13
Ca	101	9	9	0.15
Micronutrients				
Zn	4.78	2.00	42	0.033
B	4.64	1.58	34	0.026
Mn	5.30	1.31	25	0.022
Cu	0.90	0.56	62	0.0093

At DeKalb (2012 and 2013) and Champaign(2013)

For the maximum seed yield of soybean, it is necessary to use both N_2fixation and absorbed N from roots. When only N_2 fixation is available to the plant, vigorous vegetative growth does not occur, resulting in reduced seed yield. On the other hand ,a heavy supply of N often depress nodule development and N_2 fixation activity and induces nodule senescence , which also results in reduced seed yield. Compatible rhizobia species *Bradyrhizobium japonicum* for soybean, recognize the isoflavonoid released from host legume, and NOD genes are expressed by specific isoflavonoid signals to make NOD factor and induce nodule formation in the host plants with very low concentration. Host plant makes the infection thread which has a tunnel like structure and rhizobia can enter into the roots through it, a symbiotic state of rhizobia start to fix atmospheric nitrogen. So, depending on soil health ,fertilizer should be applied and seeds should inoculated earlier with rhizobium strain.

Plant Protection: Continuous soybean cultivation in the same systems has also led to disease buildup, breakdown of resistance in popular varieties, and management challenges during prolonged monsoons when frequent rains prevent the timely application of plant protection measures. The lack of effective control options against major diseases continues to worsen the situation.

Currently, soybean is severely attacked by about half a dozen major diseases, a dozen of insect pest and several major weeds. Yield losses due to individual disease/insect/weed species ranges from 20 to 100 per cent. However, with integrated pest management schedule, 30-35 per cent additional yield can be obtained. Application of biological control agents like *Trichoderma*, *Bacillus subtilis,* and P*seudomonas* are also very much useful (Singh 2026).

Economics: Agricultural economists assess the profitability and risk factors of soybean cultivation through economic feasibility studies, analyzing input costs, output prices, and yield potential. Cost-benefit analyses and financial modeling techniques are employed to optimize resource allocation, considering variables such as land, labor, machinery, fertilizers, pesticides, and other inputs. Market dynamics and pricing trends in the soybean sector are investigated to understand supply-demand factors, price volatility, market integration, and price transmission across channels and regions. This market analysis supports stakeholders, including farmers, traders, processors, and policymakers, in making informed decisions about production, storage, transportation, and marketing strategies to enhance profitability and mitigate risks. The global trade of soybeans is a critical focus area, involving studies of import-export patterns, tariffs, quotas, and trade agreements to evaluate trade policy impacts on competitiveness, market access, and geopolitical influences.

Policy actions should focus on strengthening seed hubs across agro-climatic zones, creating direct linkages between farmers and processors to bypass intermediaries, mainstreaming soybean into national nutrition schemes, establishing retail outlets for farmer-producer organizations engaged in soy food products, and promoting sustainability frameworks (Bhosle *et al.,* 2024).

Conclusion

In India soybean is grown under subtropical to tropical conditions, primarily during the kharif season. Its photoperiod sensitivity restricts cultivation largely to this period, while rainfed farming exposes the crop to drought, waterlogging, and high temperature stress. Sensitivity during the flowering and pod-filling stages often results in significant yield loss (Singh, 2026). Emphasis on cultivation of soybean in hilly tracts in terraces and slopes may be encouraged by supplying necessary inputs. Addressing climatic risks, soil fertility issues, seed system inefficiencies, market barriers, and disease pressures, while simultaneously tapping into value addition and premium export markets, presents an unprecedented opportunity.

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WHY TECHNOLOGY-LED AGRICULTURAL TRANSFORMATION IS ESSENTIAL FOR VIKSIT BHARAT 2047

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Introduction

India's vision of becoming a developed nation by 2047 Viksit Bharat cannot be realised without fundamentally transforming one of the country's most critical sectors: agriculture. The sector remains central to India's economy, food security, and rural livelihoods, employing nearly half of the country's workforce. However, behind these numbers lies a fragile ecosystem marked by structural inefficiencies, climate vulnerabilities, and income insecurity.

A significant challenge is that nearly 86 per cent of India's farming community comprises small and marginal farmers. The average landholding size is only around 0.7 hectares, making it difficult for farmers to achieve economies of scale or fully participate in India's growth narrative. According to The Indian Journal of Agricultural Sciences, less than 20 per cent of farmers receive any form of price support, while nearly 61 per cent of agricultural land remains rain-fed and vulnerable to unpredictable weather conditions.

The sector also faces major infrastructure and resource challenges. Micro-irrigation facilities currently cover only around 15 per cent of agricultural land, while inefficient supply chains and inadequate storage infrastructure result in post-harvest losses of nearly 20 to 40 per cent for perishable crops. Even though India has achieved record agricultural production of nearly 353 million tonnes, farmers often struggle to derive optimal economic value due to weak market linkages and logistical inefficiencies.

Recognising these concerns, the Government of India has introduced several important initiatives to strengthen the agricultural ecosystem. Programmes such as PM-KISAN, AgriStack, PMFBY, e-NAM, and the Agricultural Infrastructure Fund have contributed significantly towards improving farmer welfare, risk management, productivity, and market access.

However, achieving the ambitious goals of *Viksit Bharat 2047* will require more than incremental improvements. India now needs a large-scale transformation driven by technology, sustainability, entrepreneurship, policy reforms, and stronger last-mile delivery systems. Greater digitisation, intelligent decision-making systems, and efficient market integration must become central to the next phase of agricultural development.

Digital and Precision Farming: The Foundation of Future Agriculture

Digital and precision farming represent a major shift from traditional agricultural practices by replacing assumption-based decision-making with data-driven insights. Technologies such as Artificial Intelligence (AI), IoT-enabled soil sensors, satellite mapping, drones, and predictive analytics are enabling farmers to make more accurate and efficient decisions.

Traditionally, farms have often been managed as uniform systems where irrigation, fertiliser application, and pest management are carried out in the same way across entire fields. In reality, however, every farm functions as a unique ecosystem. Soil quality may differ across plots, water requirements vary according to crop maturity, and climatic conditions influence pest activity differently in different regions.

This is where AI and precision agriculture are transforming farming practices.

Soil sensors can monitor moisture and nutrient levels in real time, while drones and satellite imagery help analyse crop health and identify stress patterns early. Weather forecasting systems powered by AI can predict rainfall variations, pest attacks, and disease outbreaks before they cause significant damage. This information can then be translated into simple, actionable recommendations for farmers, helping improve productivity while reducing costs and minimising resource wastage.

Precision agriculture also contributes significantly to environmental sustainability. By optimising the use of water, fertilisers, and pesticides, smart farming technologies improve efficiency while reducing unnecessary consumption of natural resources. This becomes particularly important in a country like India, where millions of farmers operate under constrained financial conditions and limited access to resources. In addition, digital agriculture can strengthen climate resilience by enabling better preparedness against extreme weather events and changing climate conditions. As India moves towards the vision of *Viksit Bharat 2047*, agriculture must increasingly adopt predictive, data-driven, and technology-enabled systems.

Building Climate-Smart and Resilient Agriculture

Climate change has emerged as one of the most serious threats to Indian agriculture. Rising temperatures, irregular rainfall, declining groundwater levels, and increasing pest outbreaks are directly impacting crop yields and farmer incomes across the country. In this context, climate-smart agriculture is no longer optional — it is essential. Advanced AI-based climate modelling systems can help farmers anticipate risks through accurate weather forecasting, irrigation planning, and pest prediction. Instead of responding to crop stress after losses have already occurred, farmers can receive real-time alerts based on local environmental conditions and take preventive action in advance.

One example of such innovation is ANNAM.AI, IIT Ropar's flagship Centre of Excellence for Artificial Intelligence in Agriculture, established under the Government of India's ₹990 crore national AI mission. Conceived as a data-driven National Agriculture Intelligence Advisory platform, ANNAM.AI aims to build a scalable, farmer-centric AI backbone by leveraging AI/ML, IoT, computer vision, and cyber-physical systems. The initiative demonstrates the transformative potential of AI in agriculture through applications such as precision irrigation, pest prediction, soil quality assessment, and intelligent crop advisory systems. These technologies are especially critical for rain-dependent regions, where climate-related risks can have devastating consequences for farmers and agricultural productivity.

Ultimately, achieving the vision of *Viksit Bharat* will be impossible without building a climate-resilient agricultural ecosystem — and technology will play a defining role in enabling that transition.

The Road to Viksit Bharat Runs Through India's Farms

India cannot aspire to become a developed nation without empowering its farmers, who remain the backbone of the country's economy and food systems. The transformation of agriculture is no longer a matter of debate; it is an urgent necessity. The next phase of India's agricultural revolution must be guided by AI-driven innovation, precision farming, sustainable resource management, and digital inclusion. To ensure long-term food security, sustainable growth, and economic resilience, agricultural productivity must become smarter, more precise, and increasingly technology-enabled.

The journey towards *Viksit Bharat 2047* will not be defined solely by developments in urban India. It will also be shaped by the transformation taking place in the villages, farms, and rural communities that sustain the nation. The future of India lies in its farms, and the extent to which technology empowers Indian agriculture will determine how prosperous, resilient, and developed the nation becomes in the decades ahead.

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FARMER'S SUCCESS STORY: TRANSFORMING AGRICULTURE THROUGH HI-TECH CULTIVATION OF GERBERA UNDER POLYHOUSE

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Introduction

In the heart of Doddahagade Village, situated in Anekal Taluk of Bangalore Urban District, Karnataka, a remarkable agricultural transformation is unfolding. B.N. Kumar has emerged as a progressive farmer by adopting hi-tech polyhouse cultivation of Gerbera flowers and achieving an impressive net profit of nearly ₹12 lakh per acre annually.

The Journey Begins

The journey began with a vision to adopt modern horticulture practices that would provide sustainable income and improve the livelihood of the farming family. Earlier, Shri B.N. Kumar practiced traditional farming and cultivated millet crops, which resulted in low productivity and marginal profits. After learning about the schemes and benefits offered by the National Horticulture Board, he decided to venture into protected cultivation through the establishment of a hitech polyhouse for Gerbera cultivation.

With determination and entrepreneurial spirit, he established Gerbera cultivation in an area of 8,600 square metres under polyhouse conditions, following NHB specifications and standards. The project aimed at producing high-quality flowers throughout the year, irrespective of external climatic conditions.

Institutional Support and Financial Assistance

The project was implemented with support from the National Horticulture Board and financial assistance from The Karnataka Bank Ltd.

The total project cost was ₹149.20 lakh, out of which

- ➢ ₹112.00 lakh was sanctioned as a bank term loan by The Karnataka Bank Ltd., Chandapura Branch.
- ➢ ₹37.20 lakh was invested by the farmer from his own resources.

A major boost to the project came through the NHB back-ended capital subsidy of ₹56.00 lakh, which significantly reduced the financial burden and encouraged the farmer to adopt advanced horticulture technologies.

Infrastructure and Innovation

The success of the project was driven by robust infrastructure and modern cultivation practices. Two well-designed polyhouses covering 8,600 square metres formed the foundation of the enterprise.

The project included

- Advanced drip irrigation and fertigation systems
- Bore well drilled up to 700 feet depth
- 10 HP motor for assured irrigation supply
- Pack house facility for grading and handling flowers

- Horticulture machinery and equipment, including power sprayers
- One new transport vehicle for timely transportation of flowers to markets without damage

Approximately 79,000 Gerbera plants were cultivated inside the polyhouse, ensuring scientific crop management and enhanced productivity.

Reaping the Rewards

The results of the project have been extraordinary. The Gerbera cultivation unit currently produces an average of 2,15,000 flower bunches from 8,600 sq. mtrs and around 1,00,000 bunches per acre annually through efficient management, quality production and timely market supply, Shri B.N. Kumar is earning an average net profit of ₹12 lakh per acre per year.

He attributes this remarkable success to the timely support, subsidy assistance, and continuous encouragement provided by the National Horticulture Board.

Inspiration for Other Farmers

The success story of Shri B.N. Kumar stands as a shining example of how modern infrastructure, protected cultivation, and scientific farming practices can transform the economic condition of farmers. His journey demonstrates that with proper institutional support, access to credit, and adoption of innovative technologies, horticulture can become a highly profitable and sustainable enterprise. Today, his farm serves as an inspiration for many aspiring farmers across Karnataka and other states who wish to diversify into commercial floriculture under protected cultivation.

Conclusion

The story of B.N. Kumar is not merely about cultivating Gerbera flowers, it is about cultivating hope, prosperity, and a brighter future for Indian agriculture. His achievements reflect the transformative impact of the schemes implemented by the National Horticulture Board in empowering farmers and promoting sustainable horticulture development in the country.As more farmers embrace modern technologies and protected cultivation, such success stories will continue to strengthen the horticulture sector and contribute significantly to rural economic development.

Glimpse of Hi-Tech Cultivation of Gerbera under Polyhouse


Assisted by National Horticulture Board Ministry of Agriculture & Farmer's Welfare, Govt of India
PROJECT CODE NO : NHB/GoC/2024-25/29AKA0027406
Beneficiary Name : B.N. KUMAR
Crop / Activity / Capacity : Gerbera Cut Flower Production Under Poly House Conditions Area in Acre : 2.15 Acres / SM 8600 Sq mtr
Project Location : Sy No.: 20/3 Village : Doddahagade Post : Taaluka : Anekal Dist : Bangalore urban - 562106, State : karnataka
Total Project Cost : Rs. 149.00 Lakhs
Bank Team Loan : Rs. 112.00 Lakhs
Promoter Share : Rs. 37.00 Lakhs
Name of Financing Bank / FI : KARNATAKA BANK LTD. Chandapura Branch, Site No. 17,18 & 19 Ground Floor Iggaluru village, Anekal Road, Opp. Gate of KHB, Suryanagar Phase Chandapura, Bengaluru-560081
Year of Establishment : 2024-25
Subsidy Amount : Lakhs


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SUSTAINABLE PEST MANAGEMENT FOR CLIMATE-RESILIENT FARMING

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Abstract

Changing climate has severely affected crop yield and agricultural production. Increasing temperature, erratic rainfall and severe drought conditions have led to rapid multiplication of insect pests, their host range expansion and migration. Indiscriminate usage of chemical pesticides has resulted in environmental pollution, secondary outbreak of minor pests and insecticide resistance problems. So, sustainable and pest smart strategies are the need of the hour and must be incorporated into Integrated Pest Management (IPM) practices. These strategies include use of climate-resilient varieties of crops, pest defender ratio monitoring, ecological engineering, pest phenology modelling, artificial intelligence-based pest forecasting and smartphone application based pest detection. Together these approaches will help in early forecasting of pest attacks, enabling farmers to take timely pest management decisions.

Keywords: Pest smart strategies, Ecological engineering, Pest phenology modelling, Integrated Pest Management

Introduction

Climate change has become a major challenge to agriculture, affecting food security, crop productivity and is threatening the stability of our ecosystem. Increased use of petroleum products and fossil fuels has led to rise in greenhouse gas emission leading to rising temperature, global warming, erratic rainfall, drought and extreme weather conditions. Such changing weather conditions influence the life cycle of many crop pests, leading to faster multiplication, expansion of their host range and migration to new geographical areas. Pests are now able to complete multiple generations per year. Examples include the expansion and spread of fall armyworm (*Spodoptera frugiperda*) in maize, whitefly (*Bemisia tabaci*) in papaya, chilli, cotton and other crops, as well as the recent expansion of the litchi stink bug (*Tessaratoma javanica*) in Bihar. This causes huge crop losses to farmers, leading to heavy reliance on chemical insecticides.

Continuous use of chemicals will lead to environmental pollution, secondary outbreak of pests, pest resurgence and eventually the pest becomes resistant to these insecticides. Hence, innovative and sustainable pest management practices are necessary for successful management of insect pests of agricultural crops. Pest smart strategies are an advanced form of Integrated Pest Management (IPM) practices and focus mainly on climate smart agriculture. It aims to increase agricultural productivity by improving resilience to climate change and preserving our environment from degradation. Climate-resilient pest smart strategies include the use of climate-resilient variety of crops, modelling of pest phenology, ecological engineering practices, AI based pest forecasting and smartphone-based pest detection.

Climate-resilient crop varieties

Climate-resilient crop varieties can withstand both abiotic (drought, flood) and biotic (insect pests, diseases) stress. Even under high pest buildup, these varieties will offer good yield compared to normal crop varieties. These varieties can be developed using both traditional breeding techniques as well as modern biotechnological tools like RNA interference, marker assisted selection and CRISPR-Cas9. Such varieties are a need of the hour as they support food security and support sustainable agriculture. Use of such varieties will lower the use of chemical insecticides thereby reducing environmental pollution.

Ecological engineering

Ecological engineering is the manipulation of habitat or agricultural ecosystems to promote natural enemies for biological pest management. Generally, there are two approaches in ecological engineering, namely top-down approach and bottom-up approach. Top-down approach focuses on increasing the population of natural enemies of crop pests in the agroecosystem. This includes planting flowering plants like marigold, carrot, buckwheat, cowpea, french beans, maize, sorghum etc. that provide ample nectar and pollen to natural enemies. Plants like cotton and *Vicia faba* have extra floral nectaries that serve as an alternate food for adult predators and parasitoids. Planting coriander along with chickpea enhances the multiplication of the parasitoid *Campoletis chloridae* which will suppress *Helicoverpa armigera*, a major pest of chickpea crop. Floral strip cropping with alyssum and buckwheat enhances reproduction, fecundity and fitness of natural enemies. Raising beetle banks (raised earthen ridges on which tussock forming grasses are grown) in the center of fields enhances the reproduction of ladybird beetles, which are predators of pests like aphids and mealybugs. Behavioral manipulation can be done by push-pull strategy in which a suitable attractant crop and a deterrent crop are planted along with the main crop. A successful example is the maize crop-based push-pull strategy (Fig. 1) where Napier grass and Desmodium are planted along with maize. Napier grass acts as a trap crop that attracts maize stem borer (*Chilo partellus*) towards it, while Desmodium repels them. Bottom-up approach includes habitat manipulation practices which make the environment less favourable for the pests. It includes growing resistant varieties, intercropping, trap cropping, use of banker plants and nutrient and soil management.

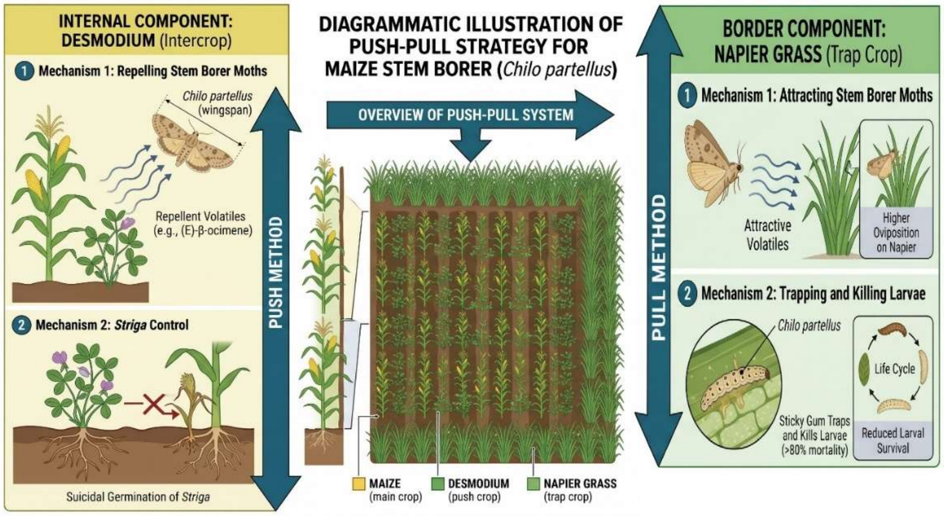

Fig 1: Diagrammatic illustration of push-pull strategy in maize crop

Pest Defender Ratio (P:D ratio)

P:D ratio is used to assess the population dynamics of the pests as well as their natural enemies like predators and parasitoids. Generally, if P:D ratio is 2:1, management practices should be adopted. Inoculative or inundative release of parasitoids or predators can be done to control the pests or use of biopesticides like entomopathogenic fungi, bacteria, viruses or nematodes can be done.

Pest Phenology Modelling

In pest management, phenology refers to the study of different life stages of the pest like oviposition, larval development, larval period, pupal period, adult emergence and how these events change with climatic and local weather conditions like temperature and humidity. By pest phenology modelling we can predict when an outbreak of the pest will occur. This will help farmers to stay prepared and apply timely control measures to protect their crops. A successful example is that of pink bollworm, where phenology modelling was done in Arizona, USA, which helped in accurately predicting the population peaks of this pest affecting cotton crop. Similarly, pest phenology modelling of whitefly was done in Israel to protect cotton and vegetable crops.

Artificial Intelligence (AI) based Pest Forecasting

The current era belongs to AI, hence use of AI based digital appliances in pest forecasting is essential for early warning and management of crop pests. Such tools use AI, machine learning, Geographic Information System (GIS) and Remote sensing (RS) for identifying pest patterns, pest prone areas and crop stress. It combines pest population data along with weather parameters like temperature, rainfall and humidity. This enables early forecasting of pest outbreaks and early control. Indian Council of Agricultural Research – Central Institute for Cotton Research (ICAR-CICR), Nagpur has developed an AI based smart trap for monitoring and early management of pink bollworm in cotton.

Smartphone Applications for Pest Detection

Plant protection applications in smartphone enables easy detection of pests in field. Farmers can easily install these applications on their smartphones and can use them to capture images of pest infested crops. The application will immediately recognize the pest and inform the farmer about it, as well as suggest different control measures to adopt to manage the pest. In India many such applications have been developed like mKisan developed by Ministry of Agriculture and Farmers welfare, Government of India, eKapas developed by ICAR-CICR, Nagpur and CROPSAP developed by Department of Agriculture, the Maharashtra State Government.

Conclusion

Climate change has led to increased pest build up in agroecosystems and conventional use of chemical pesticides is not enough to manage these pests. Hence, pest smart strategies like ecological engineering practices, climate-resilient varieties of crops, modelling of pest phenology, AI based pest forecasting and mobile application based pest detection need to be incorporated into existing IPM strategies. Use of climate resilient varieties will lower insecticide use and protect crop yield even under heavy pest infestation. Ecological engineering practices will increase natural enemy population in the ecosystem, thereby helping in biological management of insect pests. Pest phenology modelling and AI based pest forecasting methods will help in early detection and warning of pest infestation. Smartphone based pest detection applications will enable on-field detection of pests and will provide advisory to the farmers regarding various management practices to be adopted. Adoption of such climate smart strategies will increase productivity, protect food security, improve farmer livelihood and decrease the dependence on chemical pesticides.

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APPLICATION OF NANOTECHNOLOGY IN SUSTAINABLE CROP PRODUCTION SYSTEMS

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Introduction

Fertilizers remain indispensable in modern agriculture for meeting yield targets under intensifying cropping systems. Since the Green Revolution, fertilizer consumption has increased sharply; however, yield gains have not scaled proportionally in many regions due to declining partial factor productivity and inefficient nutrient recovery. Typical nitrogen use efficiency (NUE) in cereals commonly ranges from 30-50%, while phosphorus use efficiency frequently remains below 20%. Nutrient losses increase production costs and cause environmental issues such as eutrophication and greenhouse gas emissions. Nanotechnology provides tools to engineer agricultural inputs at the nanoscale (1-100 nm), where materials exhibit high surface area, enhanced reactivity and tunable release behavior. These properties enable the design of nano fertilizers that may release nutrients gradually and in a targeted manner, improving synchronization with crop demand and reducing losses Need for Nano-fertilizers. Conventional fertilizers release nutrients rapidly after application. As a result, nutrient concentration in the soil solution often exceeds crop uptake capacity, favoring loss pathways. For N fertilizers, volatilization losses are common in alkaline soils, while leaching dominates in coarse-textured soils and high rainfall areas.

For P fertilizers, immobilization as Ca-P, Fe-P or Al-P complexes drastically limits availability. Potassium losses occur via leaching in light soils and via fixation in certain clay minerals. Nano-fertilizers are proposed to address these issues through controlled release, improved solubility, targeted delivery and enhanced nutrient absorption via both foliar and root pathways. Recent reviews highlight notable improvements in cereal productivity and NUE when nano-fertilizers are integrated with conventional nutrient management.

Definition and Concept

Nano-fertilizers are fertilizer materials or formulations that contain nutrients at nanoscale dimension or use nanomaterials as carriers to enhance nutrient delivery. Broadly, nano-fertilizers fall into two groups: nutrient nanoparticles (e.g., nano-ZnO, nano-Fe) and nano-enabled fertilizers where conventional nutrients are encapsulated, coated or loaded onto nanocarriers (e.g., nano-urea, nano-DAP).The nanoscale offers high surface area and the possibility of functionalization, which can improve adhesion to leaves, penetration through stomata or cuticular pores and root uptake through apoplastic pathways.

Classification of Nano-fertilizers

Nano-fertilizers can be classified into nanoscale nutrient fertilizers, nanoscale additive fertilizers, nanoscale carrier-based fertilizers and nanocomposite fertilizers. Carrier-based systems include nano-clays, nano-zeolites, layered double hydroxides and hydroxyapatite. Nanocomposites combine multiple carriers/polymers to improve stability and release kinetics.

Table 1. Classification of nanofertilizers

Type	Examples / Description
Nanoscale nutrient fertilizers	nano-ZnO, nano-Fe2O3, nano-CaCO3
Nanoscale additive fertilizers	nanocoatings improving dissolution and stability
Carrier-based nano-fertilizers	nutrient-loaded nanozeolite, nanoclays, LDH
Nanocomposite fertilizers	polymer + nano carrier matrices; multi- nutrient systems

Synthesis and Formulation

Nanofertilizers can be synthesized by physical (milling/ultrasonication), chemical (sol-gel, precipitation, polymerization) and biological (green synthesis) methods. Green synthesis employs plant extracts or microbes to reduce metal ions and stabilize nanoparticles, reducing toxicity risks. Key formulation goals include stable dispersion, adequate nutrient loading, controlled release behavior and safe biodegradability. Encapsulation in biodegradable polymers and coating fertilizers with nanoscale films are standard techniques.

Application Methods

Soil application is suitable for slow-release nanocomposites, while foliar application is particularly effective for nano micronutrients because it bypasses soil fixation. Fertigation enables uniform distribution and lower doses of nutrients. Seed priming/coating improves early vigor and nutrient supply at critical stages. Dose optimization is crucial because excessive concentrations may cause phytotoxicity through oxidative stress. Uptake and Mechanism of Action. Plant uptake depends on nanoparticle size, surface charge and coating material. Root uptake can occur via the apoplast or symplast and particles may be translocated in xylem and phloem. Foliar uptake occurs primarily through stomatal openings and cuticle- associated pathways. Nano-fertilizers improve NUE by reducing nutrient loss pathways, increasing nutrient availability near roots and stimulating physiological processes such as chlorophyll synthesis and enzyme activation. Nano micronutrients can activate antioxidant defenses, supporting growth under abiotic stress.

Slow-release Nanocomposites

Slow-release nano-formulations are designed to supply nutrients over an extended period through diffusion-controlled or degradation-controlled release. This helps synchronize nutrient supply with crop demand. Nano-zeolite, nano-chitosan and nano-biochar are among the most promising carriers due to their porosity, biodegradability and nutrient adsorption capacity.

Nano-zeolite

Nano-zeolites are porous aluminosilicates with high cation exchange capacity. They adsorb ammonium and potassium, reducing leaching and enabling gradual nutrient release. They can improve soil moisture retention and soil structure. Field studies report improved maize growth and NUE with zeolite-based nano N fertilizers.

Nano-chitosan

Chitosan is derived from chitin and is biodegradable and non-toxic. Nano-chitosan can encapsulate nutrients and release them slowly while also acting as a bio-stimulant, inducing defense responses and supporting microbial activity. Crop studies have shown improved yield and seedling vigor with nano-chitosan-based formulations.

Nano-biochar

Nano-biochar provides high surface area for nutrient adsorption and enhances soil water holding capacity. It can improve drought tolerance and microbial habitat. Biochar-based nano systems also support carbon sequestration potential.

Crop Response (Yield, Quality and NUE)

Multiple crop studies show that nano-urea and nano NPK can increase chlorophyll content, biomass and yield attributes such as grains per panicle, fruit number and pod number. Quality improvements include better fruit size, enhanced nutrient density and biofortification potential for Zn, Fe and Mg. yield gains under reduced fertilizer doses due to enhanced NUE.

Soil Health and Microbial Effects

Nano-fertilizers may improve soil aggregation, reduce bulk density and increase hydraulic conductivity (especially with nano-zeolite/nano-biochar). They can enhance available nutrient pools by reducing fixation and improving adsorption-desorption efficiency. Nanoparticle interactions with soil microbiota can be dose-dependent. Low doses may stimulate enzyme activity and microbial biomass, whereas high doses may inhibit sensitive microbial populations. Long-term field monitoring is necessary.

Economics and Benefit–Cost Ratio

Economic performance depends on input cost, yield gain and reduced fertilizer requirement. Many studies have reported improved benefit-cost ratio where nano inputs partially substitute conventional fertilizers while maintaining or increasing yield. Nano fertilizers may also reduce labor and application frequency via slow-release designs. Market availability and initial cost, however, remain constraints.

Environmental Implications

By reducing nutrient losses and runoff, nano-fertilizers can reduce eutrophication and groundwater contamination. Controlled release and improved NUE may lower N_2O emissions indirectly by minimizing excess soil N. Life-cycle assessment is still needed to evaluate environmental trade-offs during nanoparticle production and disposal.

Toxicity and Biosafety Concerns

Risk concerns involve nanoparticle persistence, accumulation in edible tissues and entry into the food chain. High concentrations can induce reactive oxygen species (ROS), causing oxidative damage to plant cells and affecting soil biota. Therefore, safe dose recommendations, standardized testing protocols and regulatory frameworks are essential before large-scale adoption.

Future Prospects

Future work should prioritize crop- and soil-specific nano-formulations, biodegradable carriers and extensive multi-location field trials. Integration with precision agriculture tools can enable site-specific nutrient scheduling. Regulatory policy, farmer awareness and cost-effective manufacturing will be critical for scaling nano-fertilizer technologies sustainably.

Conclusion

Nano-fertilizers represent a promising approach to enhance fertilizer efficiency and sustainability. Their controlled-release and targeted delivery properties can reduce nutrient losses, improve crop uptake and support soil health. Slow-release carriers such as nano-zeolite, nano-chitosan and nano-biochar show strong potential. However, long-term ecological safety assessment and robust guidelines are essential for responsible adoption.

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TIPS FOR THE MANAGEMENT OF INSECT PESTS AND DISEASES IN RAINY SEASON GUAVA

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Introduction

Guava is a nutritious and profitable fruit crop that is harvested twice a year. The winter crop is generally healthier and remains free from most insect pests and diseases, which results in better yield and higher market price. In contrast, the rainy season crop is more prone to insect pests and diseases because of humid weather conditions. Due to this, fruit quality is reduced and farmers often receive a lower price in the market. Therefore, farmers who grow guava during the rainy season need to follow proper management practices.

Major Insect Pests

Fruit fly

Fruit fly is one of the most serious pests of guava. The female fly lays eggs on the fruit surface when it starts changing colour. After hatching, the maggots enter the fruit, feed inside, and make tunnels. The affected fruits show small holes and appear soft or sunken. When such fruits are cut with knife and open, maggots can be clearly seen inside.

Fruit fly

PAU Fruit fly trap

Management

1. **Protect the** mature fruits before ripening with white non-woven bags at the end of June to middle of July.
2. In orchards where the fruit fly infestation is already severe, avoid taking the rainy season fruits.
3. Install the fruit fly traps (16 traps per acre) in the first week of July and reinstall if required.
4. Shallow ploughing helps to expose and destroy pupating larvae and pupae that are usually found at a soil depth of 4–6 cm.

Fruit borer: The adult of this pest small butterfly and lay eggs singly on flowers or young fruits. After hatching, the larva, which is pinkish or reddish with a brown head, quickly bores into the fruit, usually from the calyx or stalk end. Once inside, it feeds on the pulp and developing seeds, remaining protected from external conditions and most control measures. As the larva feeds, the entry point on the fruit becomes deformed and is often plugged with excreta (frass). Inside the fruit, blackish excreta and silky webbing can be observed, along with rotting and foul-smelling pulp. Infested fruits typically show small holes, become deformed, and may change color. In many cases, they dry up and fall prematurely before reaching maturity, leading to significant yield loss.

Fruit borer

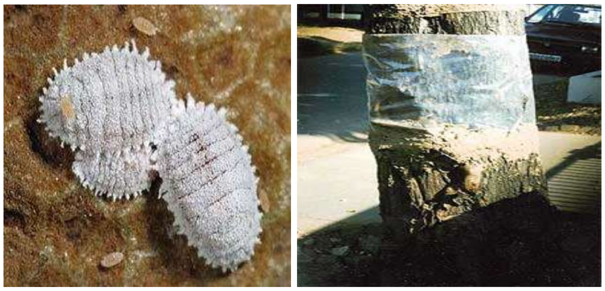
Management

1. Collect and bury the infested fruits in pits.
2. Spray neem-based formulation (PAU neem solution) at 18 ml per litre of water twice during the first and second weeks of July (rainy season crop) and again during the first and second weeks of October (winter crop).
3. Release *Trichogramma* parasitoids using Tricho-cards @ 2000 parasitized eggs per tree. Fix these cards on the underside of leaves during the 3rd, 4th, and 5th weeks of July (rainy season crop) and similarly during the 3rd, 4th, and 5th weeks of October (winter crop).

Mealy bug: This pest damages the plant by sucking sap from the leaves, tender shoots, branches, and fruits. As a result, the plant becomes weak, and its growth is reduced. The affected plant may show poor development, reduced vigor, and lower yield. In addition, the pest secretes a sticky substance called honeydew on the surface of leaves and other plant parts. This sticky layer promotes the growth of a black fungus known as sooty mould. Due to this fungal growth, the leaves and other affected parts appear black and dirty. The black coating reduces the plant’s ability to carry out photosynthesis properly, further affecting plant health and productivity.

Management

- Regularly monitor for bug infestation by checking the underside of leaves, tender shoots, branches touching the ground, and fruits. Keep the orchard clean by controlling weeds and grasses.
- Prune the branches in such a way that they do not touch the ground. Cut and destroy the infested branches in the orchard.



Mealy bugs and their management

Diseases

Wilt

This disease is a serious problem in guava plants. It develops slowly, so the symptoms are not seen immediately. In many cases, the plant starts showing signs several months after the fungus infects the roots. At the beginning, the leaves start turning yellow. As the disease progresses, the leaves lose their strength, begin to wilt, and may eventually dry up and fall off. The whole plant looks weak and unhealthy. If you check the roots and inner wood (stem), you will see that they become discolored, usually turning brown or dark. This shows that the infection has spread inside the plant. As the damage increases, the plant may finally die if proper control measures are not taken.

Management

- The crop should be planted in well-drained soil.
- Resistant rootstocks such as Sardar or Portugal should be used for planting. Over-irrigation should be avoided, and drip irrigation is preferred. Intercropping and repeated ploughing in large orchards should also be avoided
- Drench the soil in the pit with 2 per cent Formalin solution and cover with Sarkanda and old wetted gunny bags. Expose the soil for 14 days and replant healthy guava plants.

Fruit rot and twig drying

This is a fungal disease that mainly affects mature fruits and young shoots. Small brown circular spots develop on the fruit surface, which later produce pinkish fungal growth. The infected fruits rot quickly within two to three days. During the rainy season, the disease can also damage leaves and young branches.

Management

1. Do not allow irrigation and rain water to stagnate around plants during rainy season.
2. Remove and destroy infected fruits and dried branches and spray Bordeaux mixture (2:2:250) or Blitox (300 g in 100 litres of water) on the plants. Bury the rotten fruits deep in the soil.

Conclusion

Proper and timely management of pests and diseases is essential in rainy season guava due to high humidity. Regular monitoring, orchard sanitation, and use of eco-friendly methods like neem sprays, fruit bagging, and biological control help reduce damage. By adopting these practices, farmers can maintain fruit quality and achieve better yield and market returns.

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ETHICS, CHALLENGES AND FUTURE OF ARTIFICIAL INTELLIGENCE (AI) IN MICROBIOLOGY

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Abstract

Artificial Intelligence (AI) is a modern technology that helps computers perform tasks that normally require human thinking, such as learning, analyzing data, and making decisions. In microbiology, which is the study of tiny organisms like bacteria, viruses, and fungi, AI is becoming very useful. It helps scientists and doctors detect harmful microbes faster, study disease patterns, and choose the right medicines. Organizations such as the World Health Organization and Centers for Disease Control and Prevention support the use of digital tools for disease monitoring and prevention.AI can automate laboratory work like colony counting, slide reading, and data recording. This improves accuracy, saves time, and reduces human error. It also helps researchers predict antibiotic resistance and develop new drugs and vaccines. Technology companies such as IBM and Google are developing AI systems to improve medical research. However, AI also raises ethical concerns such as data privacy, bias in results, job loss, and misuse of technology. Therefore, AI should be used carefully under human supervision. Overall, AI is a powerful tool that can greatly improve microbiology, healthcare, and public health if used responsibly and ethically.

Introduction

Artificial Intelligence (AI) is a stem cell and the bone marrow is computer science, which accomplish task by machine language that usually need human intelligence, which includes learning, reasoning, problem solving and decision making. AI is currently widely used in healthcare, education, agriculture, finance and research. One of the most significant revolutions in the field of medical microbiology, AI has recently entered microbiology. It’s an AI era in the micro-world.

Microbiology is the science of organisms that are small like bacteria, viruses, fungi, and parasites. Microbes are minuscule but they have immense influence over society. These microorganisms are very important in regard to people's health. Some microbes cause sickness such as tuberculosis, typhoid, pneumonia, cholera, and urinary tract infections, and others help people keep their digestion, food production, and environment balanced. Studying these microorganisms is not simple; they grow very rapidly, change fast, and often require complicated laboratory tests. During my internship in a microbiology laboratory, I find that most laboratory procedures require careful observation, manual skills, and accurate interpretation. Culture, staining, antibiotic sensitivity testing, or sample handling require both time and precision. With the rapid increase in infectious disease and antimicrobial resistance, laboratories need faster and more accurate diagnostic systems than ever before.

AI in a microbiology lab can work as a powerful, collaborative and innovative tool to be used in generating a shower of bun of microbiological solution. AI can collate and organise large quantities of data, it can also make a database that allows us to study microbes easily. It can detect pathogenic organisms more quickly than regular techniques. Organizations such as *Centres for Disease Control and Prevention (CDC)*[1] use AI-based systems to monitor diseases and educate the public in health. AI is particularly useful in medical microbiology and identifies antibiotic resistance. The development of the antibiotic resistance is extremely important for the global problem. AI tools can also greatly increase accuracy, time productivity, reduce human errors and increase precision in the laboratory. In this way it can help produce new medicines and vaccines by predicting how microbes will respond to various drugs: AI works. This minimizes the risk of expensive, long experiments. AI also has applications in research of microbiome, where scientists analyze such communities of microbes living out in our bodies, especially in the guts. They determine how much money we live on, health-wise, nutrition-wise and even diseases such as diabetes or obesity. Another appealing application of AI comes in the area of laboratory automation.

AI-powered robots can perform routine chores such as counting colonies, monitoring growth, or scanning slides for signs that may indicate disease. This allows scientists to concentrate on big questions and discoveries. AI can also build predictive models to predict how microbes will behave in different conditions—temperature, pH or nutrient levels. This is useful in food safety, agriculture and environmental monitoring. This chapter discusses the ethics, challenges and future of AI in microbiology with practical experience and experience of an internship review literature from recognized global organisations and scientific publications. This chapter will sightsee how AI is transforming microbiology, making it faster, accurate and increasingly innovative. AI is both a powerful tool and a trusted partner in science — helping you to understand the invisible world of microorganisms and human health and well-being. AI provides many good but also poses major questions of ethics and responsibility.

Review Literature

A number of different researchers and institutions have researched the application of AI to healthcare and microbiology. Their work demonstrates AI has the potential to enhance disease diagnosis, public health monitoring and biological research as well as pose ethical concerns. Preparations in the early section of the book: Artificial Intelligence: A Modern Approach, were made through the *Stuart Russell and Peter Norvig*[3] presentation on the principles of AI. They outlined how machines can learn from raw data by discovering patterns and inform decision-making. Their work set the stage for deploying artificial intelligence in science -- the likes of microbiology and medicine. Public health organizations have even looked into how AI can benefit. According to the *World Health Organization*[4], AI can enhance disease surveillance, aid in diagnosis, and assist in delivering healthcare; Yet the WHO also raised concerns over risks around data privacy, bias in algorithms, and the requirement to provide robust guidance for good governance in ethics. AI applications have been further extended through research in technology companies. Research from *IBM*[2] found that AI can perform faster processing of medical images, genomic information, and laboratory results than the previous approaches, assist in diagnosis, and provide treatment. Technology companies including Google have likewise pioneered machine learning models for identifying infections and predicting disease spread on vast datasets. Scholars have also sounded alarms about ethical hazards. Joy *Buolamwini and Timnit Gebru* show how biased datasets can lead to unfair outcomes for AI systems. Likewise, *Jieyu Zou and Londa Schiebinger*[5] discuss how social bias can influence algorithmic decision making and stress the need for inclusive data and responsible AI creation. Recent research during the COVID-19 pandemic showed AI's practical applications in microbiology. AI had been used by researchers to assess chest scans, ferret out viral mutations and make predictions about patterns of antibiotic resistance. These findings show that AI can accelerate microbiological research, but they also confirm the importance of human supervision, ethical rules, and reliable data. Also, a number of scholars will now agree that ethical governance, transparency and adequately trained professionals would be required to ensure the public benefits from AI. But literature also mentions ethical concerns, bias risks, need for regulation and importance of human oversight. In general, scientists believe AI should work in concert with microbiologists, not as a substitute for them.

Overview of practical experience

The practical experience in Microbiology laboratory gave me a practical exposure to observe and perform routine microbiology techniques and diagnostic process. This also helped in understanding the practical importance of laboratory accuracy and the importance of AI in such context.

Sample collection and accession

A range of clinical samples were collected daily;

- Urine
- Blood
- Stool
- Sputum
- Throat swab
- Pus
- Body fluids

Each sample was appropriately labelled and accessioned, with:

- Serial number
- Accession number
- Patient details

Type of test requested

Accession is important, because it ensures traceability between the sample and the laboratory records, and also avoids sample mix-up. In this context, AI integrated Laboratory Information Systems (LIS) can automate these processes to reduce human error and save time.

Culture Techniques

Microbiological Culture is one of the basic steps in laboratory science because it allows us to grow, isolate and study microorganisms in a controlled way. It is central to the study of microbes. Various culture media were used such as Nutrient agar, MacConkey agar, Blood agar, Chocolate agar, CLED agar and the procedures were detailed:

- Sterilization of loop,
- Aseptic transfer of specimen,
- Incubation at 37°C,

Observation of colony morphology.

This may require skill and experience to observe manually. This process can be automated using AI-based colony readers. AI acts as a powerful accelerator turning culture data into actionable insights more quickly and reliably than ever before.

Fig.1.Identification of bacterial colony in MacConkey Agar for UTI examination

Staining method

Staining is one of the most fundamental techniques in microbiology because microbes are transparent and difficult to observe under microscope without contrast by staining. These stains make bacteria, protozoa and parasites visible under microscope.

Gram staining

Principle

The principle of Gram staining is based on the ability of bacterial cell walls to retain the crystal violet dye during the decolourisation with alcohol or acetone.

Gram-Negative bacteria have a thin peptidoglycan can layer and a lipid-rich outer membrane. The alcohol or acetone dissolves the lipids and allows the crystal violet- iodine complex to be washed out, so they take up the counter stain (safranin) and appear pink/red.

In other words, staining of Gram-negative bacteria the alcohol treatment extracts the liquid which result in increased porosity or permeability of the cell wall. Thus, the Crystal Violet Iodine (CVI) complex can be extracted and a Gram-negative organism is decolorized these cells subsequently ake on the colour of the Safranin counter stain.

Gram-Positive bacteria have a thick peptidoglycan layer in their cell wall which retains the crystal violet-iodine complex making them purple under the microscope. The cell wall of Gram-positive bacteria because of their different composition (lower lipid contents) becomes dehydrated during treatment with alcohol. The pore size decreases the permeability is reduced and CVI complex cannot be expected therefore these cells remain purple violet.

Gram Staining: Gram-positive bacteria → Purple, Gram-negative bacteria → Pink.

Acid-Fast Staining

The acid-fast stain is a special differential staining technique used to identify acid fast bacteria, especially Mycobacterium tuberculosis and Mycobacterium leprae. These bacteria have thick waxy cell walls containing mycolic acid, which makes them resistant to ordinary stains like gram stain. So, the acid fast stain is used to detect bacteria that do not easily take up or release dyes.

It is called Acid Fast stain because:
After staining with a red dye (carbol fuschin) and heating, the acid-fast bacteria retain the red colour even when treated with acid alcohol (a strong decolorizer).

This means they are “fast” (resistant) to acid- they do not lose their colour when exposed to acid.

In a word we can say that
Acid fast bacteria- resist decolorization by acid and remain red/pink. e.g. Mycobacterium tuberculosis (appears red)

Nonacid fast bacteria- lose the red stain take up the blue counter stain e.g. Staphylococcus aureus (appears blue)

Principle
The acid-fast stain is used to identify acid-fast bacteria (AFB), mainly Mycobacterium species such as Mycobacterium tuberculosis. These bacteria have waxy cell walls containing mycolic acid, which makes them resistant to decolorization by acid-alcohol. When stained with carbol fuchsin (a red dye) and heated, the dye penetrates the cell wall. Even after treatment with acid-alcohol, acid-fast bacteria retain the red color, while non–acid-fast bacteria lose the stain and take up a counter stain (usually blue).

The ZN stain is used to detect Mycobacterium tuberculosis which is very common among the patients due to smoking of tobacco, poor immunity, malnutrition, etc. From the observation it has been noticed that microscopic interpretation is highly dependent on the technician’s expertise. AI-based image recognition systems can assist in slide interpretation. AI can integrate into microbiology labs for enhancing both culture and staining analysis. AI can be used as Automated Microscopy for detection of stained microbes. AI can classify gram positive vs gram negative bacteria and reduces human error.

Antibiotic Sensitivity Testing
The Kirby–Bauer disc diffusion method was used to determine: Sensitive, Resistant, Intermediate. Antimicrobial resistance (AMR) is a major global problem. According to the World Health Organisation (WHO), AMR is one of the top global public health threats. AI can study the antibiotic resistance patterns and can recommend appropriate antibiotics.

Fig 3. The Antibiotic Sensitivity test for identification of Klebshiela in Sputum

Some pathogens observed:

In Microbiology laboratory some pathogens were found very regularly due to flood prone area in Assam. There is no such type filtration or chlorination process for safe drinking water system. Most common pathogens are

- Staphylococcus aureus (UTI cases)
- *Klebsiella pneumoniae* (Pneumonia cases)
- *Salmonella typhi* (Typhoid fever)
- *Vibrio cholerae* (Cholera cases)

These cases showed the importance of laboratory diagnosis in selecting proper treatment. Among the above cases it has been highlighted that a Staphylococcus aureus–caused complicated UTI in patients. Accurate identification and antibiotic susceptibility testing play essential roles in determining the correct therapy, especially due to the organism's resistance to commonly used oral antibiotics. Prompt and targeted treatment helps prevent systemic spread and recurrence.

TABLE1. BASIC REQUIREMENTS IN TRADITIONAL MICROBIOLOGY LABORATORY

Sl. No.	Requirements
1	Laboratory Infrastructure
2	Well-ventilated and illuminated room – proper air circulation and lighting are essential.
3	Wash basin and sink – for washing hands and glassware.
4	Workbenches – with smooth, easy-to-clean surfaces.
5	Bio-safety cabinet (if available) – for handling pathogenic organisms safely.
6	Proper drainage and waste disposal system – for liquid and solid biological waste.
7	Autoclave area – for sterilization of media and equipment
8	Basic Equipment
9	Autoclave – for sterilization of media and instruments.
10	Hot air oven – for dry heat sterilization.
11	Incubator – to maintain the temperature for microbial growth.
12	Microscope – for observing microorganisms.
13	Refrigerator – for storing cultures, reagents, and media.
14	Laminar air flow cabinet – for aseptic transfer of cultures.
15	Water bath – for maintaining constant temperature during tests.
16	Centrifuge – for separating cells or particles.
17	pH meter – for checking the acidity/alkalinity of media
18	Basic Glassware and Plastic ware
19	Test tubes, beakers, conical flasks
20	Culture tubes with and without cap
21	Sterilized test tubes with short swab
22	Inoculating loop
23	Petri dishes, pipettes, burettes
24	Culture tubes and bottles
25	Measuring cylinders
26	Glass slides and cover slips
27	Containers to collect sputum specimen and blood specimen for microbial culture

Sl. No.	Requirements
28	Penicillin bottle for collection of spinal fluid and other specimens.
29	Container for collecting urine specimen.
30	Container for collecting fecal specimen.
31	Culture Media and Reagents
32	Nutrient agar/broth, MacConkey agar, Blood agar, etc.
33	Staining reagents – crystal violet, safranin, Gram's iodine, methylene blue.
34	Disinfectants – phenol, 70% alcohol, Lysol, sodium hypochlorite.
35	Safety and Personal Protective Equipment (PPE)
36	Laboratory coat/apron
37	Gloves and masks
38	Goggles or face shields
39	First aid box
40	Fire extinguisher
41	Eye wash station
42	Sterilization and Aseptic Materials
43	Inoculating loops and needles
44	Bunsen burner or spirit lamp
45	Cotton plugs and sterile swabs
46	Sterile Petri plates
47	Sterile pipette tip
48	Waste Disposal
49	Autoclave bags for infectious waste
50	Sharps container for needles, glass
52	Color-coded bins (as per biomedical waste management rules

TABLE 2: BASIC REQUIREMENTS IN AN AI BASED MICROBIOLOGY LABORATORY

Sl. No	Requirements
1	Laboratory infrastructure
2	Smart laboratory Environment- equipped with IoT enabled sensor for monitoring temperature, humidity, and air quality
3	Digital workstation Computers with High speed Internet connection for running AI models
4	Cloud Integration- Access to Cloud computing platforms for digital data storage systems
5	Secure Data management System
6	AI compatible Biosafety cabinet integrated with sensor and cameras for real time monitoring of aseptic procedures.
7	Automated Easte disposal system- AI assisted segregation and disposal of biological wastes
8	Basic Laboratory Equipment
9	AI- Powered Microscope – Digital microscope with image recognition software for automated microorganism identification
10	Smart Incubator: Smart incubator with AI monitoring for calculating growth conditions

Sl. No	Requirements
11	Automated Autoclave: Integrated with AI scheduling and safety alerts for sterilization cycles,
12	Digital Water bath – for maintaining constant temperature during tests.
13	Digital Centrifuge – for separating protocols
14	AI integrated pH meter – for real time calibration, error detection etc.
15	Machine learning Platforms: Software tools for analyzing microbiological data set
16	Robotic pipetting System
17	AI enhanced Laminar Airflow Cabinet
18	Smart refrigerator or freezer
19	Digital Glassware and Plasticware
20	Smart Culture tubes and flasks
21	AI tagged specimen containers
22	Digital petri dishes
23	Robotic Inoculating loop
24	Smart pipettes and burettes
25	AI integrated sample bottles
26	Virtual Glass slides
27	Culture Media and Reagents
28	AI optimized media preparation systems – Automated preparation of Nutrient agar/broth, MacConkey agar, Blood agar, etc.
29	Digital Staining Kits: Automated staining stations with AI controlled timing for Gram stain, Acid fast stain, and fluorescent dyes.
30	Smart Disinfectant Dispensers – AI monitored usage of phenol, alcohol, Lysol, sodium hypochlorite ensuring compliance with biosafety standards.
31	Safety and Personal Protective Equipment (PPE)
32	Smart Laboratory coats and Gloves
33	AI Monitored Masks & Face Shields
34	Digital First Aid Station
35	Smart Fire Extinguishers
36	Automated Eye wash station
37	Sterilization and Aseptic Materials
38	Robotic Inoculating loops and needles
39	AI – Controlled Flame – free sterilizers- Replacing Bunsen burner with infrared or plasma sterilization
40	Smart Cotton Plugs and Swabs
41	Sterile Digital Petri Plates
42	AI-Calibrated Pipette Tips
43	Waste Disposal
44	AI Sorted Autoclave Bags- Automated segregation of infectious waste
45	Smart Sharps Containers-Equipped with fill level sensors and disposal alerts.
46	AI- Integrated Colour -Coded Bins- Ensuring compliance with biomedical waste management rules through automated monitoring and reporting.
47	Robotic Waste Handling Systems- For safe, contactless disposal of hazardous materials

Artificial Intelligence in Microbiology

AI features Machine Learning (ML), Deep Learning, Neural Networks, Predictive Analytics. The book by Stuart Russell and Peter Norvig, Artificial Intelligence: A Modern Approach provided an early and relevant introduction to the concept of AI systems and their applications in real-world problems. In microbiology, AI can Identify bacteria through digital images, predict antibiotic resistance, detect outbreaks, Automate laboratory workflow, Analyze genomic data. Organizations like the Centres for Disease Control and Prevention (CDC) utilize digital tools for disease surveillance.

AI is transforming microbiology through faster, simpler, and more accurate work. Scientists used to spend huge amounts of time performing experiments manually, and AI helps scientists by rapidly studying microbes through computers. Artificial intelligence is able to spot tiny organisms among large sets of data — say DNA sequences or pictures — which decreases the time and errors needed to process samples. In hospitals, this means AI is helping doctors and MLT professionals locate dangerous germs in patient samples for analysis; it also determines whether or not they are resistant to drug treatment so that better treatments may be chosen sooner.

Furthermore, AI is also beneficial in the development of drugs and vaccines because it can predict how microbes will respond to new medications, eliminating the need to perform expensive lab tests. In laboratories, AI powered robots can automatically count colonies, check for growth or analyze slides for analyzers. AI can also be leveraged for predictive modeling — predicting how microbes will proliferate under varied conditions including temperature and pH. It is extremely useful in food safety in food industry, farming and environmental monitoring. Most importantly, it also helps the public health by monitoring disease outbreaks and predicting diseases that will help government and physicians in preventive measures to help them to prepare the necessary for avoiding the epidemics/pandemics.

Applications of AI in Microbiology

Automated Colony Detection AI-powered systems can:
Detect colony count Identify lactose fermentation Detect haemolysis on blood agar Classify colony morphology This greatly reduces human labour and enhances accuracy.

AI in Staining Technique Deep learning models can:
Differentiate Gram-positive cocci Identify Gram-negative bacilli Detect clustering patterns. This reduces human error and speeds up reporting.

AI in Tuberculosis Detection AI tool analyzes:
Digital microscopy slides Chest X-rays Sputum smear images The *Indian Council of Medical Research*[2] promotes digital health tools for TB detection.

AI in Antimicrobial Resistance Prediction AI analyses: Previous culture data Hospital antibiotic usage patterns regional resistance data this helps doctors decide which antibiotic to prescribe is most effective and which drug to reduce resistance. AI in Outbreak Surveillance during the COVID-19 pandemic, AI was used to: Track infection trends Predict spread patterns analyse viral mutations The World Health Organization provided support for digital tools for pandemic surveillance.

Ethical Issues of AI in Microbiology

AI in microbiology has to be used ethically. Main ethical issues are

Patient Data Privacy: Microbiology reports carry: personal data, information about the disease, laboratory results. Otherwise, that information can be abused; confidentiality may be compromised.

“Privacy of Data” in microbiology deals with such things as blood or swabs or aspiration of patient samples. Such data is saved and analyzed in AI systems. Without safeguarding, personal health information might leak. For example: Imagine someone’s medical test results getting shared without permission: their dignity might be in jeopardy. A good data governance policy should be supported in *WHO*[4] report on AI ethics (2021). Microbiology data is sensitive and we do not have information that can be analyzed elsewhere. Data confidentiality must be adhered to by WHO Guidelines on AI Governance. Risk factors such as in order for Patients to maintain Data Breach and Misuse of Information there have to be a good level of cyber security, Encrypted Databases etc., for example.

Bias in AI Systems: Bias in AI, it learns from data. If the data is not complete or if it is biased, the AI can generate the wrong results. Illustration: If most training data is supplied from one region, the AI might not be suitable for microorganisms inhabiting the other region. Such information may result in incorrect or unfair diagnoses. If the data is Poor, Region-specific and Lacking so that system generates inappropriate results. Academics like *Joy Buolamwini and Timnit Gebru*[5] have explored algorithmic bias in AI systems.

Accountability: Accountability is the term for being responsible for the action of decision making, the action, and the outcomes. In microbiology in which results affect patient intervention in the outcome, accountability is essential. If AI makes the wrong diagnosis: Who is responsible? Laboratory technician? Hospital? Software company? It needs clear policies, regulations and guidelines. Accountability is crucial for: safety, ethical integrity and legal clarity for the health care staff; AI systems must be performed under the oversight of humans. They will keep regulatory standards and keep things as transparent as human decision making. AI can not only strengthen microbiology laboratories but enhance accountability and trust across all fields of research. 5.4 Dual-Use Risk: Dual use risk is when a well-intended technology can also be misused for wrong reasons. AI in microbiology has many benefits but it also comes with dual use concerns — There are many uses for AI in microbiology Good → Vaccine development Harmful → Designing dangerous pathogens Ethical codes are necessary to stop its misuse.

Job Displacement: AI Could automate: Colony counting Slide reading Data entry By using Automation AI can make job displacement for Laboratory Technicians Data Entry Staff Junior Analysts AI is just a tool not an independent decision maker. AI Should not replace microbiologist. But AI should aid MLT experts, not supplant them. Human supervision is essential.

Challenges in Implementing AI in Microbiology

These are the major challenges in AI implementation. AI has also come to rely heavily on vast amounts of bad information. Many developing countries still do not have such laboratories and databases yet.

The accuracy of AI relies on

Correct labeling, High-quality images, Standardized reports. Poor data leads to wrong predictions.

Expensive Cost of Technology: AI systems need advanced computers, special training personnel, and powerful computers to run AI software that is almost completely capable of being trained and then running, all of which come at a steep price. Smaller hospitals and laboratories may struggle to adopt these tools.

Requirement of Skilled Experts

Actively using AI requires experts in Microbiology and Computer Science. How do you get there? Technical Errors: machines and software may fail or give wrong results, so there needs to be a human check.

Infrastructure constraints

In the developing regions: Poor internet connectivity, Power cuts, No digital record systems. These are the factors limiting AI adoption. The problem of standardization: The AI systems are responsible to meet the guidelines of CLSI and International lab specifications. The results could vary without some standardization.

Data Privacy and Security concerns

Microbiology Laboratories work with sensitive information of social sensitive diseases like AIDS, HIV, Syphilis (all STDs), tuberculosis etc, of patients which are isolated types of diseases in society. In society they are not acceptable like other normal people, most of them are prohibited by the mass no of people. Along with sensitive information of diseases of patients, laboratories handle.

- Family History
- Medical History
- Disease Diagnosis
- Laboratory Reports

AI Systems store and analyze all the above information and keep forever for future study, research, or legal issues. If cyber security is weak or poor then patients' data may be mis used by the health workers. Sometimes STDs related diseases information become viral through face book, YouTube, IT system for which patients become frighten and suffer from mental stress and trauma.

Data confidentiality, secure storage, and ethical maintain of patients all the information are major challenges while applying AI in health care systems.

Technical Errors and Reliability Issues

AI systems are not perfect in all purposes. If the AI systems perform in wrong direction, then diagnosis also will be in wrong manner and the treatment also will be in incorrect direction. Technical problems may occur due to:

- Software malfunction
- Incorrect data interpretation
- System crashes
- False positive or false negative results

In microbiology, incorrect results can lead to wrong diagnosis or improper treatment, which may harm patients even sometimes death also. Therefore, human supervision is very important and always essential and necessary.

Resistance to Technical Change

Most of the laboratory professionals are habituated with traditional microbiology laboratory methods Some of them may feel uncomfortable with AI based system and many of them don't know about the using of AI in laboratory purposes because:

- They are unfamiliar with new technologies
- They fear for losing their jobs
- They do not have trust on automated systems

Proper training and awareness programs are needed to build their confidence in application of AI technology.

Ethical and Legal Issues

The application and implementation of AI raised important ethical and legal questions, such as

- Who is responsible if AI makes a wrong diagnosis?
- How should patient data be protected?
- Can AI replace human judgement in health care decisions?

Governments and Private health care organization must develop ethical and legal frameworks to regulate AI use in Microbiology laboratory.

Limited Integration with Existing Laboratory Systems

Many hospitals use laboratory Information Systems (LIS) to manage patient data and reports. AI system must be integrated with these existing systems.

However, compatibility problems between AI software and traditional laboratory system can create difficulties in implementation.

Lack of standardization and Guideline

The traditional system of Microbiology laboratories follows standardized guidelines such as:

- CLSI (Clinical and Laboratory Standards Institute)
- WHO laboratory guidelines

Yet, AI technologies in microbiology are still developing and there are limited international standards guidelines for AI based diagnostic stools. Without a clear, standard, international regulatory guidelines, laboratories may face glitches to Adopt AI System as diagnosis tool in laboratory system.

Future of AI in Microbiology

The prospect for AI in Microbiology The future AI in microbiology lies very well ahead, from there to look forward to AI in microbiology. AI could help invent customized medicines based on a person's microbiome. Laboratories with computers to do that might do experiments with very little human labor. It has resulted in research organizations, universities, and technology companies such as IBM and Google creating sophisticated AI systems to enhance medical and biological research. It may also facilitate early detection of new viruses, preventing pandemics. **AI in Automated Laboratories:** Some possible future labs include,

- ○ Robotic system may perform pipetting, streaking plates, sample processing
- ○ Culture inoculation
- ○ Colony detection
- ○ AI-based Plate readers,
- ○ Automated Reporting Systems.

The advantages are

- ○ Reduced manual errors
- ○ Increased laboratory efficiency
- ○ Faster reporting time

AI in Rapid Identification of Microorganism: AI systems analyze microscopic images, colony morphology, biochemical reactions, gram-stained slides and can identify pathogens very rapidly and by reducing time like Gram positive cocci, Gram negative bacilli, E, coli, Salmonella etc.

AI in Antibiotic Therapy: AI might advise, best antibiotic, Right dosage, Ideal duration to treat. This will help in diminishing antimicrobial resistance.

AI in Pandemic Detection: AI tools could Monitor Global data, Predict outbreaks, Alert health authorities in advance to control and overcome the pandemic environment.

AI based Integrated Electronic Health Records: AI will combine- Clinical symptoms, Lab results, Imaging data to provide comprehensive decision support.

AI Mobile Unit: It can be deployed by health care professionals and patients by providing information through mobile health report from portable AI, and in rural health care, they will save rural individuals suffering from COVID-19. Doctors will also be able to offer instant medicine.

AI in Vaccine Development: Developing vaccines traditionally takes many years where as AI can speed up this process. In future AI can help in faster vaccine development. and better protection against infectious diseases.

AI helps by

- Predicting antigen structures
- Identifying vaccine targets
- Simulating immune responses

AI in Hospital Infection Control: Hospitals face serious problems with hospital -acquired infections (HAIs). AI can provide better infection prevention strategies and improved patient safety

AI systems can monitor:

- Infections trend in hospitals
- Anti-biotic Usage
- Laboratory test results

AI in Drug discovery: AI can help to discover new antibiotics and anti-microbial agent. AI can analyze chemical structure, microbial genome, drug target interaction by which it can help to scientists to identify the new antibiotic compounds to fight against drug resistant bacteria.

Conclusion

This Chapter is a synthesis of my practical experiences in a microbiology laboratory, supplemented with literature. Based on the practical expertise in Microbiology, understanding the identification of microorganisms including viruses and bacteria, growing organisms by growth, by culture, and their management by antibiotics and sensitivity tests to identify the antibiotics, bacteriological examination of Urine, Stool, Sputum, and Blood. But microbiological diagnosis needs precision, observation and expertise. AI can enhance laboratory efficiency, decrease mistakes, and enhance disease surveillance. AI can also provide a database containing the microbiological information of patients, for researchers in race-wise, in region-wise, and in sexes, so that they can further study the areas, etc for vaccine development etc. Data science and epidemiology are crucial in addressing healthcare challenges today. Ethical concerns of data privacy, bias, accountability and dual use risks, should be taken care from the researcher scientist / doctor/ MLT professionals applying AI in Microbial research. Information pertaining to microbial and patient's health database for use should not be disclosed for dissemination and should not float to the social media. The implementation of AI in microbiology laboratories faces several challenges like lack of quality data. High technology cost, limited skilled personnels, Infrastructure problems, Data privacy and insecurity biasness and regulatory issues. To overcome these challenges, heath care systems must invest in training, digital infra-structure, ethical regulations and standardize data system. The challenges of cost, the structure challenges and the shortage of competent personnel must be overcome prior to full

application of AI in this field (Microbiological lab). For this AI must be used as a supportive tool in moderation under supervision by human staff rather than replacing human expertise.
AI can transform microbiological information for global health care. Accompanied by ethical guidelines, regulations and professional training appropriates to its nature. AI is a state of developing which the microbial world experts must enhance themselves to enhance themselves through better awareness, competence and proper nutrition to progress towards a better quality of life with the new AI system. AI in microbiology holds its bright and wonderful future to come but they need to be responsible, transparent and scientifically honest. Researchers need to make sure that AI is used safely, equitably and without compromising the ethical principles behind health care. In general, AI is a blessing to humans.

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RUMEN-DERIVED GREENHOUSE GAS EMISSIONS AND NUTRITIONAL MITIGATION STRATEGIES

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Abstract

Ruminant livestock contribute significantly to greenhouse gas emissions, particularly methane (CH_4), which is produced during rumen fermentation by methanogenic archaea. This process not only impacts the environment but also results in a loss of 2–12% of dietary energy. Methanogenesis maintains rumen function by regulating hydrogen balance, but reducing methane can improve feed efficiency and productivity. Various mitigation strategies have been explored. Feed manipulation, such as improving forage quality and increasing concentrate levels, shifts fermentation toward propionate production, reducing hydrogen availability. Feed additives, including ionophores, essential oils, plant extracts, biochar, and seaweeds, can inhibit methanogens or alter rumen microbial activity. Direct-fed microbials, particularly propionic acid bacteria, further reduce methane by redirecting hydrogen to beneficial pathways. An integrated approach combining these strategies is essential for sustainable and efficient ruminant production.

Introduction

Rising global temperatures have intensified concern over the greenhouse effect, primarily driven by gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These gases trap heat in the atmosphere, contributing to climate change with significant implications for ecosystems, livestock, and human well-being. Among them, methane is particularly potent, possessing over 21 times the global warming potential of CO_2 and accounting for a substantial loss (2–12%) of gross energy intake in ruminants through enteric fermentation. Agriculture contributes significantly to methane emissions, with enteric fermentation, rice cultivation, and manure management accounting for nearly 40% of total agricultural CH_4 output. Ruminant livestock especially cattle are the major contributors, responsible for approximately 72% of emissions, while buffaloes and small ruminants contribute comparatively less. Despite its high warming potential, methane has a relatively short atmospheric lifespan (~8.6 years), making it a critical target for short-term climate mitigation. Reducing enteric methane emissions offers dual benefits: improving feed energy efficiency and enhancing environmental sustainability. While strategies such as culling low-producing animals are practiced in developed countries, such approaches are often impractical in developing regions due to socio-economic and cultural constraints. Therefore, emphasis is placed on developing cost-effective and sustainable mitigation strategies that balance productivity with environmental responsibility.

Methanogenesis in Ruminant Animals

The rumen hosts a complex anaerobic microbial ecosystem comprising bacteria, protozoa, methanogenic archaea, and fungi that collectively degrade dietary macromolecules. Carbohydrate fermentation produces short-chain volatile fatty acids (SVFAs), primarily acetate (≈65%), propionate

(≈20%), and butyrate (≈15%) which supply up to 80% of the host's energy requirements. However, this process also generates metabolic hydrogen (H_2), which must be removed to sustain efficient fermentation. Methanogenesis serves as the principal hydrogen disposal pathway in the rumen. Methanogenic archaea, predominantly *Methanobrevibacter* spp., utilize hydrogen to reduce carbon dioxide to methane via hydrogenotrophic pathways, accounting for approximately 82% of total ruminal methane production. By maintaining low hydrogen partial pressure, methanogens facilitate optimal microbial activity and prevent inhibition of carbohydrate oxidation.

Interspecies hydrogen transfer between methanogens and hydrogen-producing microbes (bacteria, protozoa, and fungi) plays a critical role in stabilizing rumen fermentation. The balance between hydrogen production and utilization regulates metabolic flux, including competition with alternative pathways such as reductive acetogenesis. Although methanogenesis is essential for rumen function, it represents a significant loss of dietary energy and contributes substantially to greenhouse gas emissions from ruminant systems.

Mitigation Strategies

Mitigation through Feed Manipulation

Dietary manipulation is a cost-effective strategy to reduce enteric methane emissions (up to ~70%). Improving forage quality enhances digestibility and shifts fermentation toward propionate production, reducing hydrogen (H_2) availability for methanogenesis. Increasing the concentrate-to-forage ratio (35–60%) further lowers methane output but may increase the risk of Subacute Ruminal Acidosis if not properly balanced.

Mitigation through Feed Additives

Feed additives mitigate methane by inhibiting methanogens or altering rumen fermentation.

- **Ionophores:** Improve feed efficiency and reduce methane by shifting fermentation toward propionate and suppressing hydrogen-producing Gram-positive bacteria.
- **Essential Oils and Plant Extracts:** Compounds such as saponins and tannins reduce methane (≈28–30%) by inhibiting methanogens and protozoa.
- **Other Additives:** Biochar, seaweeds, and prebiotics (e.g., chitosan, inulin, yeast) show promising anti-methanogenic effects, though large-scale application requires further

Mitigation through Direct-Fed Microbials (DFMs)/Probiotics

Direct-fed microbials (DFMs) are live microbial cultures. They may consist of single or mixed strains. These microbes promote beneficial rumen microflora when fed to animals. DFMs improve rumen fermentation and animal performance. They also influence hydrogen utilization in the rumen. Several rumen microbes compete with methanogens for hydrogen. They promote alternative pathways such as propionogenesis, acetogenesis, and nitrate/nitrite or sulfate reduction. These pathways act as alternative hydrogen (H_2) sinks. As a result, hydrogen is redirected toward volatile fatty acid (VFA) production. This reduces its availability for methanogenesis.

Propionic Acid Bacteria (PAB)

Direct-fed microbials (DFMs) are live microbial cultures that enhance rumen function by modulating microbial populations and fermentation pathways. They improve animal performance and reduce methane emissions by redirecting hydrogen (H_2) toward alternative metabolic pathways such as propionogenesis, acetogenesis, and nitrate or sulfate reduction, thereby limiting substrate availability for methanogenesis.

Propionic Acid Bacteria (PAB)

Propionibacteria are Gram-positive rumen inhabitants that contribute to propionate production via the succinate and acrylate pathways, utilizing hydrogen in the process. Enhanced propionate formation acts as an alternative hydrogen sink, reducing methane production. Key strains, including *Propionibacterium acidipropionici*, *P. freudenreichii*, and *P. jensenii*, have demonstrated methane mitigation potential in both in vitro and in vivo studies.

Methane-Oxidizing Bacteria (MOB)

Methane-oxidizing bacteria utilize methane as a carbon and energy source, converting it to methanol via methane monooxygenase and further to formaldehyde for biomass synthesis. Although they present a promising biological approach to methane mitigation, their application as probiotics in ruminants remains limited, requiring further isolation, characterization, and in vivo validation.

Conclusion

Enteric methane production is an unavoidable outcome of rumen fermentation, contributing to greenhouse gas emissions and energy loss. Strategies such as dietary manipulation, feed additives, and direct-fed microbials can reduce methane by redirecting hydrogen toward more efficient pathways. However, no single method is sufficient. An integrated approach combining nutritional and microbial interventions is essential to achieve sustainable methane mitigation while maintaining animal health and productivity.

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GREEN GROWTH: WHERE AGRICULTURE MEETS AESTHETICS

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Abstract

The article explores the integration of agriculture, horticulture, and landscaping in India as a holistic land-use approach that combines productivity, ecological sustainability, and aesthetic design. It explains the shift from traditional farming to structured, multifunctional landscapes where crops, fruits, vegetables, medicinal plants, native species, and ornamentals are carefully arranged within planned spatial systems. Key principles such as layered planting, biodiversity enhancement, water conservation, and sustainable resource management are highlighted as essential for improving soil health, ecological balance, and land efficiency while generating diverse income opportunities. Through real-world examples from rural, urban, and institutional contexts, the article shows how these integrated systems are applied in food forests, organic farms, agroforestry models, and community gardens, transforming both productive and degraded lands into resilient green ecosystems. Overall, it concludes that this convergence of agriculture and landscape design offers a sustainable development pathway that unites economic viability, environmental responsibility, and aesthetic harmony within a single framework.

Keywords: Integrated agriculture, horticulture, landscape design, sustainable land use, agroforestry, biodiversity, green infrastructure

Introduction

India's agricultural transformation is increasingly being guided by a shift from conventional land use toward planned, multifunctional landscape systems. In this context, landscaping is emerging as a strategic framework that integrates productivity, ecology, and design. Rather than being confined to aesthetic urban gardens, landscaping principles are now influencing the organization of agricultural and horticultural spaces, enabling land to be viewed and managed as a coherent, efficient, and environmentally balanced system. This evolution reflects a broader movement toward structured green infrastructure across rural and peri-urban regions.

Within this integrated approach, agriculture and horticulture form the productive foundation of modern landscapes. While staple crops continue to ensure food and nutritional security, horticultural systems comprising fruits, vegetables, flowers, and ornamental plants introduce diversity, economic value, and ecological richness into land-use planning. Orchards, cultivated beds, and plantation blocks are increasingly being arranged within designed spatial frameworks that align productivity with visual and environmental coherence. As a result, agricultural land is progressively transitioning into purposefully designed productive landscapes rather than fragmented cultivation zones.

As these disciplines converge, landscaping is no longer an auxiliary element but a guiding principle in the structuring of agricultural spaces. This integration is evident in emerging models such as agro-tourism landscapes, orchard-based garden systems, and peri-urban horticultural corridors. Collectively, the synthesis of agriculture, horticulture, and landscaping is fostering systems that enhance economic viability, environmental sustainability, and spatial efficiency, thereby contributing to a more resilient and development-oriented agricultural framework in India.

Integration of Agriculture, Horticulture, and Landscaping Matters

The integration of agriculture, horticulture, and landscaping introduces a functional and design-oriented approach to land use, where plant selection is guided by both productivity and aesthetic value. Unlike conventional farming systems, it combines edible crops, horticultural species, and medicinal or aromatic plants within planned landscape frameworks, transforming land into a multi-purpose productive green space. Edible horticultural crops such as fruits and vegetables are integrated with medicinal and aromatic plants like rosemary, lavender, and ornamental ginger, along with flowering species that enhance visual appeal. This creates landscapes that are both economically useful and visually enriched.

The significance of this approach lies in its ability to generate multiple income streams while improving ecological quality. It supports edible production, medicinal plant use, nursery development, and eco-tourism opportunities, while also enhancing biodiversity and microclimatic stability. By merging productivity with landscape design, this integrated system creates sustainable, resilient, and aesthetically balanced environments, aligning with modern goals of green development and efficient land utilization.

Designing Sustainable Landscapes with Edible, Medicinal, and Native Plants

Modern landscaping is evolving beyond aesthetics to embrace functionality, sustainability, and ecological balance. Integrating edible, medicinal, and native plant species into landscape design offers a powerful way to create spaces that are not only visually appealing but also beneficial to human health and the environment. By thoughtfully combining these elements, landscapes can become self-sustaining ecosystems that support biodiversity, improve soil health, and provide a steady supply of useful plants.

Establishing a Clear Design Theme

A successful landscape begins with a clear and cohesive theme. This helps unify the design while ensuring that each plant serves a purpose. One popular approach is the food forest, inspired by permaculture principles, where plants are arranged in layers to mimic a natural forest ecosystem. Another option is an Ayurvedic healing garden, which focuses on medicinal plants traditionally used in Indian systems of medicine. Native biodiversity gardens emphasize indigenous species that naturally thrive in local conditions, while a kitchen garden combined with ornamental plants balances productivity with visual appeal. Choosing a theme early on helps guide plant selection and spatial organization.

Embracing Layered Planting

Layered planting is a key strategy in creating resilient and productive landscapes. This method involves arranging plants at different vertical levels, similar to a forest structure. Tall canopy trees such as mango, tamarind, and neem provide shade and structure. Beneath them, smaller trees like guava and moringa form the sub-canopy. Shrubs such as hibiscus and curry leaf fill the mid-layer, while herbs like tulsi, mint, and aloe vera occupy the lower levels. Groundcovers, including sweet potato and brahmi, protect the soil, and climbers like bitter gourd utilize vertical space efficiently. This multi-layered approach maximizes productivity while reducing maintenance and conserving resources.

Selecting the Right Plant Species

Choosing plants that are both useful and suited to the local climate is essential. Edible plants like moringa, banana, and coconut offer nutritional benefits while contributing to the landscape's structure. Medicinal plants such as tulsi, ashwagandha, and aloe vera provide natural remedies and enhance the garden's value. Native species like neem, peepal, and amla are particularly important, as they are well-adapted to local conditions and play a crucial role in supporting wildlife and maintaining ecological balance.

Supporting Biodiversity

A well-designed landscape should encourage biodiversity. Including flowering plants such as marigold and jasmine attracts pollinators like bees and butterflies, which are essential for plant reproduction. Small water features, such as ponds or bird baths, provide habitats for birds and beneficial insects. Avoiding chemical pesticides further ensures that the ecosystem remains healthy and balanced, allowing natural processes to thrive.

Incorporating Sustainable Practices

Sustainability is at the heart of this landscaping approach. Techniques such as rainwater harvesting and drip irrigation help conserve water, which is especially important in regions with variable rainfall. Composting organic waste enriches the soil naturally, reducing the need for chemical fertilizers. Mulching helps retain soil moisture, suppress weeds, and improve soil structure over time. Together, these practices create a low-maintenance and environmentally friendly landscape.

Balancing Aesthetics and Functionality

While functionality is important, visual appeal should not be overlooked. Thoughtful design elements such as curved pathways, a mix of plant textures and colours, and well-planned spacing contribute to an inviting and harmonious environment. Frequently used herbs can be placed near the kitchen for convenience, while taller trees can provide shaded seating areas. Vertical gardening techniques can be used to incorporate climbers without overcrowding the space.

Creating a Harmonious Landscape

Ultimately, the goal is to strike a balance between productivity and beauty. A landscape should not feel like a dense farm but rather a carefully curated space that is both practical and enjoyable. By integrating edible, medicinal, and native plants within a cohesive design, it is possible to create landscapes that nourish people, support biodiversity, and contribute positively to the environment. Such landscapes represent a shift toward more responsible and regenerative design practices, offering a sustainable way to connect with nature while enhancing everyday living spaces.

Case Studies: Green Growth in Practice

Across India, several initiatives demonstrate how the integration of agriculture, horticulture, and landscaping is not just theoretical but actively shaping sustainable and productive landscapes. These real-world examples highlight how design, biodiversity, and functionality can come together to create resilient land-use systems.

One of the most influential models is Navdanya, established by Vandana Shiva. Based in Dehradun, Navdanya's farms move away from monoculture and instead adopt biodiverse, layered cropping systems that resemble naturally designed landscapes. Here, traditional crops such as rice, pulses, and vegetables are interwoven with medicinal plants like tulsi and ashwagandha. The farm functions as both a productive agricultural unit and a living ecological system, enhancing soil fertility, conserving indigenous seed varieties, and improving resilience to climate variability. Its structured yet organic layout exemplifies how productivity and ecological design can coexist seamlessly.

A similarly transformative approach can be seen in the work of Aranya Agricultural Alternatives in the region surrounding Hyderabad. Aranya specializes in permaculture-based landscape design, converting degraded lands into thriving food forests. Their projects integrate fruit trees, vegetables, herbs, and native plants in carefully planned layers, mimicking forest ecosystems. Water harvesting systems, natural soil regeneration techniques, and minimal external inputs are central to their design philosophy. The result is a self-sustaining landscape that is not only productive but also visually rich and ecologically balanced.

Urban and peri-urban contexts also reflect this integration through initiatives led by ICLEI South Asia. In cities such as Hyderabad and Kochi, projects have promoted kitchen gardens, terrace farming, and community green spaces that blend edible crops with ornamental plants. These spaces are often designed with structured layouts, vertical gardening techniques, and composting systems, demonstrating how even limited urban spaces can be transformed into productive and aesthetically pleasing landscapes. Beyond food production, these initiatives contribute to improved microclimates, waste recycling, and community engagement.

At a larger scale, the state-led transformation of Sikkim into India's first fully organic state presents a compelling example of integrated landscape management. Agricultural lands across Sikkim combine organic farming with horticulture and agroforestry, often arranged in terraced designs that conserve soil and water. Fruit trees, vegetables, and flowering plants are cultivated together, creating landscapes that are both productive and visually appealing. This holistic approach has not only improved environmental health but also boosted eco-tourism and strengthened rural livelihoods, illustrating the economic potential of well-designed green systems.

Another notable example is the ecological restoration work at the Rishi Valley Education Centre in Rishi Valley. Once a degraded and drought-prone area, the region has been transformed into a thriving green landscape through the systematic planting of native species, development of orchards, and integration of small-scale agriculture. Water conservation measures such as check dams and contour bunding have been incorporated into the landscape design, enabling long-term sustainability. Today, the area stands as a model of how ecological restoration and productive land use can be combined within a thoughtfully designed framework.

Grassroots efforts also play a crucial role in this transformation. The work of Annapurna Krishi Prasar Seva in Maharashtra highlights how small-scale, women-led initiatives can adopt integrated landscape principles. Through the development of nutritional kitchen gardens, women farmers cultivate vegetables, fruits, medicinal plants, and ornamental species within organized layouts. These gardens are designed for efficiency and accessibility, often including pathways and plant zoning. The result is improved household nutrition, supplementary income, and enhanced empowerment, all within compact and well-managed green spaces.

Finally, Auroville in Auroville offers an internationally recognized example of integrated landscape development. Once characterized by barren land, Auroville has been transformed into a mosaic of forests, farms, and gardens through decades of ecological restoration and planning. Agroforestry systems, orchards, and vegetable gardens are seamlessly integrated with native vegetation, creating landscapes that are both productive and aesthetically harmonious. The emphasis on spatial design, biodiversity, and sustainability has made Auroville a global model for regenerative land-use practices.

Together, these case studies illustrate that the integration of agriculture, horticulture, and landscaping is not merely an abstract concept but a practical and scalable approach. Whether on large farms, in urban spaces, or within small household gardens, the fusion of productivity with ecological design is creating landscapes that are economically viable, environmentally sustainable, and visually enriching.

Conclusion

The evolving relationship between agriculture, horticulture, and landscaping reflects a broader transformation in how land is conceptualized and managed in modern India. No longer treated as isolated or purely functional domains, these disciplines are increasingly integrated to create multifunctional landscapes that balance productivity, ecological stability, and visual coherence. This shift signifies a move away from fragmented land-use practices toward more structured, design-oriented systems that maximize both efficiency and sustainability.

By incorporating edible, medicinal, and native plant species within thoughtfully planned layouts, landscapes can serve multiple purposes—ranging from food production and income generation to biodiversity conservation and climate resilience. The emphasis on layered planting, sustainable resource management, and biodiversity enhancement further strengthens the ecological foundation of these systems, making them more adaptive to environmental challenges. Importantly, this integrated approach also redefines the role of aesthetics in agriculture. Visual design is no longer secondary but becomes a functional element that enhances usability, accessibility, and overall land value. As a result, agricultural spaces are transformed into productive environments that are not only efficient but also engaging and harmonious. In the face of increasing pressures such as urbanization, resource depletion, and climate variability, the integration of agriculture, horticulture, and landscaping offers a practical and forward-looking pathway. It promotes a holistic model of development—one that aligns economic viability with environmental responsibility and social well-being. Ultimately, such landscapes represent a sustainable vision for the future, where productivity and ecological balance coexist in a unified and regenerative system.

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CLIMATE CHANGE AND ITS EFFECT ON AQUACULTURE

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Abstract

Aquaculture is one of the fastest-growing sectors of the food production industry, yet it is seriously threatened by the unavoidable impacts of climate change. The current investigation examines how aquaculture production is affected by climate change and provides need-based solutions for its sustainable management with an emphasis on climate-resilient techniques. In this article, innovative scientific studies and climate-resilient aquaculture tactics are meant to increase the adaptability of aquaculture methods. The study focuses at the many ways that climate change affects aquaculture, including changes in water temperature, rising sea levels, acidity of the ocean, dangerous algae blooms, harsh weather, and changes in biological dynamics.

Introduction

There is mounting evidence in recent years that climate change and increased unpredictability, especially catastrophic conditions like droughts and floods, can have a major global influence on water quality. Increased precipitation intensity, longer periods of time during low flows brought on by rising temperatures, and deteriorating water quality are all signs of how climate change is affecting aquatic ecosystems and human health. Food production is threatened in terms of both quality and quantity due to climate change. Numerous climatic factors have the potential to impact future food production and human food demands, and many developing nations, particularly those experiencing poverty, are extremely concerned about the effects of these changes. Following the release of the Intergovernmental Panel on Climate Change's Fourth Assessment Report, much focus has been placed on the threats that climate change poses to human society and its natural resources. As the frequency and intensity of storms and rainfall increase, it is clear from recent events that both semi-arid and arid regions are getting drier. Furthermore, there is a tendency toward larger extremes in both dry and semi-arid regions.

The effects of climate change have been receiving a lot of attention lately, partly because of the importance of aquaculture to global nutrition, food security, and livelihoods due to the industry's substantial contribution to international trade. Since the aquaculture sector is now heavily reliant on the weather, climate change may endanger the sector's capacity to develop and produce fish in the future. Numerous fish species are predicted to suffer in the future due to the warming of ocean and inland surface waters, sea level rise, and glacier melting.

According to data and analysis, these factors generate greenhouse gasses that tend to shade the earth, causing floods, global warming, and ozone layer depletion. Increased frequency and severity of droughts, floods, and other extreme weather events are among the predicted effects, which will put further pressure on infrastructure, food security, infrastructure, health, and water resources. A significant danger to the stability and productivity of aquaculture operations across the world is posed by these issues taken together. The purpose of this study was to offer helpful details on climate-smart solutions that might improve aquaculture's sustainability. Aquaculture systems can adapt to and lessen the effects of climate change by using techniques and tactics that are identified and evaluated.

Climate change's effects on aquaculture production systems

Aquaculture output is directly and indirectly impacted by climate change, which has both immediate and long-term effects on the industry. Rising temperatures, ocean acidification, toxic algal blooms, and other effects of climate change can have a direct impact on the physiological and physical traits of shellfish and finfish. Among the implications of climate change on aquaculture include decreased output, unexpected mortality, and changes in spawning seasons and quantity.

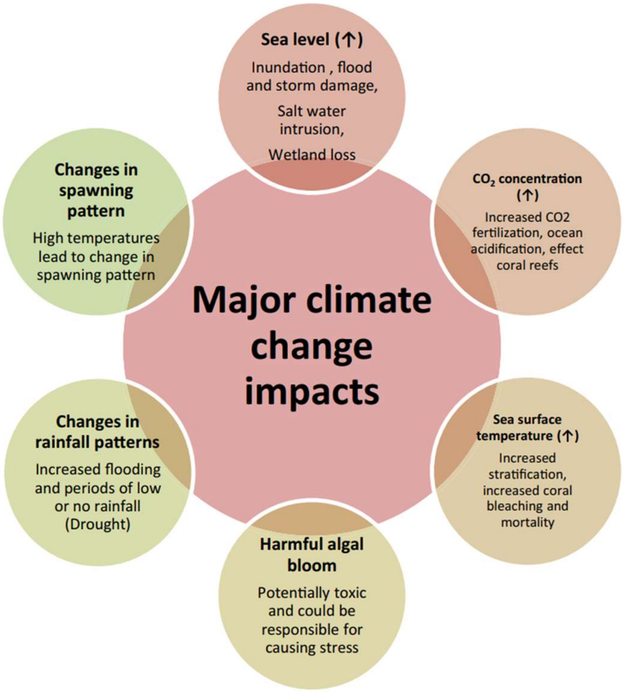

Fig.1 Major climate change impact on aquaculture

Temperature increase

Fish and aquatic invertebrates are examples of aquatic species that are poikilothermic, meaning that their internal temperatures vary in relation to the water's surrounding temperature. Their survival depends heavily on their sensitivity to temperature fluctuations outside of their typical environment. Numerous finfish and shellfish species are expected to be impacted, along with their physiology, metabolism, feeding patterns, and growth performance. The impacts of rising temperatures and global warming affect pond aquaculture. Many research suggests that increasing temperatures in freshwater ponds may have negative effects on the ecology, such as altering how the ponds work together. Heat-tolerant cyanobacteria in ponds can develop quickly as a result of global warming, causing extreme eutrophication from increased temperatures and pollution. Even other cyanobacteria species are impacted by massive cyanobacteria blooms in eutrophic ponds, which decrease diversity. As shown in streams, higher temperatures, like those brought on by the Urban Heat Island (UHI) effect, may drastically change the growth season for aquatic life. A slight rise in water temperature (1-2 °C) may have sub-lethal physiological consequences on tropical fish.

Effects of rising temperatures on the health of aquatic animals

Temperature variations are anticipated to have unexpected effects on aquaculture-related bacterial, parasite, viral, and fungal illnesses. Rising temperatures may promote the spread of exotic diseases, and heat stress increases the susceptibility of cultured animals to disease. Increases in water temperature can directly affect fish and their diseases, but multivariate environmental change may have unanticipated impacts on both. The incidence and severity of the disease may increase, decrease, or simply fluctuate across time and space depending on the combined impact of all three interconnected components. Climate change will most certainly have an effect on disease emergence by making certain diseases more common in already-existing regions and bringing them to new ones. Climate change is predicted to impact the aquatic ecosystem and increase factors that encourage the entry of exotic fish species, increasing the likelihood of the establishment and spread of exotic parasites and diseases. Rising temperatures are predicted to enhance the replication rate, virulence, duration of life cycles, and transmission of infections in a number of finfish and shellfish species. In aquaculture, rising temperatures may potentially increase the development of epizoonotic illnesses, posing major financial challenges. In many parts of the world, epizootic disease outbreaks are already one of the main challenges to the viability of aquaculture production systems.

HABs

Many scientific studies have focused on the impact of HABs on climate change, particularly warming. In order for a HAB to increase in a particular area, temperatures below those that enable maximal growth must exist. This is a prerequisite for higher temperatures increasing the intensity of the HAB. As water temperatures get closer to the ideal range for HAB development, it has been noted that these blooms become more intense. From an environmental perspective, algal bloom poses a major danger to the sustainability of aquaculture output. According to certain reports, the taxonomic groupings of flagellates and dinoflagellates, together with other dangerous species, may be poisonous and might be the cause of stress or even death in shellfish and finfish. According to some **research**, fish and bivalve mollusks may experience necrosis, atrophy, and inflammation of various animal organs as a result of harmful algal blooms. Based on multiple case studies, the HABs caused by cyanobacterial blooms in freshwater are the most evident example of warming-induced intensification. These blooms show that the temperatures that yield maximum growth rates for many cyanobacterial HABs are evenly higher than those that yield maximum growth rates for non-harmful eukaryotic algae. The water column experiences simultaneous hypoxia and acidification during the spring diatom blooms in temperate latitudes because surface waters quickly warm and stratify, preventing incoming water with dissolved oxygen and lower CO2 concentrations from reaching the bottom waters.

Sea level increase

The susceptibility of many coastal ecosystems, such as coral reefs and coastal wetlands like salt marshes and mangroves, to sea level rise or direct effects from human activity has come to light in recent decades. A graphic depiction of the direct and indirect effects of climate change on aquaculture is provided in Fig. 2. In reaction to the consequences Freshwater cultivation methods are becoming increasingly susceptible to rising sea levels and an increase in saline incursions upstream as a result of climate change. Sea level rise may cause salty water from rising sea levels to overwhelm aquaculture equipment, such as ponds, cages, tanks, and pens, particularly in lowlands and coastal locations. Sea level rise will have a significant effect on estuarine zones, including biotic changes and salty water incursion. These will have a negative effect on coastal ecosystems, such as mangroves, salt marshes, and other areas crucial to maintaining wild fish populations and supplying aquaculture seeds. According to earlier studies, intertidal habitat is predicted to decline by 13 to 64% over the course of the next century due to sea level rise in ecologically sensitive bays with steep topography and man-made features like sea walls. Because of the steep terrain and man-made features (such sea walls), mudflats and sandy beaches do not move inward. Aquaculture operators can shift their operations upstream, create or switch to more salt-resistant strains of these species, or import species that can withstand high salinity in order to adjust to environmental changes. The expense of such changes and their impact on the socioeconomic standing of the communities involved are undeniable.

Rainfall pattern

Typhoons, hurricanes, and unplanned floods have damaged cage culture systems along rivers and lakes and caused large-scale economic losses in recent years, which has led to the escape of numerous finfish. According to a study by Schewe and Levermann (2012), the rise in temperatures in the late 21st and early 22nd centuries is expected to cause regular fluctuations in monsoon precipitation levels, which might drop by as much as 70% below average. Excessive monsoon flooding has become a problem in some places of Southeast Asia in recent years and has to be addressed. Extreme weather, poor water quality from plankton blooms, and destructive discharge from floods are just a few of the negative consequences of climate change that cause structural damage and force aquaculture enterprises to relocate. Floods, which are categorized as natural catastrophes, affect aquaculture productivity and earnings when water floods in typically arid locations. Flooding alters the fish populations' natural habitats or makeup in a given location. The number and distribution of different fish species that are farmed or produced for aquaculture purposes have changed as a result. Farmers reported higher Indian major carp (IMC) death rates as a result of low dissolved oxygen levels following rains on hot summer days. Fish movement from one pond to another after storms or significant floods was also seen. Additionally, floods disrupt the food chain in the river, which has a negative impact on fish populations. A hazard to public health, economic stability, and international commerce can occasionally arise from water stress, which varies greatly throughout areas. Furthermore, it may serve as a trigger for major migrations and wars.

Ocean acidification

Although there is far less information available than on temperature changes, an increase in ocean salinity may be an indirect but sensitive indicator of several climate change processes, such as precipitation, evaporation, river runoff, and ice melt. Ocean acidification is caused by a number of reasons, including rising atmospheric CO_2, which the oceans absorb and cause low pH levels. The most common exchange of CO_2 with the atmosphere occurs in the seas. Nearly half of the CO_2 emissions from cement manufacturing and fossil fuel combustion during the last 200 years, since the start of industrialization, have been absorbed by the seas. This demonstrates the vital role that oceans play in the "carbon cycle," which is the term for the natural processes that cycle carbon worldwide. This subject is beginning to get a lot of attention in various parts of the world's scientific community, including at the 2004 UNESCO conference on the Oceans in a High-CO_2 World. It is very well known what chemical processes occur when CO_2 is drawn from the atmosphere and dissolved in seawater. However, little is known about the chemical and biological processes that underpin marine life. Therefore, predicting the consequences of ocean acidification is a challenging yet crucial undertaking. Some marine species have weaker calcified skeletons and/or lower net calcification rates as a result of a drop in the calcium carbonate saturation state, which has been linked to rising OA, according to several studies. Ocean acidification is expected to have an impact on consumer choices as well as the physiological, organoleptic, and nutritional traits of commercial species.

Effect in biodiversity

As a result of climate change's effects on biodiversity, native species are competing with them for resources and habitat, changing habitats, spreading pathogenic organisms, and causing genetic interactions through introgression and hybridization. Local biodiversity may be impacted as a result of fish species moving to other areas with better climatic conditions due to rising temperatures and changing ocean currents. Fish reproductive cycles are disrupted by climate change, which also modifies spawning habits and breeding seasons. Population dynamics and biodiversity may be impacted by warmer seas as certain species may develop more quickly while others may grow more slowly. Fish breeding, feeding, and nursery habitats are diminished by habitat loss, which lowers population variety and abundance. Furthermore, it is asserted that genetic drift and selective breeding methods have altered the genetic makeup of aquaculture populations, occasionally resulting in severe inbreeding. By means of genetic mutation between the wild equivalents and the fugitives, such modifications may affect the gene pools of the natural animals and their equivalents in culture.

Climate change's effects on fish physiology, breeding and spawning

Variations in temperature, acidity, hypoxia, and pluviosity regimes brought on by global climate change are anticipated to have an impact on fish reproductive behavior. Due to thermal stress brought on by the anticipated 1.5 °C increase in global temperature this century, fish, particularly those from colder waters like the Atlantic halibut, salmon, and cod, as well as intertidal shellfish, are expected to die at higher rates. Thus, extended temperature stress may have a variety of effects on aquaculture production, with a particular emphasis on lower output. Chronic stress can alter the immune systems, cardiorespiratory systems, and aerobic capacity of a number of economically significant species. Climate change has long-term effects on aquatic creatures' physiology, development patterns, and behavior that reduce their geographic range and impair their capacity for reproduction. One of the most detrimental effects of climate change, the harm that high temperatures do to the gonads. Elevated temperatures can have irreversible effects on fish during sensitive early developmental stages, impacting sex differentiation/determination, larval growth, and the frequency of malformations. This can lead to functional masculinization in fish. Climate change is already having an impact on early life cycle events and reproduction in the majority of fish. In order to do this, many kinds of systems at different levels are involved, and as our knowledge of them grows, they become more complicated.

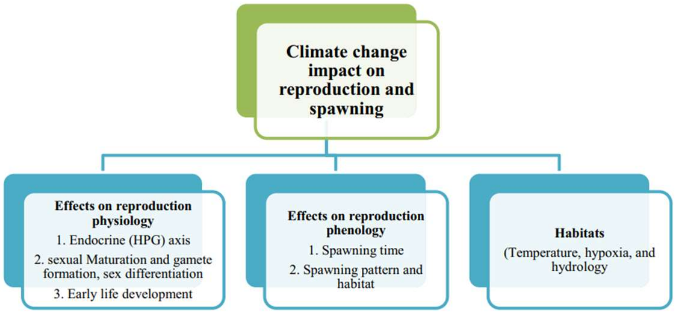

Fig.2 Climate change impact on spawning

The timing of spawning, the degree to which extreme temperature events cause physiological stress, the fish's energy reserves and reproductive maturity, its previous exposure to temperature fluctuations, and its ability to adapt are all important factors that can be impacted by thermal challenges during the reproductive cycle. In both freshwater and marine animals, the process of spawning and successful reproduction is essentially controlled by evolutionary mechanisms. In order to reproduce and complete their life cycle, organisms have evolved to take into consideration the circumstances in their environment and perhaps the unpredictability of these factors. In order to promote a larva's chances of surviving to become a reproducing adult or, at the very least, reduce the disturbance brought on by unpredictable climatic events (food), spawning times and locations have evolved to correspond with the current physical (temperature, salinity, currents) and biological conditions.

Conclusion

The many effects of climate change on aquaculture have been examined in this article, emphasizing the urgent need for sustainable management techniques. The data presented in this analysis highlights how aquaculture is vulnerable to climate change, which is shown in temperature fluctuations, ocean acidity, and an increase in the frequency of extreme weather events. The productivity, sustainability, and socioeconomic worth of aquaculture are seriously threatened by these changes. Additionally, the article emphasizes how well climate-resilient adaptation strategies work to mitigate these effects. Aquaculture can overcome the difficulties of climate change and thrive to improve global food security and livelihoods by adopting innovative techniques, technology, and policies.

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MULCHING: A KEY TOOL FOR SUSTAINABLE SOIL AND WATER MANAGEMENT

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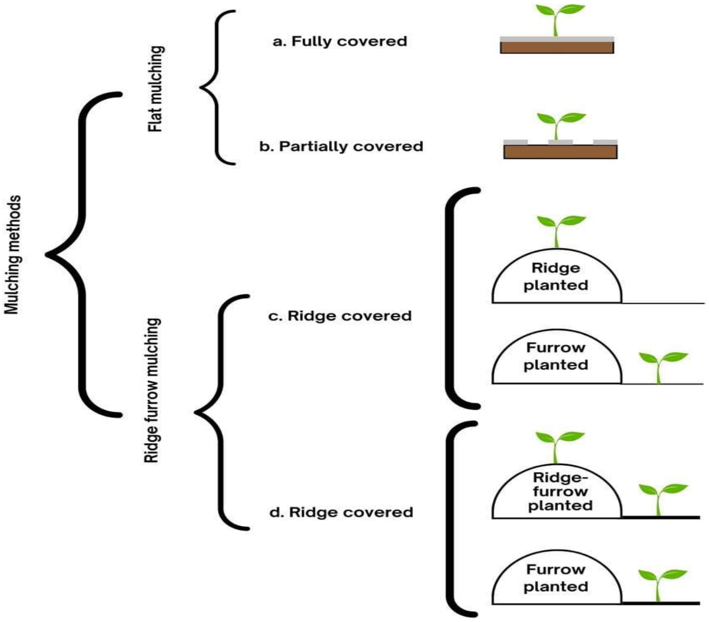
In an era of increasing emphasis of sustainable agriculture, mulching has emerged as a simple and cost-effective soil and water conservation practice that involves covering the soil surface with organic or inorganic materials. It plays the vital role in enhancing crop productivity while preserving natural resources, improving fertility, and protecting land from degradation across a variety of environmental conditions. In any agro-ecosystems, mulching with organic crop residues like straw mulch has been recognized as an effective management practice for reducing soil erosion, conserve soil moisture while improving soil microclimate, plant growth, soil health, and water use efficiency.

Concept of Mulching

The term “Mulch,” derived from the German word molsch means soft or decaying, refers to the practice of covering soil with organic (straw, leaves, compost) or inorganic (plastic, gravel) materials to conserve moisture, regulate temperature, improve soil conditions, and support efficient crop growth in both rain-fed and irrigated systems.

Mulching in Indian Agriculture

In countries like India, where agriculture heavily depends on monsoons, mulching is particularly valuable. Farmers in states such as Maharashtra, Rajasthan, and Karnataka are increasingly adopting plastic and organic mulching techniques to combat water scarcity and improve crop yields. Government schemes and agricultural extension programs are also promoting mulching as part of sustainable farming practices.



Types of Mulching Materials

Mulching materials can be broadly classified into two categories:

Organic Mulch: Organic mulches are made up of materials such as straw, grass clippings, and composted leaves. They can be applied to bare ground or existing plantings. Below are the types of organic mulching:

Dry leaves

Dry leaves can be used as traditional mulch, covering the soil like a blanket, or can be buried beneath the ground in a bed, where they will break down.

Grass clipping

Grass clippings degrade quite quickly. This is one of the most abundantly and easily available mulch materials across the country. It provides nitrogen to the soil, if incorporated fresh. However, application of green grass in rainy season may result into the development of its own root system which will be detrimental to plant growth. Therefore, use of dry grass as mulch material is suggested.

Compost

Compost functions in the same manner as any other kind of mulch, improving soil texture, tilth, and nutrients that seep right into the ground.

Straw and seedless hay

Both straw and seedless hay are effective mulches but thin layers tend to blow away quickly.

Wood chips or shredded bark

Both wood chips and shredded bark are common mulches, but they are both robust materials that decompose slowly.

Living mulch: The living mulch is a crop that can be cultivated concurrently with the primary crops throughout the same growing season.

Benefits: Organic mulches enrich the soil with organic matter as they decompose and improves soil fertility. They improve soil structure making it easier for plants to grow and thrive. They also increase organic matter in the soil which improves drainage and aeration.

Inorganic Mulch: Inorganic mulches are manufactured from materials that do not decompose, such as plastic and other synthetic materials. Inorganic mulches are made from items that are not organic, such as Plastic sheets, Pebbles and stones, landscape fabric.

Black plastic film: It helps in conserving moisture, controlling weed and reducing outgoing radiation.

Silver plastic film: It repels pests, cool the root zone, and enhance photosynthesis. **Transparent plastic film**: It increases the soil temperature and preferably used for solarization.

Benefits: It is long-lasting, effective in weed control, suitable for commercial farming. It provides moisture conservation, soil Conservation, Soil Solarization, regulates soil temperature and provide a barrier to weed.

Special type materials: Some special materials, such as sand and concrete that are easily available and have also been used for mulching.

The choice of selection of an appropriate mulching material depends on local climate, cost-effectiveness and feasibility for the crop.

Type	Mulching Materials	Best Suited For
Organic	Paddy straw, wheat straw, sugarcane trash, dried leaves,	Sustainable farming, soil building, orchards, and low-cost cereal production.
Inorganic	Perforated mulch	Rainy season
	Black film	Sandy soil, saline water use
	Transparent film	Weed control through solarization
	Silver coloured film	Insect repellant
Special type	Gravel, stones, or bio-plastics.	Arid zones like Rajasthan (layered mulching)


Compost mulch


Straw mulch


Bark mulch


Newspaper mulch


Wood chips mulch


Sawdust mulch


Plastic mulch film


Black plastic mulch


LDPE plastic

Role in Water Conservation

Water scarcity is one of the biggest challenges in modern agriculture. Mulching directly addresses this issue in several ways:

Reduces Evaporation: Mulching helps to conserve soil moisture by reducing surface evaporation. By covering the soil with a protective layer, less water is exposed to air and sun, minimizing evaporation and ensuring a more stable water supply for crops.

Enhances Water Retention: It helps the soil retain moisture for a longer period, ensuring plants have consistent access to water.

Minimizes Irrigation Needs: A mulch layer acts as a barrier, preventing direct sunlight from hitting the soil and reducing water loss. Reduced evaporation can lead to a reduction in irrigation requirements, conserving water resources and decreasing agricultural water consumption – a crucial step towards sustainable farming.

Studies have shown that mulching can reduce water loss by up to 50%, making it an essential technique in drought-prone regions.

Contribution to Soil Conservation

Mulching conserves water while improving soil properties such as structure, aeration, organic matter, and moisture–temperature balance, thereby enhancing soil physical conditions and microbial activity.

Prevents Soil Erosion and Water Runoff:

Mulching protects exposed soil from wind and water erosion by reducing raindrop impact, minimizing runoff, enhancing infiltration, and preventing the loss of topsoil and nutrients.

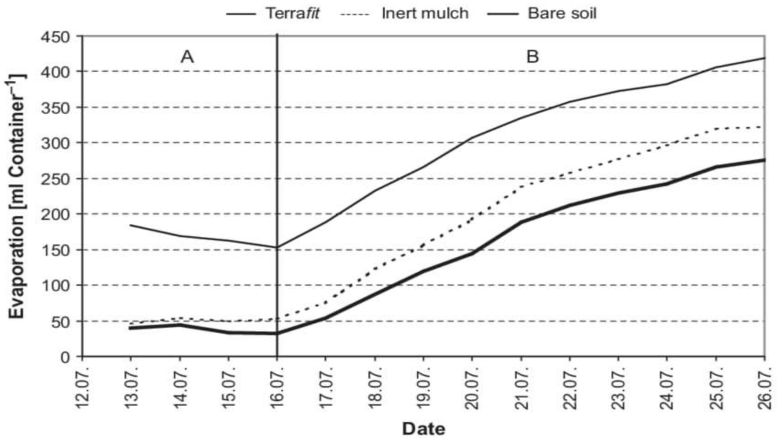
Improves Soil Structure: Mulching enhances soil structure by preventing compaction and erosion, while decomposing organic mulches add nutrients, improve porosity and moisture retention, and support beneficial organisms that promote soil health and crop productivity.

Regulates Soil Temperature: Mulching stabilizes soil temperature by insulating the soil—keeping it cooler in hot conditions and warmer in cold—thereby improving germination, crop growth, and yield.

Suppresses Weed Growth: Mulching suppresses weeds by blocking sunlight, reducing competition for water and nutrients, and minimizing the need for chemical herbicides, thereby supporting eco-friendly crop production.

Increase in Yield of Fruit Crops through Plastic Mulching

Crop	Economic yield ha^{-1}		% Increase in yield	References
	Un-mulched	Mulched		
Tomato	6.02	8.27	27.20	Moursy et al.(2015)
Cotton	1.67	2.22	24.77	Ahmad et al.(2015)
Mustard	0.41	0.61	32.78	Saikia et al.(2014)
Rice	5.39	0.83	21.08	Devasinghe et al.(2015)
Lentil	0.80	0.89	10.11	Alami-Milani et al.(2013)
Maize	2.49	4.76	47.68	Hashim et al.(2013)



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Challenges and Considerations

While mulching offers numerous benefits, it is not without challenges:

- Mulching requires a lot of labour.

- It might spread new pathogens and pests across a field.
- There is a fire risk with the dried organic mulches.
- Risk of Nitrogen-immobilization: Addition of organic materials stimulates microbial growth, and when these are low in nitrogen, microbes temporarily immobilize soil nitrogen, leading to short-term nutrient competition and possible crop deficiency.
- *Initial Cost*: Inorganic mulches like plastic sheets can be expensive.
- *Improper Application*: Too thick or too thin a layer may harm plant growth.
- *Environmental Concerns:* Non-biodegradable mulches can cause pollution if not managed properly.

Conclusion

Mulching is a low-cost, high-impact practice that conserves water, reduces erosion, improves soil health, and supports sustainable, climate-resilient agriculture while enhancing crop productivity.

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NEGLECTED COASTAL SHELTER VEGETATION: SCIENTIFIC EVIDENCE FOR THE ROLE OF COASTAL GRASSES AND LITTORAL BIO-SHIELDS IN TSUNAMI PROTECTION, COASTAL STABILITY AND CLIMATE CHANGE MITIGATION

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Introduction

Coastal regions are among the most hazard-prone landscapes in the world, facing shoreline erosion, cyclones, storm surges, saline intrusion, sea-level rise, and occasional tsunami events. In many countries, including India, coastal protection has traditionally relied on hard engineering structures such as seawalls, groynes, revetments, and embankments. Although such measures may provide localized short-term protection, they often involve high capital costs, recurring maintenance, and unintended erosion transfer to adjacent shorelines. Consequently, recent coastal management approaches increasingly recognize nature-based solutions that integrate ecological processes with disaster risk reduction (Chang & Mori, 2021; Morris *et al.*, 2018; Van Zelst *et al.*, 2021). Natural coastal vegetation functions as a living protective barrier capable of growth, regeneration, and adaptation to environmental change. Coastal grasses, creepers, shrubs, palms, littoral forests, wetlands, and mangroves help stabilize sediments, reduce wave energy, trap sand, attenuate wind, and enhance shoreline recovery after storms (Gedan *et al.*, 2011; Temmerman *et al.*, 2022; Chang & Mori, 2021). Unlike rigid structures, vegetative systems also provide biodiversity benefits, carbon sequestration, fisheries support, and livelihood opportunities for coastal communities (Silver *et al.*, 2019; Veetil *et al.*, 2021). Quantitative studies confirm the protective value of vegetation. Dense coastal vegetation reduced tsunami-like solitary wave run-up by 52%**,** while lower density vegetation still reduced run-up by 17% (Torabbeigi *et al.*, 2024). Integrated vegetation-dune systems reduced flooded area by 77%**,** maximum inundation depth by 58%**,** and beach erosion volume by 55% in modelling applications (Unguendoli *et al.*, 2023). Mangrove scenarios reduced sediment erosion by 97–99% under present and future sea-level rise conditions (Jayson-Quashigah *et al.*, 2025). These findings demonstrate that coastal vegetation is measurable protective infrastructure rather than ornamental greenery. Among the most neglected yet strategically important coastal species are *Spinifex littoreus, Ipomoea pes-caprae, Pandanus odoratissimus, Casuarina equisetifolia*, and Palmyra. Each occupies a distinct ecological niche and contributes to integrated bioshield formation.

Role of *Spinifex littoreus*

Spinifex littoreus is one of the most important pioneer grasses of tropical sandy coasts. It spreads through stolons and rhizomes, producing dense mats that trap wind-blown sand and gradually build fore dunes. These dunes function as natural elevated barriers against storm surge and wave attack (Song *et al.*, 2021; Huyen *et al.*, 2019). Comparative studies on tropical fore dune pioneers found *Spinifex* to possess strong anti-wind erosion capacity and excellent suitability for dune stabilization

(Lee *et al*., 2020). Its extensive root architecture also reinforces sand structure and reduces blowout formation (Jian-Hui *et al.*, 2014). Despite this importance, *Spinifex* is frequently removed during beach cleaning, tourism expansion, vehicle traffic, and unscientific beautification programs. Such removal can destabilize dunes and accelerate shoreline retreat (Durai *et al*., 2024).

Role of *Ipomoea pes-caprae*

Ipomoea pes-caprae is a fast-growing creeping vine widely distributed on tropical beaches. It forms dense surface cover over exposed sand, protecting it from direct wind impact and reducing desiccation stress (Devall, 1992). This species plays a major role in stabilizing embryo dunes and reducing erosion of dune faces under wave attack.

Experimental and field studies indicate that vegetated dunes experience significantly lower erosion than unvegetated dunes during storm events (Martínez *et al*., 2016; Maximiliano-Cordova *et al*., 2019).When combined with Spinifex, Ipomoea creates a highly effective front-line dune system in which rapid cover establishment is paired with deeper structural reinforcement (Lee *et al*., 2020; Huang & Yim, 2014).

Role of *Pandanus odoratissimus*

Pandanus odoratissimus is a valuable woody littoral species characterized by dense branching and prop roots. These structural traits create significant drag against incoming water and help trap floating debris during storms and tsunami inundation (Tanaka *et al*., 2007). Research on bioshield configurations found that *Pandanus* belts positioned in front of Casuarina forests substantially improve tsunami mitigation performance. In Sri Lankan case studies, adding a 10 m *Pandanus* front belt reduced destructive force ratios from 1.4 to 0.7**,** demonstrating the importance of layered design (Samarakoon *et al*., 2013). Pandanus also stabilizes sandy ridges and supports local livelihoods through weaving materials and fibre products.

Role of *Casuarina equisetifolia*

Casuarina equisetifolia has been extensively planted across South Asian coasts as a shelterbelt species. Its height and branching pattern reduce wind speed, protect inland agriculture from salt spray, and provide timber and fuelwood resources (Purwono *et al*., 2017). However, scientific evaluations caution that *Casuarina* monocultures or fragmented belts may not always provide optimal protection during extreme events. Vegetation gaps can concentrate water flow and increase localized force unless belts are dense and well-designed (Tanaka *et al*., 2009; Samarakoon *et al*., 2013). *Casuarina* is therefore best used as a second-line inland shelterbelt behind dune vegetation and native littoral species rather than as a stand-alone frontline defence.

Role of Palmyra

Palmyra is a hardy, drought-tolerant palm of major ecological and socioeconomic importance in South India and Sri Lanka. It develops deep roots and strong trunk architecture, making it highly tolerant of wind stress and harsh coastal climates (Krishnaveni *et al*., 2020). Recent studies highlight Palmyra-based land-use systems as significant contributors to carbon stock enhancement and floristic diversity in dry tropical landscapes (Gnanavelrajah *et al*., 2025). Additional reviews identify Palmyra as a potential climate mitigation crop with multiple pharmaceutical and livelihood benefits (Jayaraj *et al*., 2025; Nancy & Priya, 2020). Reviving Palmyra belts in coastal dry districts can therefore contribute simultaneously to shoreline resilience, carbon sequestration, and rural livelihoods.

Why Layered Bioshields Work Best?

Scientific evidence indicates that vegetation performance depends on species traits, stem density, belt width, vertical layering, and continuity (Chang & Mori, 2021). No single species can provide complete protection across all coastal zones.An effective bioshield may include *Spinifex littoreus* and *Ipomoea pes-caprae* in the foredune zone, *Pandanus odoratissimus* on sandy ridges, Casuarina equisetifolia and Palmyra inland, and mangroves in estuarine sectors (Tanaka *et al*., 2007; Athikalam & Vaideeswaran, 2022).Such layered systems combine dune formation, wave friction, wind buffering, biodiversity enhancement, and long-term resilience.

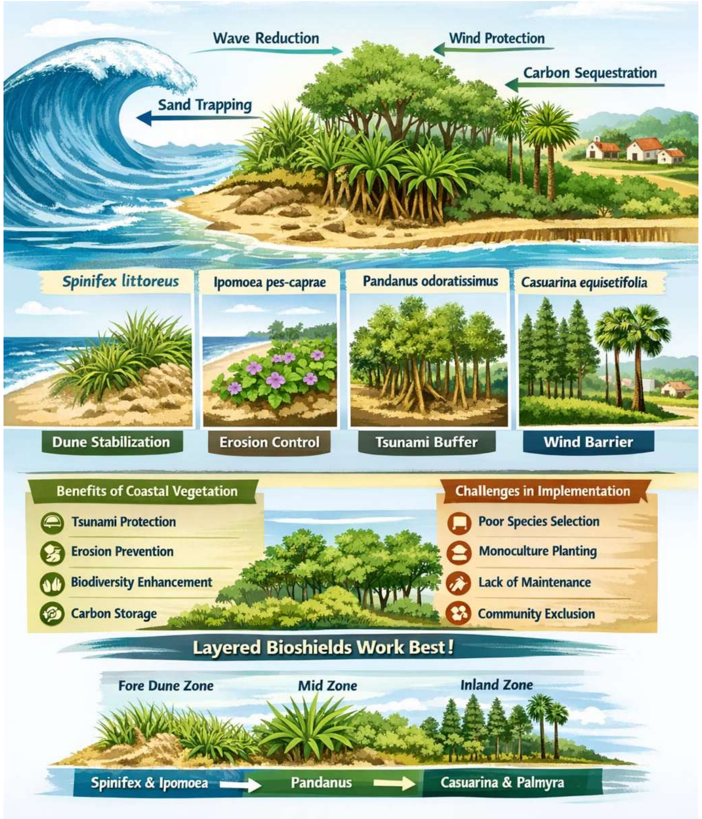

Figure: Conceptual model of layered coastal bio-shield for hazard mitigation and climate resilience

Why Many Coastal Programs Fail?

Many post-tsunami bioshield projects in South Asia underperformed because of poor species selection, monoculture planting, weak maintenance, lack of community participation, and failure to match species with local geomorphology (Feagin *et al*., 2010; Athikalam & Vaideeswaran, 2022; Veetil *et al*., 2021). Programs focused only on tree numbers often ignored dune grasses and creepers, even though these species create the geomorphic foundation needed for successful inland plantations.

Recommendations

Forest agencies should classify dune grasses and littoral vegetation as protective infrastructure. Nurseries should raise S*pinifex littoreus, Ipomoea pes-caprae, Pandanus odoratissimus*, Palmyra, and appropriate mangrove species. Existing dunes should be protected from sand mining, vehicle movement, and vegetation clearing. Restoration should prioritize mixed native species, zonation-based planting, GIS monitoring, and community stewardship (Athikalam & Vaideeswaran, 2022; Veetil *et al*., 2021).

Conclusion

The scientific evidence clearly shows that coastal vegetation can reduce run-up, flooding, erosion, and sediment loss by substantial margins ranging from 17% to over 90%, depending on species composition and density. Pioneer species such as *Spinifex littoreus* and *Ipomoea pes-caprae* create the first line of defence by building dunes, while *Pandanus odoratissimus, Casuarina equisetifolia*, and Palmyra strengthen inland resilience. Protecting and restoring these neglected species is not only an ecological priority but also a strategic investment in disaster preparedness, climate adaptation, and sustainable coastal development.

Acknowledgement

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GREEN MILK: A STEP IN MAKING GREEN INDIA

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Abstract

India being the world's largest milk producer, faces the dual challenge of increasing dairy productivity while reducing carbon footprints, particularly methane emissions from ruminants. Methane production in the rumen not only contributes to climate change but also represents a significant loss of dietary energy. The concept of "Green Milk" emphasizes eco-friendly milk production through improved feeding and management practices. This article highlights practical and farmer-friendly feeding strategies which can enhance feed efficiency, improve milk yield and reduce carbon footprint. Promoting greener milk production aligns with the vision of sustainable agriculture and supports India's goal of achieving *Viksit Bharat 2047* through climate-resilient and resource-efficient dairy farming.

Keywords: Green milk, Methane emissions, Smart feeding, Ruminant nutrition, Climate change, Feed efficiency

Introduction

India is the world's leading milk producer. Most of the milk is obtained from cattle and buffalo. But did you know that when a cattle or buffalo burps, it is actually losing energy? Energy is lost in form of methane gas. Scientific studies show that a buffalo can lose up to 12% of its feed energy just by producing this gas. If we can stop this waste, that energy can instead go toward making more milk or keeping the animal healthier. As India marches towards its centenary of independence in 2047, the vision of a "Viksit Bharat" encompasses not just economic wealth, but environmental leadership. We aim to produce "Green Milk"- milk that is good for the pocket and for the planet.

What is Green Milk?

Milk which is obtained by eco-friendly methods. It nourishes the nation without depleting the planet.

Why Green Milk?

Think of animal's stomach (rumen) like a big fermentation tank. Inside, there are millions of tiny "workers" (microbes) breaking down the fodder. Some workers are "helpers" that contribute in making milk, but others are "wasters" that produce methane gas. There is a need to reduce the waste and obtain more milk by using eco-friendly interventions.

How to obtain Green Milk?

Smart feeding

1) **Stop feeding dry fodder only**

   Why it's bad: Dry straw is very hard to digest. The "workers" in the stomach have to work overtime to break it down, which creates massive amounts of methane gas.

   The Green Fix: Always mix straw with a little bit of green fodder or soak it with urea-molasses treatment to make it easier to digest.

2) **Avoid "Sudden" Diet Changes**
Why it's bad: The useful stomach "workers" may die off, and the gas-producing microbes take over. This leads to indigestion and a spike in methane burps.
The Green Fix: Always change feed gradually over 7-10 days by mixing the old and new feed together.

3) **Don't Ignore the "Particle Size" of Fodder**
Why it's bad**:** If the pieces are too big, the animal spends too much energy chewing (rumination), which produces more gas. If it's too fine (like a powder), it passes through the stomach too fast without being fully digested.

The Green Fix**:** Use a high-quality chaff cutter to maintain a consistent size (around 1–2 inches) for optimal digestion.

4) **Stop Using "Unbalanced" Concentrates**
Some farmers only feed mustard cake (*sarson khali*) or just crushed grains.
Why it's bad**:** An imbalanced diet lacks the minerals needed for efficient fermentation. A "hungry" microbe is a wasteful microbe. It produces more gas and less energy for milk production.

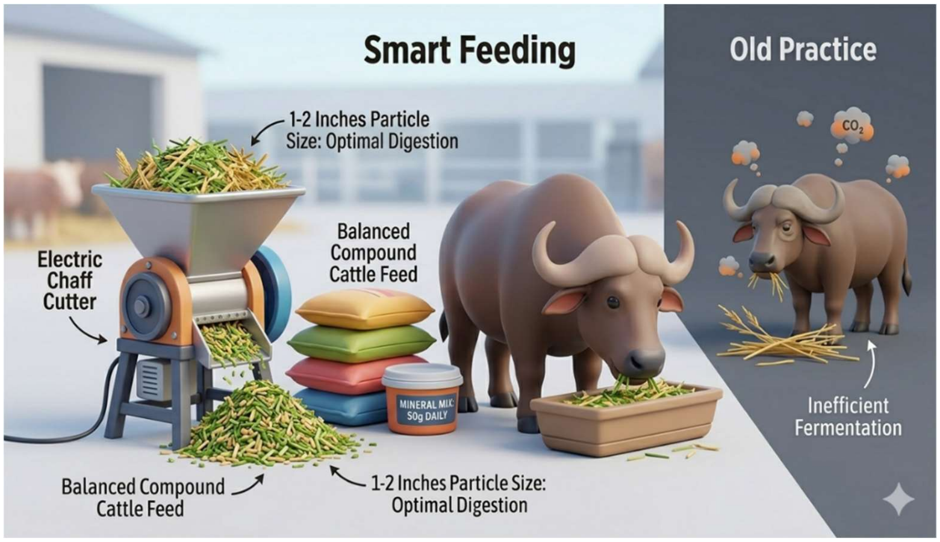
The Green Fix**:** Use a balanced Compound Cattle Feed or ensure you are adding a good Mineral Mixture (about 50g daily) to the ration.

5) **Don't Waste Energy on "Heat Stress"**
Leaving buffaloes tied in the direct sun or in poorly ventilated sheds is a major "Green Milk" killer.

Why it's bad: When a buffalo is hot, it pants. Panting uses up the energy that should go towards milk production.

The Green Fix: Use fans, misting, or simple wallowing in the afternoon.

6) **Including "feed additives"**
Inclusion of locally available plant-based feed additives which are sources of tannins, saponins and essential oils (e.g. eucalyptus, neem), as they inhibit the growth of methane producing microbes.

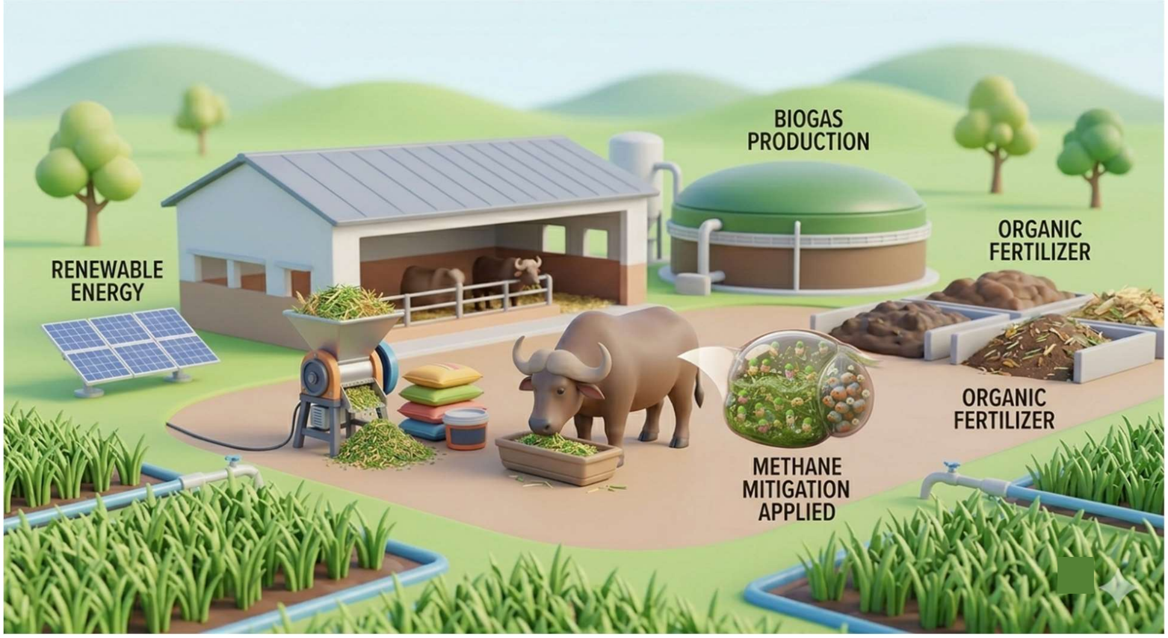


Future outlook

Research in animal nutrition is rapidly advancing, with new feed technologies aimed at reducing methane emissions without compromising animal productivity. In the coming years, methane-reducing feed additives may become a standard practice in dairy farming.

Conclusion

Green Milk is the future of Indian dairying. By making small changes in feeding strategy, we can build a cleaner, greener, and more prosperous future for Indian agriculture under the vision of Viksit Bharat 2047.



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BEYOND FERMENTATION: THE AGRICULTURAL POWER OF LACTIC ACID BACTERIA

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Abstract

Lactic acid bacteria (LAB), commonly known for their role in fermented foods, are emerging as a powerful tool in sustainable agriculture. Beyond improving food quality, these beneficial microbes—including *Lactobacillus*, *Lactococcus*, and *Pediococcus* can protect crops from harmful pathogens and help in removing pesticide residues from food and the environment. They act through natural mechanisms such as antimicrobial compound production, enzymatic degradation, and toxin binding. Additionally, LAB enhances plant growth and resilience, making them valuable allies in eco-friendly farming systems. While challenges remain in large-scale applications, their safety and multifunctional nature highlight their potential as sustainable alternatives to chemical pesticides. LAB thus represents a promising bridge between food science, agriculture, and environmental protection.

Introduction

For decades, modern agriculture has depended heavily on chemical pesticides and fungicides to protect crop plants from pests. While these chemicals help ensure high yields, they also leave residues in food and the environment. Over time, these residues have been linked to health concerns such as hormonal imbalance, neurological effects, and other health risks. At the same time, fungi not only contaminate but also produce toxins such as aflatoxins B1 and Ochratoxin A, which are difficult to remove once they are formed.

Lab In Agriculture and Biocontrol

In recent years, the importance of LAB has grown from food technology to sustainable agriculture and environmental management. One key role they play in agriculture is as biocontrol agents, helping protect crops from harmful microorganisms. LAB produces various antimicrobial compounds, including organic acids, antimicrobial peptides, and other secondary metabolites, which stop the growth of plant pathogens like fungi and spoilage organisms. By lowering the pH and competing for nutrients and ecological niches, they create an unfavourable environment for harmful microbes. This natural way of fighting pathogens reduces the reliance on chemical pesticides and supports environmentally friendly farming practices. Besides disease control, LAB also supports plant growth by improving nutrient availability, enhancing soil fertility, and boosting plant tolerance to environmental stress. Their interaction with the plant microbiome encourages better root and shoot development, making them valuable in sustainable agricultural systems.

Lab In Pesticide Degradation and Detoxification

Another important application of LAB is their ability to break down pesticide residues and detoxify contaminated food and environments. The excessive use of pesticides in agriculture has led to toxic residues accumulating in soil, water, and food products, putting human health and ecosystems at risk. LAB provide a biological solution through processes such as enzymatic breakdown, adsorption, and biotransformation. They produce enzymes like phosphatases that can decompose complex pesticide molecules, especially organophosphates like chlorpyrifos, into simpler and less toxic compounds. Studies show that LAB can degrade a significant amount of pesticide residues quickly, and in some cases, achieve almost complete removal under ideal conditions. Additionally, some LAB strains can use pesticides as a source of carbon and energy, which boosts their detoxification effectiveness. Besides breaking down pesticides, LAB can bind pesticide molecules to their cell wall components, lowering their availability and toxicity. These combined actions make LAB effective for bioremediation and food detoxification.

Advantages and Applications

The benefits of using LAB in agriculture and food systems are many. They are non-toxic, biodegradable, and safe for the environment compared to synthetic chemicals. Their multifunctional nature allows them to work as biopesticides, biofertilizers, and detoxifying agents at the same time. Furthermore, their compatibility with organic farming makes them especially appealing in sustainable agriculture. Compared to conventional pesticides, LAB-based methods have a lower environmental impact and reduce the chance of resistance developing in target organisms.

Challenges and Future Perspectives

Despite these advantages, some challenges persist, including differences in strain performance, limited large-scale field validation, and issues with formulation and stability during use. Overcoming these challenges requires more research focused on selecting strains, optimizing culture conditions, and developing effective delivery systems.

Conclusion

Lactic acid bacteria are a promising and adaptable group of microorganisms with significant potential beyond their traditional role in food fermentation. Their ability to protect crops, promote plant growth, and break down harmful pesticide residues positions them as essential players in creating sustainable agricultural practices and safer food systems. As scientific understanding and technology continue to advance, LAB are likely to become key elements in future strategies to reduce chemical inputs and enhance environmental health.

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AGRI STARTUPS POWERING INDIA 2047

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Abstract

India is moving closer to a hundred years of independence from British rule. By 2047, farming must change from just survival to smart, science-led growth. Backed by a strong push in the 2026–27 national budget, over ₹4.35 lakh crore flows into villages. Money builds roads, networks, and labs - tools farmers once lacked. Innovation will thus rise, not only from labs but also from small towns where new businesses take root with startups rooted in the soil, powered by data, and driven by youth. These ventures may turn waste into fuel or crops into medicine. Progress won't arrive through policy alone - it grows where risk meets land. Behind every breakthrough is someone who dares to grow differently. By adopting a synergistic approach of biotechnology, digital precision, and regenerative practices, these rural enterprises are actively localizing Mission LiFE and accelerating India's progress toward SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

Introduction

The roadmap to a developed India relies on transforming agriculture into a resilient, globally competitive enterprise. This transition cannot be achieved through traditional input-intensive methods; it requires "knowledge-intensive" disruption. Right where science meets soil, agri-startups move lab discoveries straight into farming practice. Pushing further, the ecosystem now shapes a shift - fueled by deep-tech, digital tools, less carbon. Not just change but rewiring how agriculture evolves. Each piece connects: smarter tech underpins data use, which cuts emissions naturally. Progress grows quietly here, step by grounded step.

Deep-Tech: The Biotechnology and Seed System Frontier

Fueled by a fresh wave of innovation, the BioE3 Policy (Biotechnology for Environment, Economy, and Employment) - focusing on biotech's role in environment, economy, and jobs - is taking root through agile farm-tech ventures. Instead of one-size-fits-all fixes, emerging companies in seed science craft answers tuned to regional needs, proposed solutions are:

- **Microbial Biomanufacturing:** Production of targeted bio-fertilizers and nano-biostimulants are being scaled by emerging companies, reducing reliance on import of chemical fertilizers, supporting Sustainable Soil and Water Management.
- **Bio-fortification:** Zinc and Iron profiles of staple crops are being enhanced to address issues of "Hidden Hunger".

Digitization: Empowering FPOs and Precision Farming

For technology to be impactful, it must be accessible. High-end technology for smallholder farmers is being democratized by startups leveraging Farmer Producer Organizations (FPOs) as central distribution hubs.

- **Precision Advisory:** Localised, real-time crop advisory, transforming how rural cooperatives manage pest outbreaks are being provided by platforms utilizing AI (such as *Bharat Vistar*).
- **Drone-as-a-Service (DaaS):** Startups allow small-scale farmers to utilize drone-based targeted spraying and IoT soil moisture sensors to drastically optimizing input efficiency by offering Digital & Precision Farming tools on a rental basis.
- **Transparent Value Chains:** Blockchain-enabled market linkages are being used to remove intermediary bottlenecks, ensuring better price realization for rural produce.

Decarbonization: Mission LiFE and Regenerative Business Models

Agri-startups, by embedding Mission LiFE (Lifestyle for Environment) into their core business models, are proving that ecological sustainability and economic profitability are not mutually exclusive. They are thus championing Natural & Regenerative Farming:

- **Waste-to-Wealth:** Aligning with **SDG 12**, agricultural residue (like paddy stubble) are being converted into high-value bio-plastics and compressed biogas (CBG) by startups, effectively mitigating air pollution.
- **Agroforestry and Carbon Markets:** Farmers practicing **Agroforestry & Carbon Sequestration** can monetize their efforts in global carbon markets through the establishment of verification frameworks by startups that allow them to create a lucrative secondary income stream (**SDG 13**).

Leading Agri-tech startups in India

Startup	Founded / HQ	Problem they solved	What they actually do	Key Achievement
Ninjacart	2015, Bengaluru	Farmers sell vegetables through 4–5 middlemen. By the time produce reaches a Mumbai shop, the farmer has earned a fraction of the shelf price.	Connect farmers directly to retailers and restaurants. 1,400+ tonnes of fresh produce move daily from farm to shelf — no middlemen.	17,000+ retail stores supplied across 20 states. Farmers get better prices. Shops get fresher stock. ₹2,003 Cr revenue in FY24.
DeHaat	2012, Patna	A farmer in rural Bihar needs seeds, crop advice, a loan, and a buyer — four different problems with no single place to solve them.	11,000+ village-level 'DeHaat Centres' run by local entrepreneurs. One stop for inputs, advisory, micro-credit, and market linkage.	2 million+ farmers across 11 states. It works because there's a trusted local face behind the technology — not just an app.
WayCool Foods	2015, Chennai	Fresh food rots in transit or sells	Full supply chain — grains, fresh produce,	900+ tonnes of food moved daily. Food that used to

Startup	Founded / HQ	Problem they solved	What they actually do	Key Achievement
		at distress prices when farmers have no direct link to buyers.	dairy — from 85,000 farmers to over 1 lakh retailers and cloud kitchens in Tamil Nadu and beyond.	spoil now reaches the plate fresh — and farmers earn more for it.
AgroStar	2013, Pune	A cotton farmer in Gujarat spots disease on his crop. He has no agronomist nearby, no one to call, and cannot read English.	Farmers photograph crop problems and get expert advice in their own language — Gujarati, Marathi, Hindi and 9 others — within hours. Also sells agri-inputs via the same app.	5 million+ farmers served across 5 states. India's largest digital farmer network — built on language, not just technology.
CropIn	2010, Bengaluru	Banks can't verify crop health. Governments can't spot drought stress early. No one can predict yields before harvest.	Monitors farms via satellite imagery and AI. Tells banks, governments, and agribusinesses what is growing, how healthy it is, and what yield to expect — before harvest. Now powered by Google Gemini AI.	No drone, no inspector needed. Serves agribusinesses and governments globally. Became the invisible intelligence layer of Indian agriculture.
Arya.ag	2013, Delhi	After harvest, everyone sells at once. Prices crash. Farmers must sell immediately — or let their grain rot.	Store farmers' grain in warehouses and lend them money against it. Farmers wait for prices to rise, then sell. The warehouse becomes a bank.	1 million+ farmers. It turns a storage shed into a financial tool — giving farmers the power to choose when to sell, not just sell in desperation.
Fasal	2018, Bengaluru	India uses more groundwater for farming than any country — and it is running out. Farmers also lose entire seasons to pest attacks they never saw coming.	Sensors in fields measure soil moisture and microclimate every few minutes. AI tells the farmer exactly when to water, how much — and gives a 48-hour early warning on pests.	3 billion litres of water saved. A 48-hour pest warning can save an entire crop season. That's not data — that's a livelihood.

Startup	Founded / HQ	Problem they solved	What they actually do	Key Achievement
Stellapps	2011, Bengaluru	India is the world's largest milk producer, but dairy farmers don't know if their milk was adulterated in the supply chain or why their monthly payout changes.	IoT sensors on milking equipment and cold-storage units create a full data trail — from cow to cooperative. Spoilage falls. Payouts become transparent.	Works with major dairy cooperatives across India. In a ₹10 lakh crore dairy economy, making payouts fair for the farmer at the bottom matters enormously.

Conclusion

Women and young people farming hold the key to how well India's farm revival does in the future. Starting smart, technology-focused businesses in village areas helps stop young people from moving to cities. Agri-businesses turn the youth from those looking for work into those creating jobs. To keep progress going toward a developed India by 2047, new rules should support local biotech labs that operate independently. Clearer trial zones with lighter regulations could speed things up. When small farm companies lead change, India strengthens its ability to feed its population. This path may also set what others follow in eco-friendly, tech-powered farming worldwide.

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INDUSTRIAL APPLICATIONS OF HIGH FRUCTOSE CORN SYRUP (HFCS)

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Abstract

High-fructose corn syrup (HFCS) is widely known as a sweetening ingredient in a variety of food and beverage products. However, its importance in the food industry extends beyond simply providing sweetness. This review examines the technological, functional, and economic roles of HFCS in several industrial sectors, particularly within food processing. HFCS is produced through the enzymatic conversion of corn starch into glucose, followed by the partial conversion of glucose into fructose. Due to characteristics such as its liquid form, stability in acidic environments, resistance to crystallization, and relatively low cost compared with sucrose, HFCS has become an important component in modern food manufacturing. This article reviews the production process, major types of HFCS, and its functional roles including moisture retention, improvement of browning reactions, texture enhancement, use as a fermentation substrate, and shelf-life extension. In addition, the review highlights its applications in bakery products, beverages, confectionery, dairy products, sauces, and other processed foods. Current discussions surrounding the health implications of HFCS and recent market trends in sweetener use are also considered. Understanding the various functional properties of HFCS helps explain its continued use in industrial food production and technological applications.

Keywords: High-fructose corn syrup, industrial applications, food processing, sweeteners, corn starch processing, humectant, food additives

Introduction

High-fructose corn syrup (HFCS) is a liquid sweetener produced from corn starch that contains varying proportions of fructose and glucose. Since its commercial introduction during the 1970s, HFCS has become one of the most widely used sweeteners in the food and beverage industry. Its growing popularity can be attributed to both economic factors and its functional benefits in food processing.

The production of HFCS begins with the conversion of corn starch into glucose through enzymatic hydrolysis. In the next stage, a portion of the glucose is transformed into fructose using the enzyme xylose isomerase. The final product is a syrup composed mainly of free glucose and fructose molecules, which together provide sweetness and several useful technological properties.

Several commercial forms of HFCS are produced, with HFCS-42 and HFCS-55 being the most commonly used. HFCS-42 contains about 42% fructose and is typically used in processed foods such as baked goods and cereals. HFCS-55 contains around 55% fructose and is widely used in soft drinks and other sweetened beverages because its sweetness level is comparable to that of sucrose.

In addition to providing sweetness, HFCS offers several advantages in food manufacturing. Its liquid form allows it to be easily transported, pumped, and mixed during large-scale production. HFCS also performs well in acidic environments and has a reduced tendency to crystallize compared with other sugars. These characteristics make it especially suitable for products such as beverages, syrups, sauces, and confectionery items (Akram, M., Hamid, A., & Khalid, M. 2020).

Production and Types of HFCS

The industrial production of HFCS involves several enzymatic and purification steps that convert corn starch into a syrup containing both glucose and fructose.

Starch Hydrolysis

The first step in HFCS production is the hydrolysis of corn starch into glucose. This process is carried out using enzymes such as alpha-amylase and glucoamylase, which break down the large starch molecules into smaller glucose units.

Isomerization

In the next stage, a portion of the glucose is converted into fructose through the action of the enzyme xylose isomerase. This enzymatic reaction produces a mixture of glucose and fructose that forms the base composition of HFCS.

Purification and Concentration

After the isomerization process, the syrup is purified and filtered to remove impurities. It is then concentrated to achieve the desired composition and sweetness level required for different industrial applications.

Major Types of HFCS

Type of HFCS	Fructose Content (%)	Relative Sweetness	Main Industrial Uses
HFCS-42	~42%	Less sweet than sucrose	Baked goods, cereals, sauces
HFCS-55	~55%	Similar to sucrose	Soft drinks, beverages
HFCS-90	~90%	Very high sweetness	Used for blending (not direct use)

HFCS-42: Contains approximately 42% fructose and is commonly used in bakery products, cereals, and processed foods.

HFCS-55: Contains around 55% fructose and is widely used in soft drinks and other beverages.

HFCS-90: Higher-fructose syrup that is typically blended with other syrups to produce specific sweetness levels.

Functional Properties of HFCS in Industry

Sweetening Ability

HFCS-55 provides a sweetness level similar to that of sucrose, which makes it particularly useful in beverage production (Walker, L.2024).

Humectant Properties

HFCS acts as a humectant, meaning it helps retain moisture in food products. This property is especially beneficial in baked goods, where it contributes to improved texture and longer shelf life.

Anti-Crystallization

Because HFCS contains both glucose and fructose in solution, it helps prevent sugar crystallization. This property is important in products such as candies, syrups, and jams, where a smooth texture is desired.

Browning and Flavor Development

HFCS can participate in Maillard reactions during heating processes. These reactions contribute to browning and the development of desirable flavors in baked foods.

Stability in Acidic Conditions

HFCS remains stable in acidic environments, making it suitable for products such as carbonated beverages, fruit drinks, and sauces.

Industrial Applications of HFCS

Beverage Industry

The beverage sector represents one of the largest markets for HFCS. It is commonly used in carbonated soft drinks, fruit beverages, flavored waters, and energy drinks. HFCS is widely used in the beverage industry, especially in carbonated soft drinks, fruit juices, sports drinks, flavored waters, iced teas, and ready-to-drink coffees. HFCS provides consistent sweetness, balances acidity, prevents crystallization, and blends easily in liquid form. Its cost-effectiveness, stability, and ease of handling make it the preferred sweetener for large-scale beverage production.

Bakery Industry

In bakery products such as bread, cakes, and muffins, HFCS helps maintain moisture, improve browning, and produce a softer texture. HFCS is used to enhance sweetness, retain moisture, and improve texture in products like breads, cakes, cookies, and pastries. It helps prevent staling, supports browning during baking, and provides a smooth mouthfeel. HFCS also stabilizes fillings and frostings, ensuring consistent flavor and extended shelf life.

Confectionery Industry

HFCS is widely used in confectionery products including candies, caramels, and syrups. Its ability to prevent crystallization contributes to smoother textures and improved product stability. One of its most important roles is preventing sugar crystallization, which ensures smoothness in candies, chocolates, jams, and jellies. This property helps manufacturers produce confections with a glossy finish and uniform texture.

Dairy Industry

In the dairy industry, HFCS is widely used to enhance sweetness, improve texture, and extend shelf life in dairy products such as flavored milk, yogurt, and ice cream, HFCS serves as both a sweetener and a texture-enhancing ingredient. Overall, HFCS is valued in dairy applications for its functional properties, stability, and cost-effectiveness.

Processed Foods

HFCS is also used in a variety of processed foods including sauces, salad dressings, breakfast cereals, and snack products. In canned fruits and jams, HFCS balances acidity, prevents crystallization, and improves texture. It is also common in condiments like ketchup, salad dressings, and sauces, where it adds viscosity and flavor stability. Overall, HFCS is valued in processed foods for its cost-effectiveness, ease of blending, and ability to improve flavor, texture, and product stability.

Advantages of HFCS in Industrial Processing

Cost Efficiency

One of the main reasons for the widespread use of HFCS is its relatively low cost compared with sucrose. This economic advantage is partly due to the large-scale production of corn.

Liquid Form

Unlike crystalline sugar, HFCS is available in liquid form, which makes it easier to handle during manufacturing processes.

Shelf-Life Extension

By helping foods retain moisture, HFCS contributes to longer shelf life and improved product quality during storage.

Flavor Enhancement

HFCS can enhance the flavor profile of certain foods, particularly fruit-based products, by balancing sweetness and acidity.

Health and Regulatory Considerations

Despite its functional benefits, HFCS has been the subject of considerable debate regarding its potential health effects. Some researchers have suggested that excessive consumption of fructose-containing sweeteners may contribute to obesity and metabolic disorders (White, J. S.2023). However, many regulatory agencies consider HFCS to be safe when consumed in normal dietary amounts.

Economics and Market value of HFCS

Brand/ Company	Weight	Price (INR)
Urban Platter corn syrup	700g	₹499
Puramio corn syrup	1 kg	₹367
UMAI corn syrup	1.2 kg	₹649
NatureOnus pure corn syrup	650g	₹636
PURIX corn syrup	200g	₹97

Future Trends in HFCS Applications

1. Shift toward “Clean Label” & Natural Products
2. Competition from alternative sweeteners
3. Development of specialized HFCS Product
4. Continued growth in emerging market
5. Technological advancements in production
6. Focus on sustainability
7. Expansion into functional foods
8. Regulatory pressure and health awareness

In recent years, consumer preferences have shifted toward natural ingredients and products with simpler labels. As a result, some food manufacturers have explored alternative sweeteners or reformulated existing products. Nevertheless, HFCS continues to be widely used because of its functional advantages and cost efficiency.

Emerging areas of interest include fermentation processes, bio-based chemical production, and other applications within industrial biotechnology.

Conclusion

High-fructose corn syrup plays an important role in modern food processing beyond its basic function as a sweetener. Its physicochemical properties—such as moisture retention, resistance to crystallization, stability in acidic conditions, and economic advantages—make it a versatile ingredient in many food products. HFCS is widely used in beverages, bakery items, confectionery, dairy products, and other processed foods, where it contributes to improved texture, flavor stability, and extended shelf life.

Although concerns about potential health effects continue to be discussed, HFCS remains an important ingredient in industrial food production. Future research should focus on improving the sustainability of its production and balancing technological benefits with public health considerations.

From an industrial perspective, HFCS is not just a sweetener—it is a multi-functional ingredient**.** It enhances flavour, texture, and appearance**,** helps retain moisture in baked goods, prevents crystallization in confectionery products, and improves the stability and shelf life of processed foods. In beverages, it ensures uniform sweetness and easy mixing**,** making it ideal for soft drinks and packaged juices. Additionally, its role extends to fermentation industries and pharmaceutical formulations, where it acts as a reliable and efficient carbohydrate source.

Despite these advantages, the use of HFCS faces growing challenges. Rising consumer awareness about health issues such as obesity, diabetes, and metabolic disorders has led to increased scrutiny. Governments and health organizations are introducing regulations**,** sugar taxes, and labelling requirements**,** encouraging manufacturers to reduce or replace HFCS in their products. This has also accelerated the development and adoption of alternative sweeteners**.**

Looking ahead, the industrial use of HFCS is expected to evolve rather than disappear**.** It will likely shift toward:

- More controlled and moderate usage
- Blended formulations with natural or low-calorie sweeteners
- Specialized applications in processed and functional foods
- Improved, sustainable production technologies

Declarations

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No new data were generated or analyzed in this study. Data sharing is not applicable to this article.

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FARMER PRODUCER ORGANISATIONS (FPOs) UNDER PMKSY: A REVIEW OF THEIR ROLE IN SUSTAINABLE SOIL AND WATER MANAGEMENT

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Abstract

Farmer Producer Organisations (FPOs) have emerged as a key institutional mechanism for enhancing farmers' collective strength, improving market access, and promoting sustainable agricultural practices in India. In parallel, the *Pradhan Mantri Krishi Sinchayee Yojana (PMKSY)* has focused on expanding irrigation coverage and improving water-use efficiency through integrated soil and water management strategies. This review paper examines the convergence between FPOs and PMKSY, highlighting how collective action among farmers can accelerate the adoption of climate-resilient practices, efficient irrigation systems, and watershed-based approaches. The paper synthesizes existing literature, policy frameworks, and field-level insights to assess the potential, challenges, and future prospects of integrating FPOs within PMKSY for sustainable agricultural development.

Keywords: Farmer Producer Organisations, PMKSY, irrigation, water management, soil health, collective farming, sustainability

Introduction

Indian agriculture is dominated by small and marginal farmers who often face constraints such as limited access to irrigation, fragmented landholdings, and weak market linkages. To address these challenges, Farmer Producer Organisations (FPOs) have been promoted as collective institutions that enable farmers to pool resources, access technology, and improve bargaining power.

Simultaneously, the *Pradhan Mantri Krishi Sinchayee Yojana (PMKSY)* has been implemented to ensure water availability and promote efficient irrigation practices under the guiding principles of *"Har Khet Ko Pani"* and *"Per Drop More Crop."*

The convergence of FPOs and PMKSY presents a unique opportunity to scale sustainable soil and water management practices through community-led approaches. This paper reviews the role of FPOs in strengthening PMKSY outcomes and enhancing agricultural resilience.

Conceptual Framework: FPOs and Collective Action

FPOs are legally registered groups of farmers who collaborate to improve production, processing, and marketing of agricultural produce. They operate on principles of collective ownership, democratic governance, and shared benefits.

Theoretical frameworks on collective action suggest that group-based approaches reduce transaction costs, improve access to resources, and facilitate technology adoption. In the context of natural resource management, FPOs can play a crucial role in managing common resources such as water, soil, and infrastructure.

Overview of PMKSY and Its Relevance to FPOs

PMKSY is a flagship programme aimed at improving irrigation efficiency and expanding coverage. Its key components include:

- **Per Drop More Crop:** Promotion of micro-irrigation systems
- **Har Khet Ko Pani:** Expansion of irrigation access
- **Watershed Development:** Soil and water conservation measures
- **Irrigation Infrastructure Development:** Strengthening water delivery systems

FPOs can act as implementing and facilitating agencies for these components by mobilizing farmers, coordinating activities, and ensuring efficient utilization of resources.

Role of FPOs in Soil and Water Management under PMKSY

Promotion of Micro-Irrigation

FPOs enable bulk procurement and shared use of drip and sprinkler irrigation systems, reducing costs for individual farmers. They also facilitate training and technical support, improving adoption rates.

Watershed-Based Resource Management

Through collective planning, FPOs can manage watershed interventions such as check dams, farm ponds, and contour bunding. This ensures equitable water distribution and long-term sustainability.

Enhancing Soil Health

FPOs promote sustainable farming practices including organic inputs, crop rotation, and balanced fertilization. Efficient water use under PMKSY further supports soil conservation and fertility.

Capacity Building and Knowledge Dissemination

FPOs act as platforms for extension services, enabling farmers to access information on best practices in irrigation, soil management, and climate adaptation.

Market Linkages and Value Addition

Improved irrigation and soil health lead to higher productivity, which FPOs leverage by connecting farmers to better markets and facilitating value addition.

Socio-Economic and Environmental Impacts

The integration of FPOs with PMKSY has multiple benefits:

- **Economic Gains:** Increased productivity and reduced input costs enhance farmer incomes
- **Resource Efficiency:** Optimized water use and improved soil management reduce environmental degradation
- **Risk Reduction:** Collective action improves resilience to climate variability
- **Social Inclusion:** FPOs empower smallholders, women, and marginalized groups

Challenges in Convergence

Despite the potential, several challenges limit the effectiveness of FPOs under PMKSY:

- Limited technical expertise within FPOs
- Inadequate access to finance and credit
- Weak institutional coordination between agencies
- Low awareness and participation among farmers
- Variability in performance and governance of FPOs

Policy Implications and Way Forward

To strengthen the role of FPOs under PMKSY, the following measures are recommended:

- Enhancing capacity-building programs for FPO leaders and members
- Providing financial incentives and credit support for irrigation investments

- Strengthening convergence between government departments and FPOs
- Promoting digital tools for resource management and monitoring
- Encouraging public-private partnerships to support FPO-led initiatives

Conclusion

FPOs have the potential to transform the implementation of PMKSY by enabling collective, efficient, and sustainable management of soil and water resources. Their role in promoting micro-irrigation, watershed development, and knowledge dissemination is critical for achieving climate-resilient agriculture.

However, realizing this potential requires addressing institutional, financial, and capacity-related challenges. With the right policy support and strategic interventions, the convergence of FPOs and PMKSY can significantly contribute to sustainable agricultural development and rural prosperity in India.

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POLICIES FOR SUSTAINABLE AGRICULTURAL WATER MANAGEMENT

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Abstract

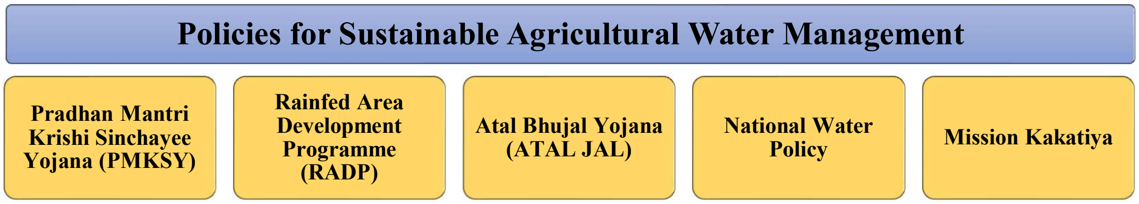
Sustainable agricultural water management is a key aspect in ensuring food security in a climate- and resource-stressed environment. India has taken a multi-pronged approach to agricultural water management through initiatives such as Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), Rainfed Area Development Programme (RADP), Atal Bhujal Yojana (Atal Jal), National Water Policy, and Mission Kakatiya. These initiatives include micro-irrigation, watershed development, groundwater management, and rejuvenation of traditional water bodies. These initiatives promote water use efficiency through the concept of "more crop per drop." From a scientific perspective, these initiatives are a step towards ensuring hydrological sustainability and agro-ecological stability. In addition, groundwater management is a key aspect in ensuring agricultural water sustainability.

Keywords: Sustainable water management, Micro-irrigation, Groundwater governance, Climate resilience

Introduction

Out of 141.01-million-hectare (Mha) Net sown area, only 122.29 Mha under Gross Irrigated Area with 79.31 Mha of Net Irrigated Area which highlights the need of sustainable water management for expanding irrigation coverage. The policies which can improve Irrigated Area can be achieved through micro-irrigation to save water.

Irrigation Schemes in India



Pradhan Mantri Krishi Sinchayee Yojana (PMKSY):

Launched year: 1st July, 2015

Supervising and monitoring agency:
Inter-Ministerial National Steering Committee (NSC) - overall guidance
National Executive Committee (NEC) - implementation, coordination, monitoring, and administration.

Motto: Har Khet Ko Paani

Aim: To expand cultivated area with assured irrigation, improve water use efficiency and reduce water wastage.

Objectives

- Integration of water source, distribution and its efficient use, to make best use of water through appropriate technologies and practices.
- Expand cultivable area under assured irrigation (Har Khet Ko Pani) and enhance the access of physical farm water.
- Improve on – farm water use efficiency to reduce wastage.
- Enhance water saving technologies and precision – irrigation (More Crop Per Drop).
- Enhance recharge of aquifers and introduce sustainable water conservation practices.
- Ensure the integrated development of rainfed areas using the watershed approach towards soil and water conservation, ground water regeneration, arresting runoff, providing livelihood options and other NRM activities.
- Promote extension activities relating to water harvesting, water management and crop alignment for farmers and grass root level field functionaries.
- Explore the feasibility of reusing treated municipal waste water for peri-urban agriculture.
- Investments in irrigation at field level to achieve convergence.

Programme Components of PMKSY

1. **Accelerated Irrigation Benefit Programme (AIBP):** Speeds up the completion of major and medium irrigation projects.
2. **Har Khet Ko Pani:** Provides assured irrigation water to more agricultural land through the existing Command Area Development and Water Management (CADWM) programme.
3. **Per Drop More Crop:** Improves water use efficiency through drip and sprinkler irrigation.
4. **Watershed Development:** Conserves rainwater and soil moisture through watershed activities.

Rainfed Area Development Programme (RADP)

Launched year: 2014–15

Supervising and monitoring agency: State Agriculture Department (Nodal Agency), under the National Mission for Sustainable Agriculture (NMSA)

Motto: Sustainable and resilient farming in rainfed areas

Aim: To promote sustainable and climate-resilient agriculture in rainfed regions through integrated farming system (IFS) approaches.

Objectives:

- To improve productivity and income of rainfed farmers through agro-climatic zone–specific IFS models developed by ICAR.
- To enhance soil health, efficient rainwater usage and crop diversification while reducing climate risks such as droughts and floods.
- To generate on-farm employment, restore farmer confidence and improve livelihoods in arid, semi-arid and sub-humid regions.

Programme Components / Key Features

1. Implemented as a sub-scheme of Rashtriya Krishi Vikas Yojana (RKVY).
2. Covers districts with less than 60% irrigated area, giving priority to rainfed agro-ecosystems.
3. Follows an area-based “watershed plus” approach with convergence of schemes like Mahatma Gandhi National Rural Employment Guarantee Scheme, PMKSY-Watershed Development Component, and RKVY.

4. Integrates crops, horticulture, livestock, fisheries, and allied value-added activities for sustainable income generation.

Atal Bhujal Yojana (ATAL JAL)

Launched year: 25th December, 2019

Supervising and monitoring agency: Ministry of Jal Shakti, Government of India, with support from the World Bank

Motto: Community-led sustainable groundwater management

Aim: To improve groundwater sustainability in water-stressed areas through community participation and demand-side water management.

Objectives:

- To strengthen groundwater governance through data transparency, planning, and local participation.
- To promote efficient water use, support the Jal Jeevan Mission, and improve agricultural water-use efficiency.
- To enhance groundwater levels and farmer livelihoods by encouraging sustainable practices and scheme convergence.

Programme Components

1. **Institutional Strengthening and Capacity Building (₹1,400 crore):** Focuses on strengthening institutions, groundwater databases, scientific planning, and community capacity building.
2. **Incentive Component (₹4,600 crore):** Rewards States based on performance indicators such as water security planning, data disclosure, efficient water-use practices, convergence of schemes, and improvement in groundwater levels.

National Water Policy

Launched year

- First National Water Policy: 1987
- Revised Policies: 2002 and 2012
- Draft New National Water Policy: 2020

Supervising and monitoring agency: Ministry of Jal Shakti, Government of India; approved by the National Water Resources Council

Motto: Sustainable, equitable, and efficient management of water resources

Aim: To ensure optimal, sustainable, and integrated development and management of water resources for social, economic, and environmental needs.

Objectives

- To prioritise drinking water, sanitation, food security, and ecological sustainability.
- To promote demand-side management, groundwater regulation, and decentralised governance.
- To enhance climate resilience through efficient water use, recycling, reuse, and community participation.

Programme Components / Key Policy Features

- Early phase (1950s–60s): Infrastructure-led development through major irrigation and multipurpose river projects such as Bhakra–Nangal Project and Damodar Valley Corporation.

- Integrated phase (1970s–80s): Shift towards Integrated Water Resources Management, leading to the National Water Policy 1987.
- Reform phase (1990s–2000s): Focus on economic efficiency, environmental sustainability, demand management, and decentralisation under the National Water Policy 2002.
- Sustainability phase (2012): Recognition of water as an economic good, emphasis on climate change adaptation, environmental flows, groundwater regulation, water auditing, and public–private participation under the National Water Policy 2012.
- Draft NWP 2020: Strong focus on sustainability and resilience, promotion of less water-intensive crops, treated wastewater reuse, micro-irrigation, SCADA-based water delivery, rainwater harvesting, rejuvenation of traditional water bodies, and blue–green urban infrastructure.

Mission Kakatiya

Launched year: 2014

Supervising and monitoring agency: Government of Telangana, led by the Panchayat Raj, Rural Development, and Rural Water Supply Departments

Motto: Revival of tanks for sustainable water security

Aim: To restore and rejuvenate minor irrigation tanks for improving water availability, agricultural productivity, and rural livelihoods.

Objectives:

- To restore 46,300 tanks and efficiently utilise 265 TMC of water allocated to minor irrigation in the Godavari River and Krishna River basins.
- To recharge groundwater, reduce farm power consumption, increase crop yields, and promote livestock-based livelihoods.
- To strengthen decentralized, community-based irrigation management and revive the rural economy.

Programme Components

- Tank de-siltation and restoration of feeder channels.
- Re-sectioning of irrigation channels and repair of bunds, weirs, and sluices.
- Raising of Full Tank Level (FTL) to enhance storage capacity.
- Laying of about 1.26 lakh km of pipelines to supply drinking water to towns, villages, and industries.

Conclusion

India's policies for sustainable water management for agricultural development clearly demonstrate a paradigm shift from the conventional supply-driven approach to a more robust and sustainable approach to water management. This has been achieved by incorporating various aspects of water management, such as groundwater management, rain-fed development, revival of traditional water bodies, and the use of modern irrigation technology. This shift not only improves the resilience of agro-ecosystems but also helps to protect rural livelihoods in the backdrop of water scarcity and climate change. In the future, the focus on data-driven water management and the use of water management technology will be crucial for improving the efficiency of water management. This will be coupled with the need to improve institutional and community convergence.

Reference:

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https://nwm.gov.in/sites/default/files/national%20water%20policy%202012_0.pdf
https://static.pib.gov.in/WriteReadData/specificdocs/documents/2022/jul/doc20227169101.pdf
Mission Kakatiya/District JOGULAMBA GADWAL, Government of Telangana/India

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PESTICIDES AND PUBLIC HEALTH: BALANCING FOOD SECURITY WITH SAFETY

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Abstract

Modern agriculture's increasing reliance on pesticides is a response to the need to boost crop yields and ensure food security for a growing global population. On the other hand, the widespread and lasting use of these substances has raised considerable concern about environmental safety and public health. This study investigates the main ways people are exposed to pesticides, the methods used to apply them, and the resulting health effects, both short-term and long-term. Dietary consumption constitutes the principal avenue of exposure; however, environmental and occupational routes amplify the inherent hazards. Health effects encompass both chronic conditions, such as cancer, endocrine disruption, and neurological disorders, and acute symptoms like nausea and respiratory distress. Furthermore, the analysis underscored regulatory deficiencies, thereby highlighting the critical necessity for sustainable solutions. This encompasses biopesticides and integrated pest management approaches.

Keywords: Food Safety, Pesticide Residues, Environmental Pollution, Toxicology, Health, biopesticides, Organic Farming.

Introduction: Feeding The World at What Cost?

Agriculture has undergone a transformation in the past few decades. With the world's population climbing, farmers are turning to advanced technologies, growing high-yield crops, and using chemicals to boost their harvests. Modern agriculture depends on pesticides, which are essential for protecting crops from pests, weeds, and diseases. On the other hand, this progress has its drawbacks. Pesticides, which are meant to protect crops, are actually getting into the food we eat. Even with careful washing and cooking, pesticide residues can remain, eventually entering the human body through food. This problem is especially significant in places like India, where regulatory oversight and farmer training might be lacking. The improper use, over-application, and distribution of banned pesticides contribute to contamination levels that can exceed established safety limits.

Types of Pesticides and Their Usage

Pesticides can be categorized in many ways, depending on the specific organisms they are meant to control. The three primary categories consist of insecticides, herbicides, and fungicides, with each serving a unique function in the protection of crops.

Insecticides are used to manage insect pests that harm crops at different stages of growth. Organophosphates and carbamates, which are commonly used insecticides, work by disrupting the nervous systems of insects, leading to paralysis and death. Even though these substances are effective, they often have significant toxic effects and can potentially harm humans and other living things if used incorrectly.

Herbicides serve the purpose of managing weeds that compete with cultivated plants for vital resources like nutrients, water, and light. Glyphosate-based formulations are widely adopted due to their efficacy in diverse agricultural contexts. However, the potential health risks and environmental persistence associated with their frequent and widespread application have raised concerns, particularly given research suggesting possible correlations with health problems, including cancer, and apprehensions regarding the enduring consequences on soil and water quality.

Fungicides are used to reduce or control fungal infections, which can significantly affect crop yield and overall quality. Typical instances comprise azoles and copper-based compounds, which impede fungal growth and reproduction. While often viewed as less harmful than certain insecticides, the overuse of fungicides can nonetheless lead to environmental pollution and the emergence of resistant strains of pathogens. The growing dependence on these chemical agents highlights the necessity for meticulous oversight and regulation. While pesticides are indispensable in modern agricultural methods, their improper application poses risks to public well-being and threatens environmental integrity.

Therefore, a strategy that integrates effective pest control with safety protocols is vital for fostering enduring agricultural practices and safeguarding societal health. People can be exposed to pesticides in different ways, which highlights how widely these chemicals are used and how long they stay in the environment. Understanding how people are exposed is essential for assessing health risks and developing effective prevention strategies.

Human Exposure Routes

Human exposure to pesticides takes place through various channels, highlighting the extensive application and enduring presence of these substances in the environment. Grasping these exposure pathways is crucial for evaluating related health hazards and formulating effective prevention measures.

Dietary Exposure

Dietary exposure is the main way the general public encounters pesticides. Pesticide residues are often found in fruits, vegetables, grains, and other agricultural products. This is due to the use of pesticides before and after harvesting. Even when used correctly, some chemicals can remain on food surfaces or inside plants. Poor washing, improper handling, and eating raw produce can significantly increase exposure. The prolonged consumption of low-dose residues has been linked to cumulative health risks, especially impacting sensitive populations like children and pregnant women. Health risks, particularly for vulnerable groups like children and pregnant women, are a major concern.

Occupational Exposure

Occupational exposure poses a considerable risk for farmers, pesticide applicators, and agricultural workers. These individuals face direct exposure while mixing, loading, and spraying pesticides, frequently lacking sufficient protective gear. The main pathways in these environments are through dermal contact and inhalation. Consistent exposure over time may result in immediate toxic effects as well as long-term health issues, underscoring the importance of adequate training, utilization of personal protective equipment (PPE), and strict compliance with safety protocols.

Environmental Exposure

Environmental exposure takes place when pesticides spread beyond their intended targets via air drift, surface runoff, and leaching into groundwater. The presence of this contamination significantly affects nearby communities, leading to the pollution of drinking water, soil, and the air. As a result, indirect exposure to pesticides through these environmental pathways greatly increases the overall pesticide burden on human populations, including those not directly involved in agricultural activities.

Health Impacts of Pesticide Exposure

Human health is significantly jeopardized by pesticide exposure, which can induce a spectrum of adverse effects, ranging from immediate toxic reactions to long-term chronic ailments. The nature and severity of these impacts are contingent upon several variables, such as the particular pesticide involved, the duration of exposure, the concentration of the pesticide, and the individual susceptibility of those exposed.

Acute Health Effects

People often experience immediate health effects after being exposed to high levels of pesticides. These effects usually come from accidentally swallowing, breathing in, or touching the pesticide. Common symptoms include headaches, dizziness, nausea, vomiting, and irritation of the skin and eyes. Respiratory distress can occur, especially when inhaling toxic vapours or aerosols. In critical situations, acute pesticide poisoning may result in neurological damage, unconsciousness, and potentially fatal outcomes if prompt medical assistance is not administered. Incidents of this nature are increasingly documented among those in the agricultural sector, attributed to improper handling techniques and insufficient utilization of protective gear, which can lead to serious health consequences such as respiratory issues and long-term neurological effects.

Chronic Health Effects

Prolonged exposure to low levels of pesticide residues is linked to chronic health effects, typically arising from contaminated food and environmental sources. The manifestation of these effects may require years, raising significant concerns regarding their long-term implications for public health.

Carcinogenicity

Epidemiological and toxicological investigations have implicated numerous pesticides as probable or possible carcinogens. Extended exposure to these substances has been correlated with an elevated incidence of cancers, encompassing leukaemia, lymphoma, and neoplasms impacting diverse organs.

Endocrine Disruption

Certain pesticides act as endocrine disruptors, interfering with hormonal systems. These chemicals can mimic, block, or change how hormones are made, leading to imbalances that affect growth, metabolism, and reproduction. This disruption poses considerable dangers during crucial developmental periods, such as pregnancy and early childhood.

Neurological Disorders

Exposure to pesticides over a long period has been linked to negative effects on the nervous system. These effects include problems with thinking, memory issues, and changes in behaviour. Research suggests a connection between pesticide exposure and neurodegenerative diseases, particularly Parkinson's disease, especially in people with long-term work-related exposure.

Effects on Reproduction and Development

Exposure to pesticides can negatively affect reproductive health, possibly leading to infertility, hormonal imbalances, and pregnancy complications. In developing fetuses and children, exposure can result in birth defects, developmental delays, and compromised immune function, underscoring the susceptibility of these groups.

Sustainable Alternatives to Conventional Pesticide Use

Given the growing apprehension regarding the detrimental effects of synthetic pesticides on human health and the environment, sustainable alternatives to traditional pesticide application are becoming increasingly prominent. These approaches seek to sustain agricultural output while concurrently reducing chemical inputs and their inherent risks.

Integrated Pest Management (IPM)

Integrated Pest Management (IPM) is a strategic approach that combines various management practices to control pest populations effectively and sustainably. Integrated Pest Management (IPM) represents a thorough and informed methodology that integrates various pest control techniques to minimize dependence on chemical pesticides. This approach combines the use of biological control agents, like natural predators and parasitoids, with cultural practices such as crop rotation, intercropping, and adjustments in planting times, along with mechanical methods, including traps and manual removal. Chemical pesticides are employed only as a final measure and with considerable caution. Integrated Pest Management (IPM) strategies contribute to minimizing environmental contamination, mitigating the acceleration of pest resistance, fostering biodiversity, and advancing the enduring viability of agricultural practices. This approach's success depends on educating farmers, consistent monitoring, and providing advisory services.

Organic Farming

Organic farming avoids synthetic pesticides and fertilizers, relying instead on natural resources and ecological processes. In organic farming, pest control uses biological methods, botanical products like those made from neem, and habitat management to encourage beneficial organisms. Furthermore, practices such as composting, green manuring, and crop diversification contribute to soil health and strengthen resistance to pests. While organic farming might initially produce lower yields compared to conventional methods, it provides considerable long-term advantages, encompassing improved food safety, enhanced soil fertility, and diminished environmental pollution. The growing consumer demand for organic products has substantially accelerated its implementation.

Biopesticides

Biopesticides, derived from natural origins including plants, microorganisms, and minerals, present a potentially advantageous substitute for synthetic chemicals. Biopesticides are classified into several categories. These include microbial pesticides, such as bacteria, fungi, and viruses. These methods also include botanical pesticides and biochemical agents, which affect how pests behave or reproduce. Biopesticides are generally designed to be specific, break down naturally, and have less harmful effects on species that aren't the target, including humans.

Advancements in Technology

Recent developments in agricultural technology have led to the implementation of precision farming techniques that enhance the efficiency of pesticide application. Incorporating advanced technologies like GPS-guided equipment, drones, and sensor-based monitoring systems allows for precise application of pesticides, effectively decreasing overuse and limiting environmental impact. Advanced spraying technologies are capable of identifying areas affected by pests and administering chemicals precisely where necessary, thus enhancing efficiency and lowering expenses. Furthermore, systems that rely on data for decision-making and mobile advisory platforms equip farmers with immediate insights regarding pest outbreaks and suitable control strategies.

Conclusion

Pesticides present a complex dilemma. They have contributed to the stability of global food supplies, yet this benefit has come with increasing health and environmental issues. The focus should be on using pesticides wisely, rather than completely banning them. Substantial advancement demands the implementation of more rigorous regulatory frameworks, the enhancement of agricultural education initiatives, and the fostering of increased public understanding. Concurrently, the allocation of resources to sustainable practices, coupled with the deployment of advanced monitoring technologies, can significantly diminish inherent hazards; this encompasses the reduction of pesticide runoff and the strengthening of crop resistance to pest infestations. The future of agriculture necessitates achieving equilibrium, thereby safeguarding the availability and safety of our food sources.

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DIVERSITY IN EDIBLE OILS: A PATHWAY TO NUTRITIONAL SECURITY IN INDIA BY 2047

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Abstract

Edible oils are an essential component of human diets, providing energy, essential fatty acids, and bioactive compounds. However, the quality and balance of dietary fats significantly influence public health outcomes. The edible oil consumption in India has been increased dramatically over the past two decades, accompanied by rising import dependency and growing concerns related to non-communicable diseases. This article reviews the nutritional composition of major edible oils consumed in India and evaluates their fatty acid profiles, bioactive components, and health implications. Using published datasets and national reports, we compare different edible oils and analyse their role in achieving nutritional security under the vision of Viksit Bharat 2047. The analysis highlights that no single oil meets all nutritional requirements; rather, diversified consumption and crop breeding strategies are very much essential. Policy initiatives such as the National Mission on Edible Oils and advancements in oilseed breeding can support both farmer income and public health.

Keywords: Edible oils, Fatty acid composition, Nutritional security, Oilseed crops, Viksit Bharat 2047, Omega-3, Omega-6 balance, India agriculture

Introduction

Edible oils play a dual role in agriculture and nutrition. They contribute to dietary energy, fat-soluble vitamins, and essential fatty acids, while also representing an important economic sector for farmers. Oilseed crops such as mustard, soybean, groundnut, sunflower, sesame, and safflower occupy a significant share of cultivated land in India. India has one of the largest oilseed cultivation areas globally, yet domestic production is insufficient to meet the growing demand. The country fulfils only around 44% of its edible oil requirement through domestic production, indicating continued reliance on imports. (Press Information Bureau) At the same time, per capita consumption has increased sharply to about 23.5 kg per person annually, nearly double the recommended level suggested by health authorities. (Business Standard) This shift underscores the importance of improving oil quality, nutritional balance, and sustainable production systems as India progresses toward Viksit Bharat 2047.

Nutritional Components of Edible Oils

Fatty Acid Classes

The nutritional value of edible oils depends mainly on their fatty acid composition.

Fatty Acid Type	Description	Nutritional Role
Saturated fatty acids (SFA)	No double bonds	Excess linked with cardiovascular risk

Fatty Acid Type	Description	Nutritional Role
Monounsaturated fatty acids (MUFA)	One double bond	Improves lipid profile
Polyunsaturated fatty acids (PUFA)	Multiple double bonds	Essential for metabolism
Omega-3 fatty acids	Multiple double bonds	Cardio protective
Omega-6 fatty acids	Multiple double bonds	Must balance with omega-3
Omega-9 fatty acids	One single double bonds	Inhibits cardiovascular (CV) and cancer disorders

*Balanced dietary intake ideally maintains a **4:1 to 5:1 omega-6 to omega-3 ratio**

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Nutritional Comparison of Major Edible Oils

Table 1. Fatty Acid Composition of Common Edible Oils

Oil Type	SFA (%)	MUFA (%)	PUFA (%)	Omega-3	Key Feature	Source/Reference
Mustard	6–8	55–60	20–25	High (ALA ~6%)	Balanced fatty acids; rich in erucic acid	Bhatnagar et al. (2011); PharmEasy (2025)
Soybean	14–16	22–26	55–60	Moderate (~7% ALA)	PUFA-rich; important source of LA and ALA	Backes et al. (2024); Codex Alimentarius (FAO/WHO, 2015)
Sunflower	9–11	18–22	65–70	Very low (<0.5%)	High linoleic acid (omega-6); low ALA	Knothe & Dunn (2015); Codex Alimentarius (FAO/WHO, 2015)
Groundnut	16–18	45–50	30–35	Low (<1%)	High MUFA (oleic acid); stable for frying	Gopalakrishna et al. (2006); Codex Alimentarius (FAO/WHO, 2015)

Oil Type	SFA (%)	MUFA (%)	PUFA (%)	Omega-3	Key Feature	Source/Reference
Rice bran	18–22	38–42	33–37	Low (<2%)	Contains γ-oryzanol; balanced SFA:MUFA:PUFA ratio	Gopalkrishna (2002); Fraterrigo Garofalo et al. (2021); Dunford (2019)
Coconut	80–85	5–7	1–2	Negligible	Rich in lauric acid (C12:0); highly saturated	Dayrit (2015); Lopes et al. (2023)
Palm oil	48–50	37–40	10–12	Negligible	Semi-solid; heat stable; palmitic acid dominant	Edem (2002); Codex Alimentarius (FAO/WHO, 2015)
Olive	12–15	70–75	10–12	Low (~1%)	Cardioprotective; rich in oleic acid and polyphenols	Merone et al. (2025); Jimenez-Lopez et al. (2020)
Flaxseed	8–10	18–20	65–75	Very high (~55% ALA)	Richest plant source of omega-3 (ALA)	Kajla et al. (2015); Prasad (2009)

NB// SFA = Saturated Fatty Acids; MUFA = Monounsaturated Fatty Acids; PUFA = Polyunsaturated Fatty Acids; ALA = Alpha-Linolenic Acid (omega-3); LA = Linoleic Acid (omega-6). All values represent typical ranges reported across published literature. Variations may occur due to cultivar, processing method, and geographic origin.

No single oil is nutritionally complete — rotation is not just recommended, it is essential. Olive and mustard oils, rich in MUFA and balanced fatty acids respectively, should form the daily cooking base, while rice bran oil's heat stability and unique gamma-oryzanol make it ideal for high-temperature cooking (Merone et al., 2025; Bhatnagar et al., 2011; Fraterrigo Garofalo et al., 2021). Flaxseed oil, with the highest plant-based omega-3 content (~55% ALA), should be used cold — drizzled over salads or blended into smoothies — to correct the omega-6/omega-3 imbalance caused by frequent use of sunflower or soybean oils (Kajla et al., 2015; Prasad, 2009). Coconut and palm oils, being highly saturated (80–85% and 48–50% SFA respectively), should be used sparingly and occasionally rather than as primary cooking oils (Dayrit, 2015; Edem, 2002).

A practical rotation — mustard or olive for everyday cooking, rice bran for frying, and flaxseed as a raw supplement — offers the broadest spectrum of fatty acids and bioactive compounds for optimal long-term health.

Bioactive Compounds in Edible Oils

Table 2. Functional Compounds and Health Benefits

Oil Type	Bioactive Compound	Nutritional Benefit	Additional Notes / Mechanism	Source / Reference
Rice bran oil	Gamma-oryzanol	Reduces cholesterol	Inhibits HMG-CoA reductase; reduces LDL-C; improves antioxidant status in hyperlipidemic subjects	Bumrungpert et al. (2019); Berger et al. (2005); Cicero & Gaddi (2001)

Sesame oil	Sesamin (lignan)	Antioxidant activity	Scavenges ROS; increases SOD and catalase; exhibits anti-inflammatory, antihypertensive, and hypocholesterolemic effects	Hadipour et al. (2023); Majdalawieh et al. (2020); Ghazzawi et al. (2023)
Mustard oil	Glucosinolates (sinigrin, glucoraphanin)	Anti-microbial effects	Hydrolysed by myrosinase to allyl isothiocyanate (AITC), which inhibits pathogenic bacteria and fungi; used in food preservation	Melrose (2019); Kozlowska et al. (2022); Cartea & Velasco (2008)
Olive oil	Polyphenols (hydroxytyrosol, oleocanthal, oleuropein)	Anti-inflammatory	Inhibits NF-κB pathway; reduces pro-inflammatory cytokines (TNF-α, IL-1β, IL-6); protects against cardiovascular and neurodegenerative diseases	Bucciantini et al. (2021); Jimenez-Lopez et al. (2020); Mehmood et al. (2020)
Groundnut oil	Vitamin E (α- and γ-tocopherols)	Cellular protection	Fat-soluble antioxidant; scavenges lipid peroxyl radicals; protects cell membranes from oxidative damage; prevents LDL oxidation	Sarpong (2025); Fernandes-Silva et al. (2021); Ejoh & Ketiku (2013)

Rice bran oil's gamma-oryzanol is clinically proven to lower LDL cholesterol, while sesame oil's sesamin acts as a potent antioxidant that combats inflammation and oxidative stress (Bumrungpert et al., 2019; Hadipour et al., 2023). Mustard oil contains glucosinolates that convert into natural antimicrobial compounds, earning its long-standing role as a food preservative across cultures (Melrose, 2019). Olive oil polyphenols such as hydroxytyrosol and oleocanthal directly suppress inflammatory pathways, offering measurable protection against cardiovascular and neurodegenerative diseases (Bucciantini et al., 2021). Together, these bioactive compounds reveal that edible oils are far more than cooking fats — they are functional foods with significant therapeutic potential.

India-Specific Edible Oil Consumption Trends

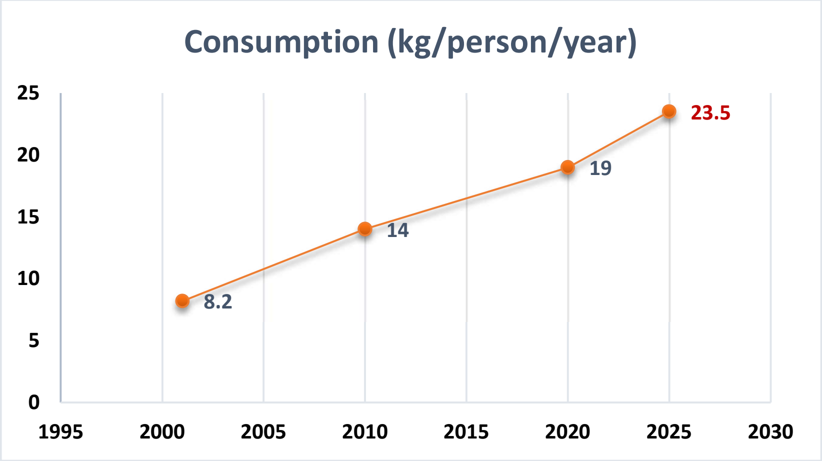

Figure 1. Rising Per Capita Edible Oil Consumption in India (Conceptual Trend)

This rising consumption pattern reflects: Dietary transition toward processed foods, Urbanization, Changing lifestyle patterns. However, excessive consumption may contribute to **obesity, cardiovascular diseases, and diabetes risk**.

Import Dependency and Production Gap

India’s edible oil sector faces a structural gap between demand and supply:

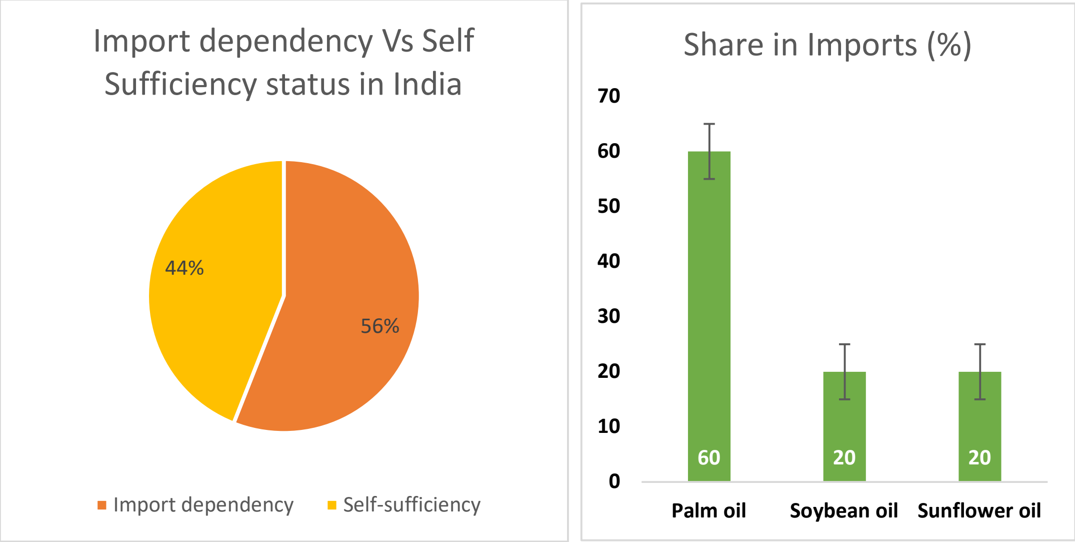

Figure 2 & 3: India’s Edible Oil Balance and Edible Oil Imports (%) share.

The domestic production in India is near about 12 million tonnes which is not yet sufficient for domestic demands and consumption. Hence, a huge amount still have to dependent on importing edible oils from foreign through investing more money. Palm oil constitutes the largest share of India’s edible oil imports (~55–60%), mainly sourced from Indonesia and Malaysia. These import spends approximately ₹1.2–1.5 lakh crore annually, with palm oil contributing the largest share. It also depends on price volatility in global market. This highlights the need for strengthening domestic oilseed production systems to avoid foreign exchange burden and supply chain vulnerability.

Conclusion

India's edible oil landscape stands at a critical crossroads — caught between rising consumption, import dependency, and growing diet-related disease burden. Here, clearly demonstrates that no single edible oil is nutritionally complete; mustard and olive oils offer superior fatty acid balance for daily cooking, rice bran oil provides heat stability with the added benefit of cholesterol-lowering gamma-oryzanol. The dominance of imported palm oil reflects both a nutritional and an economic vulnerability that demands urgent policy attention. Achieving the vision of Viksit Bharat 2047 requires a twin-track approach: accelerating oilseed crop improvement through targeted breeding programs to boost domestic production, and promoting diversified, rotation-based oil consumption patterns at the household level to improve public health outcomes. Edible oils must therefore be recognized not merely as a kitchen commodity but as a strategic nutritional resource — one whose diversity, quality, and self-sufficiency are indispensable to India's long-term food security and population health.

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EMPOWERING WOMEN AND YOUTH IN AGRICULTURE: A PATHWAY TO VIKSIT BHARAT 2047

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Abstract

The vision of *Viksit Bharat 2047* aims to transform India into a developed nation by strengthening key sectors such as agriculture while ensuring inclusive participation of women and youth. This article examines the critical role of women and young people in driving sustainable agricultural development and rural transformation. Women constitute a substantial portion of the agricultural workforce, yet they often face challenges such as limited access to resources, financial services, technology and decision-making opportunities. Empowering women through education, institutional support, financial inclusion and leadership in agricultural cooperatives can significantly enhance productivity and social equity. Similarly, youth engagement in agriculture is essential for fostering innovation, entrepreneurship and modernization of the sector. With the adoption of emerging technologies such as precision farming, biotechnology and digital agriculture, young entrepreneurs can reshape traditional farming systems and create new employment opportunities in rural areas. The article also highlights the importance of sustainable agricultural practices, policy support and public–private partnerships to strengthen the agricultural ecosystem. Despite promising opportunities, structural challenges including socio-economic disparities, inadequate infrastructure and environmental concerns must be addressed. Promoting inclusive policies, technological adoption and capacity building can empower women and youth to become key drivers of agricultural innovation and rural prosperity. Strengthening their participation will improve agricultural productivity as well as contribute significantly to achieving the broader goals of sustainable development and the vision of Viksit Bharat 2047.

Keywords: Women empowerment, Youth engagement in agriculture, Viksit Bharat 2047, AgriTech innovation, Sustainable agriculture, Rural development, Agricultural entrepreneurship and Inclusive agricultural growth.

Introduction

The vision of Viksit Bharat 2047 aims to transform India into a developed nation by its centenary of independence, with a strong focus on agriculture, women and youth as pivotal elements in this transformation. Women and youth in agriculture are seen as crucial contributors to achieving this vision, given their potential to drive innovation, sustainability and inclusivity in the sector. The integration of advanced technologies, empowerment of women and active participation of youth are key strategies outlined in the literature to enhance agricultural productivity and socio-economic development. The following sections delve into these aspects, highlighting the challenges and opportunities associated with empowering women and youth in agriculture within the Viksit Bharat 2047 framework.

Role of Women in Agriculture

- Women play a significant role in the informal agricultural sector, yet they face challenges such as lack of job security, limited access to resources and inadequate representation in policy discussions (Thomas *et al.*, 2025).

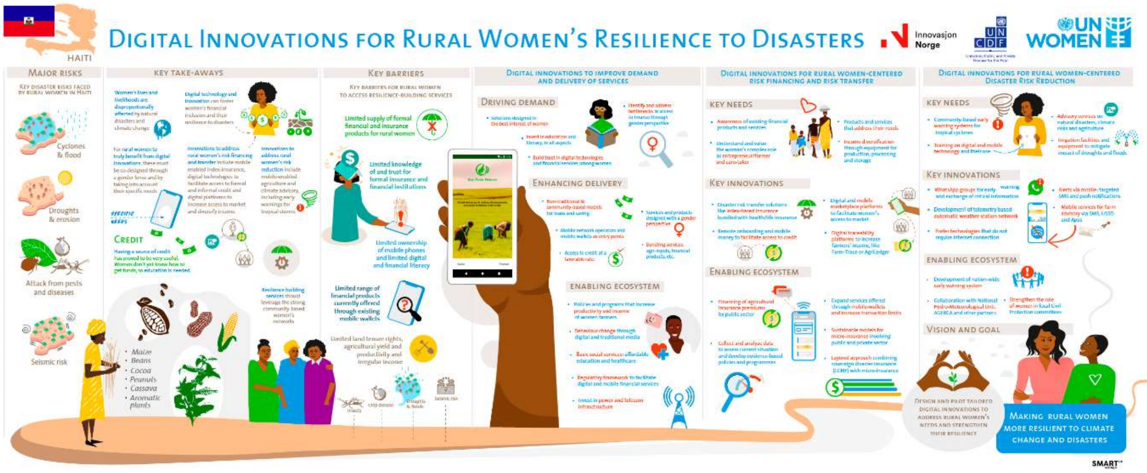

Fig. 1: Digital Innovations for Rural Women's Resilience to Disasters.

- Empowering women through education, healthcare and financial freedom is crucial for achieving gender equality and enhancing their contribution to agriculture (Agarwal *et al*., 2024).
- Strategies to empower women include policy reforms, promoting women's leadership in agricultural cooperatives and ensuring access to agricultural finance and technology (Negi *et al*., 2025).

Youth Engagement in Agriculture

- The Viksit Bharat 2047 vision emphasizes the importance of engaging educated young people in agriculture to boost rural economies and drive innovation (Das & Darshan, 2025).
- Youth are seen as critical stakeholders in national development, with a focus on quality education, meaningful employment and environmental sustainability (Tank & Sabharwal, 2025).
- Encouraging youth participation in policy-making and governance can lead to more inclusive and sustainable agricultural practices (Bansal *et al*., 2025).

Technological Advancements and Sustainable Practices

- The integration of AgriTech, such as precision farming, biotechnology and digital agriculture, is essential for modernizing Indian agriculture and increasing productivity (Hamid *et al*., 2024).

Fig. 2: Women Participation in Agriculture and Policy Making

- Sustainable farming practices, including organic farming and agroecological principles, are emphasized to ensure environmental sustainability and food security (Das & Darshan, 2025).
- Public-private partnerships and agricultural finance are highlighted as vital components for supporting technological advancements and sustainable development in agriculture (Hamid *et al*., 2024).

Challenges and Opportunities

- Despite the potential benefits, challenges such as socioeconomic disparities, limited access to quality infrastructure and environmental concerns must be addressed to achieve the Viksit Bharat 2047 objectives (Tank & Sabharwal, 2025).
- The empowerment of women and youth in agriculture can lead to substantial societal benefits, including higher efficiency, enhanced communities and more inclusive governance (Agarwal *et al*., 2024).
- Addressing structural challenges, such as farmer debt and regional disparities in rural credit accessibility, is necessary to create a more equitable agricultural sector (Das & Darshan, 2025).

The vision of Viksit Bharat 2047 presents a promising framework for transforming India's agricultural sector, it is essential to recognize the complexities involved in empowering women and youth. Structural and societal challenges, such as entrenched gender norms and limited access to resources, must be systematically addressed to realize the full potential of these groups. By fostering an inclusive and participatory approach, India can harness the capabilities of women and youth to drive sustainable agricultural development and contribute significantly to the nation's overall progress.

Conclusion

Empowering women and engaging youth in agriculture are essential steps toward achieving the vision of Viksit Bharat 2047. Strengthening access to education, financial resources, technology and policy support can enable these groups to actively participate in agricultural innovation and rural development. By fostering inclusive participation, promoting AgriTech adoption and encouraging sustainable farming practices, India can build a resilient agricultural system that enhances productivity, supports rural livelihoods and contributes to national economic growth.

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PGPR (PLANT GROWTH PROMOTING RHIZOBACTERIA): AN ECOLOGICAL ACCELERATOR OF PHYTOREMEDIATION OF HEAVY METALS

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Abstract

Fast industrial growth, intensive agricultural practices, and various anthropogenic activities have significantly increased the release of toxic heavy metals into the environment. These contaminants persist in ecosystems, accumulate in living organisms, and magnify along the food chain, posing serious threats to human health. Addressing this global environmental concern has led to the development of advanced remediation strategies. Among these, phytoremediation has emerged as a sustainable and eco-friendly approach. The integration of plant growth-promoting rhizobacteria (PGPR) with phytoremediation further enhances its efficiency by improving plant growth and facilitating metal detoxification through mechanisms such as chelation, redox reactions, acidification, and secretion of metabolites. This article systematically analyzes the role of PGPR in heavy metal phytoremediation based on a comprehensive survey of peer-reviewed literature retrieved from major scientific databases. The article highlights the contribution of rhizospheric and endophytic bacteria in accelerating phytoremediation processes and presents schematic interpretations and synthesized data. Additionally, it outlines future research directions and emphasizes the potential for translating this technology into practical agricultural applications for farmers.

Keywords: Heavy metals, PGPR, phytoremediation, detoxification, environmental concern

Introduction

The global population is expected to reach nearly 9 billion by 2050, intensifying the challenge of ensuring food security (Singh *et al.*, 2019). Simultaneously, increasing industrialization and modern agricultural inputs have resulted in widespread contamination of ecosystems with heavy metals. Industrial effluents from sectors such as textiles, fertilizers, and electrochemical industries often contain high concentrations of toxic metals, which are discharged into soil and water bodies with minimal treatment. Due to their non-degradable nature (Song *et al.*, 2022, these metals accumulate over time, posing long-term ecological and health risks. Heavy metals such as mercury (Hg), cadmium (Cd), lead (Pb), arsenic (As), and chromium (Cr) are particularly hazardous due to their toxicity, mutagenicity, and carcinogenic potential. These elements enter the environment through both natural processes and human activities, including mining, agrochemical usage, wastewater irrigation, and atmospheric deposition. Additionally, excessive use of fertilizers, pesticides, and organic amendments contributes to metal accumulation in soils. Traditional remediation methods, including excavation, incineration, and chemical treatments, are often expensive and environmentally disruptive. In contrast, phytoremediation offers a cost-effective and sustainable alternative by utilizing plants to absorb, stabilize, or detoxify contaminants. Furthermore, microbial-assisted bioremediation (Pratush *et al.*, 2018), especially involving PGPR, has gained attention due to its ability to enhance plant growth and improve metal uptake or immobilization through multiple biochemical processes.

Heavy Metals: Definition and Properties

Heavy metals are generally defined as elements with high density (greater than 5 g cm^{-3}) and significant toxicity at low concentrations. They can be broadly categorized into two groups:

Toxic metals (e.g., Pb, Cd, As), which have no biological function and are harmful even in trace amounts.

Essential metals (e.g., Zn, Cu, Fe, Mn), which are required in small quantities but become toxic at higher concentrations. These metals are persistent in the environment and cannot be degraded, leading to long-term ecological consequences.

Sources of Heavy Metals

Heavy metal contamination arises primarily from anthropogenic activities such as mining, industrial discharge, fossil fuel combustion, and intensive agriculture. Fertilizers, pesticides, and sewage sludge contribute significantly to soil contamination. Long-term irrigation with wastewater also leads to gradual accumulation of metals. Additionally, atmospheric deposition from industrial emissions and vehicular sources plays a major role in dispersing metals across wide areas. Natural processes such as weathering of rocks also contribute, although to a lesser extent compared to human activities.

Toxic Effects on Environment and Health

Heavy metals are persistent pollutants that accumulate in soils and living organisms, leading to bioaccumulation and biomagnification. Their presence reduces soil fertility and disrupts ecosystem functions. In plants, toxicity symptoms include chlorosis, necrosis, reduced growth, and impaired photosynthesis. In humans and animals, exposure can cause neurological disorders, immune dysfunction, reproductive issues, and even cancer. Metals such as Pb, Cd, Hg, and As are particularly dangerous due to their long-term persistence and ability to interfere with biological systems.

Plant Response to Heavy Metal Stress

Heavy metals affect plant metabolism by disrupting enzyme activity, protein synthesis, and nutrient uptake. They induce oxidative stress through the generation of reactive oxygen species (ROS), damaging cellular components. Plants have developed defense mechanisms such as antioxidant production, metal sequestration, and reduced uptake to tolerate stress. PGPR further enhances these defense systems by improving antioxidant activity and reducing metal toxicity.

Phytoremediation

Phytoremediation involves the use of plants to remove, stabilize, or detoxify pollutants. It is an environmentally friendly and cost-effective method that utilizes natural plant processes. Key mechanisms include:

Phytoextraction: Uptake and accumulation of metals in plant tissues
Phytostabilization: Immobilization of metals in soil
Phytofiltration: Removal of contaminants from water
Phytovolatilization: Conversion of metals into volatile forms

The effectiveness of phytoremediation depends on plant species, soil properties, and environmental conditions.

Role Of PGPR In Phytoremediation

PGPR are beneficial soil bacteria that enhance plant growth and stress tolerance. They promote phytoremediation by: producing phytohormones, solubilizing nutrients, fixing nitrogen, reducing metal toxicity. They also help control plant pathogens and improve soil health. Their interaction with plant roots enhances metal uptake or immobilization depending on the remediation strategy.

Mechanisms of PGPR-Assisted Phytoremediation

Phytoextraction Enhancement: PGPR increase metal bioavailability by producing organic acids, siderophores, and biosurfactants. These compounds solubilize metals and facilitate their uptake by plants.

Phytostabilization: Some PGPR immobilize metals through biosorption, precipitation, and transformation, reducing their mobility and toxicity.

Phytovolatilization: Certain bacteria can convert toxic metals into less harmful volatile forms, thereby reducing their environmental impact.

Some examples of PGPR assisted phytoremediation are listed below.

Table 1: Examples of PGPR assisted phytoremediation of metal-contaminated soils

Host	PGPR strain	Source	Beneficial features	Effects on plants	Reference
Brassica juncea	*Pseudomonas sp.* PsA, *Bacillus sp.* Ba32 (RS)	Cr contaminated soil near Chennai, India	1-Aminocyclopropane-1-carboxylate deaminase (ACCD), siderophore, Indole-3-Acetic Acid (IAA), Phoshphorus (P) solubilization	↑Plant growth (Phytostabilization)	Rajkumar *et al.* (2006)
Lycopersicon esculentum	*Burkholderia sp.* J62 (RS)	A heavy metal polluted paddy field, China	ACCD, siderophore, IAA, P solubilization	↑ Root and shoot dry weight ↑Total shoot [Pb, Cd] uptake (Phytoextraction)	Jiang *et al.* (2008)
Pisum sativum	*Rhizobium sp.* RP5 (RS)	Nodules of pea grown in metal-contaminated Indian soils	N_2 fixation, IAA, siderophore	↑ Dry matter, nodule numbers, root N, shoot N, leghemoglobin, seed yield, grain protein under in vitro conditions ↓ [Ni, Zn] toxicity and uptake (Phytostabilization)	Wani *et al.* (2007)
Zea mays	*Burkholderia sp.* J62 (RS)	A heavy metal polluted paddy field, China	ACCD, siderophore, IAA, P solubilization	↑ Root and shoot dry weight ↑Total root [Pb, Cd] and total shoot [Pb] uptake (Phytoextraction)	Jiang *et al.* (2008)

Advantages and Limitations

The advantages of PGPR assisted phytoremediation include - cost-effectiveness and environmentally sustainability, improvement of soil health and fertility, minimal disturbance to ecosystems, suitability for large-scale applications. Whereas, on other side there are some limitations also like - slow procedure, less effectiveness at high contamination levels, requirement of suitable environmental conditions, risk of contaminant transfer through biomass.

Challenges in Phytoremediation

Despite its potential, phytoremediation faces several challenges, including long remediation time, low biomass of hyperaccumulators, limited metal bioavailability, and environmental constraints such as climate and pests. Proper disposal of contaminated biomass is also a critical concern.

Conclusion and Future Prospects

Microbial-assisted phytoremediation, particularly involving PGPR, represents a promising approach for sustainable management of heavy metal contamination. These microorganisms enhance plant growth, improve metal uptake, and modify metal bioavailability, thereby increasing remediation efficiency. However, further research is required to understand plant–microbe interactions under contaminated conditions, especially regarding metal speciation and microbial colonization. Field-based studies are essential to validate laboratory findings and assess long-term effectiveness under natural conditions. Future work should focus on identifying robust PGPR strains, improving their adaptability to diverse environments, and optimizing their interaction with host plants. Understanding microbial diversity and ecological dynamics in contaminated soils will further enhance the application of this technology.

Overall, integrating PGPR with phytoremediation holds great potential for improving soil health, ensuring agricultural sustainability, and mitigating environmental pollution. With continued research and field validation, this approach can be effectively translated into practical solutions for farmers and environmental management systems.

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AGRI-STARTUPS AND RURAL YOUTH IN PROTECTED CULTIVATION

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Introduction

Agriculture has always been the backbone of the Indian economy, contributing significantly to employment and food security. However, the sector is currently facing multiple challenges such as climate change, declining farm profitability, fragmented land holdings, and increasing migration of rural youth towards urban areas. Traditional farming practices are often unable to meet the demands of modern markets due to low productivity and high risks.

In this context, the emergence of Agri-startups and the adoption of protected cultivation technologies have opened new avenues for agricultural transformation. Protected cultivation involves growing crops under controlled environmental conditions using structures such as polyhouses, greenhouses, and shade nets. These systems protect crops from adverse weather conditions and pests, thereby ensuring higher yield and quality.

Agri-startups integrate innovation, technology, and entrepreneurial approaches into agriculture. They provide solutions related to production, processing, marketing, and supply chain management. When combined with protected cultivation, these startups create a sustainable and profitable model that can attract rural youth back to agriculture.

Keywords: Agri-startups, Protected Cultivation, Rural Youth, Polyhouse Farming.

Objectives of the Study

The study focuses on the following objectives:

- To understand the concept and role of Agri-startups in agricultural development
- To analyse the importance of protected cultivation
- To examine the role of rural youth in agricultural entrepreneurship
- To evaluate the cost and returns of protected cultivation
- To identify challenges and opportunities in the sector
- To explore future prospects for sustainable agriculture

Concept of Agri-Startups- Agri-startups are entrepreneurial ventures that focus on solving agricultural problems through innovation and technology. These startups operate in various domains such as precision farming, farm mechanization, Agri-fintech, digital marketplaces, and post-harvest management.

They play a crucial role in modernizing agriculture by:

- Increasing productivity

- Reducing input costs
- Improving market access
- Enhancing value addition

Agri-startups bridge the gap between farmers and markets by using digital platforms and data-driven solutions. They also promote sustainable farming practices and efficient resource utilization.

Protected Cultivation: Meaning and Importance- Protected cultivation is a scientific method of growing crops under controlled environmental conditions. It allows farmers to regulate temperature, humidity, light, and irrigation, thereby creating an ideal environment for plant growth.

Its importance includes:

- Higher yield (3–5 times more than open farming)
- Better quality produce
- Efficient water and nutrient use
- Reduced pest and disease incidence
- Off-season production

This method is particularly useful for high-value crops such as capsicum, tomato, cucumber, and flowers.

Glimpses of Our College Polyhouse With my Students

Role of Rural Youth- Rural youth play a vital role in transforming agriculture through Agri-startups and protected cultivation. They are more educated, innovative, and willing to adopt modern technologies.

Key Contributions:

1. **Technology Adoption:** Use of drip irrigation, sensors, and automation
2. **Entrepreneurship:** Establishing polyhouse units and startups
3. **Marketing Innovation:** Direct selling and online platforms
4. **Employment Generation:** Creating jobs in rural areas
5. **Sustainability:** Promoting eco-friendly farming practices

Their involvement can significantly reduce rural unemployment and improve income levels.

Cost of Protected Cultivation- The initial investment in protected cultivation is relatively high but offers substantial returns.

Approximate Cost (1000 sq. meter):

- Polyhouse: ₹8–12 lakh
- Shade net: ₹3–6 lakh
- Greenhouse: ₹15–25 lakh

Additional Costs:

- Irrigation system
- Planting material
- Labor
- Maintenance

Returns:

- Annual income: ₹3–8 lakh
- Payback period: 2–4 years

Glimpses of Our College Polyhouse With my Students

Government Policies and Subsidy- The government supports protected cultivation through subsidies and schemes.

Key Features:

- 40–50% subsidy for general farmers
- 50–60% for SC/ST and women
- Support under horticulture missions
- Bank loans and training programs

These policies reduce financial burden and encourage adoption.

Challenges- Despite its benefits, protected cultivation faces several challenges:

- High initial investment
- Lack of technical knowledge
- Market fluctuations
- Maintenance issues
- Limited awareness

Opportunities- Protected cultivation offers immense opportunities:

- Export-oriented farming
- Floriculture
- Organic farming
- Agri-tourism
- Startup ecosystem development

Future Perspective- The future of protected cultivation and Agri-startups is very promising. Integration of technologies such as Artificial Intelligence, IoT, and automation will further enhance productivity and reduce risks.

With increasing demand for quality food and climate-resilient agriculture, protected cultivation will play a key role in ensuring food security and sustainable development.

Conclusion

Agri-startups and protected cultivation together offer a sustainable and profitable model for modern agriculture. They enhance productivity, improve income, and reduce risks associated with traditional farming. Most importantly, they attract rural youth towards agriculture by making it more innovative, technology-driven, and economically viable. With proper government support, training, and awareness, this model can lead to sustainable agricultural development, rural employment generation, and long-term food security in India.

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FROM SOIL AND WATER TO FOOD: BIOACCUMULATION, TOXICITY, AND THE PATH TO RESPONSIBLE AQUACULTURE

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Abstract

Aquaculture is one of the fastest-growing food production sectors globally, contributing significantly to food security and nutritional demand. However, the rapid intensification of aquaculture practices has increased the risk of environmental contamination, leading to the accumulation of toxic substances in aquatic systems. This review focuses on the processes of bioaccumulation and toxicity in aquaculture, highlighting their sources, mechanisms, and impacts on aquatic organisms and human health. Contaminants such as heavy metals, pesticides, antibiotics, and industrial chemicals enter aquaculture systems through agricultural runoff, industrial discharge, and aquaculture inputs. These substances accumulate in fish tissues over time when the rate of uptake exceeds elimination, resulting in adverse physiological, biochemical, and reproductive effects. Furthermore, the process of biomagnification leads to increased concentrations of these toxicants across trophic levels, posing serious risks to human consumers through the food chain. Environmental factors such as temperature, pH, salinity, and dissolved oxygen, along with biological characteristics like metabolic rate and feeding behavior, significantly influence the extent of bioaccumulation. The review also emphasizes the importance of effective prevention and management strategies, including water quality monitoring, use of high-quality feed, reduced chemical usage, and adoption of eco-friendly technologies such as biofilters and integrated aquaculture systems. Ensuring the safety and sustainability of aquaculture production requires a comprehensive understanding of contaminant dynamics and strict implementation of regulatory frameworks. Overall, integrated management approaches are essential to minimize contamination risks, protect aquatic ecosystems, and safeguard human health.

Keywords: Bioaccumulation, toxicity, aquaculture, biomagnification

Introduction

Aquaculture is one of the fastest-growing food production sectors worldwide and plays a vital role in global food security and nutrition by supplying a substantial proportion of animal protein, essential fatty acids, vitamins, and minerals to the human population. The rapid expansion of aquaculture has been driven by increasing global demand for fish and seafood, population growth, urbanization, and the stagnation of capture fisheries. As a result, aquaculture has evolved from traditional extensive systems to more intensive and semi-intensive production practices aimed at maximizing yield and economic returns. However, this intensification has also introduced significant environmental challenges, particularly in relation to water quality degradation, waste accumulation, and the increased risk of contamination. Pollutants originating from multiple anthropogenic sources, including agricultural runoff, industrial discharge, urban effluents, and aquaculture-specific inputs, can enter aquatic systems and persist in the culture environment. Agricultural runoff often carries fertilizers, pesticides, and herbicides, which contribute to nutrient enrichment and chemical toxicity. Industrial effluents introduce heavy metals such as mercury, cadmium, and lead, as well as various organic pollutants that are resistant to degradation. Additionally, aquaculture practices themselves contribute to contamination through the use of medicated feeds, antibiotics, disinfectants, and the accumulation of uneaten feed and metabolic wastes. These inputs can alter key physicochemical parameters such as dissolved oxygen, pH, ammonia, and salinity, thereby creating stressful conditions for cultured organisms. The presence of these contaminants in aquaculture systems can disrupt ecological balance and interfere with biological processes at multiple levels of organization. At the organismal level, toxic substances can impair physiological functions, including respiration, osmoregulation, and metabolism. At the cellular level, they can induce oxidative stress, damage biomolecules such as proteins and DNA, and disrupt enzymatic activities. Furthermore, many contaminants exhibit high persistence and lipophilicity, enabling them to accumulate within tissues over time through the process of bioaccumulation. This process becomes more pronounced in higher trophic levels through biomagnification, where the concentration of toxic substances increases progressively along the food chain. Consequently, these contaminants not only compromise fish health, manifested as reduced growth performance, immunosuppression, behavioral abnormalities, and reproductive failure, but also have broader implications for aquaculture productivity and economic sustainability. The deterioration of fish health can lead to increased disease outbreaks, higher mortality rates, and reduced product quality. More importantly, the accumulation of toxic substances in edible tissues poses significant risks to human health. Consumption of contaminated fish may result in serious health consequences, including neurological disorders associated with mercury exposure, renal dysfunction linked to cadmium, and potential carcinogenic effects of certain organic pollutants. In addition to direct health impacts, the presence of contaminants in aquaculture products raises concerns regarding foodsafety standards, market acceptance, and international trade regulations.

Bioaccumulation and Toxicity in Aquaculture Systems

Bioaccumulation is defined as the gradual accumulation of chemical substances within an organism when the rate of uptake exceeds the rate of elimination (Newman, 2015; Walker *et al*., 2012). In aquaculture systems, contaminants enter aquatic organisms through multiple pathways, including direct absorption from water via gills, ingestion of contaminated feed, and interaction with polluted sediments. Lipophilic substances, in particular, tend to accumulate in fatty tissues due to their low solubility in water and high affinity for biological membranes. Over time, this results in an increase in internal concentrations of toxic substances, even when environmental levels remain relatively low. Toxicity refers to the inherent ability of a substance to cause adverse biological effects in living organisms (Rand, 1995; Gupta, 2018). In aquaculture, toxicity can be broadly classified into acute and chronic forms. Acute toxicity results from short-term exposure to high concentrations of toxicants, often leading to rapid mortality. In contrast, chronic toxicity arises from prolonged exposure to low concentrations, causing sub-lethal effects such as physiological stress, impaired growth, and reproductive dysfunction. The severity of toxicity depends on factors such as concentration, duration of exposure, species sensitivity, and environmental conditions.

Mechanisms of Bioaccumulation and Toxic Action

Bioaccumulation involves a series of processes including uptake, distribution, storage, and elimination of contaminants within the organism. Toxic substances are primarily absorbed through the gills, digestive tract, and skin, after which they are transported via the bloodstream to various tissues. Organs such as the liver and kidney play a major role in detoxification; however, continuous exposure can overwhelm these systems, leading to accumulation. Many toxicants exert their effects by disrupting cellular processes, including enzyme activity, membrane integrity, and metabolic pathways. Additionally, the generation of reactive oxygen species (ROS) induces oxidative stress, which damages cellular components and impairs normal physiological functions.

Impacts of Bioaccumulation on Fish Physiology and Growth (Toxic effects)

The accumulation of toxic substances can lead to increased internal concentrations within aquatic organisms, even when environmental contamination levels are relatively low (Newman, 2015; Walker *et al*., 2012). This progressive buildup is particularly critical in aquaculture systems, where organisms are continuously exposed to pollutants. As contaminants accumulate in vital tissues such as the liver, kidney, and muscle, they interfere with normal physiological and biochemical processes essential for growth and survival. At the cellular level, accumulated toxicants induce oxidative stress by generating reactive oxygen species, which damage lipids, proteins, and DNA. This leads to disruption of enzymatic functions and metabolic pathways, ultimately affecting nutrient assimilation and energy utilization. As a result, fish exhibit reduced growth rates, poor feed conversion efficiency, and overall decline in health status. Furthermore, chronic exposure to bioaccumulated toxicants results in prolonged physiological stress. This stress is often associated with hormonal imbalances, particularly involving cortisol, which disrupts homeostasis and reduces the organism’s ability to adapt to environmental changes. The immune system is also compromised, increasing susceptibility to diseases and infections in aquaculture systems. Reproductive performance is significantly affected by bioaccumulation. Toxic substances can impair gonadal development, reduce gamete quality, and disrupt endocrine regulation. These effects may lead to decreased fecundity, delayed maturation, and reduced larval survival rates. Although such impacts are often sub-lethal, they have long-term consequences on population dynamics and aquaculture productivity. Therefore, even low concentrations of contaminants in the environment can have significant biological impacts due to their cumulative nature (Rand, 1995; Gupta, 2018).

Types of Pollutants in Aquaculture Systems

Contaminant Type	Examples	Sources	Effects on Cultured Organisms
Heavy Metals	Mercury (Hg), Cadmium (Cd), Lead (Pb), Arsenic (As)	Industrial discharge, mining, agricultural runoff	Gill damage, organ toxicity (liver/kidney), oxidative stress, reduced growth, reproductive failure, mortality
Pesticides	Organophosphates, Organochlorines, Pyrethroids	Agricultural runoff, nearby farming activities	Neurotoxicity, erratic swimming, enzyme inhibition (AChE), reduced feeding, immune suppression
Antibiotics & Pharmaceuticals	Oxytetracycline, Sulfonamides, Chloramphenicol	Disease treatment, medicated feed	Gut microbiota disruption, antimicrobial resistance, reduced immunity, residue accumulation

Contaminant Type	Examples	Sources	Effects on Cultured Organisms
Industrial Chemicals	PCBs, Dioxins, PAHs	Industrial effluents, oil spills	Bioaccumulation, carcinogenic effects, endocrine disruption, growth retardation
Nutrients (Excess)	Ammonia, Nitrates, Phosphates	Overfeeding, waste accumulation, fertilizers	Toxicity (ammonia), eutrophication, oxygen depletion, stress, reduced survival
Suspended Solids	Organic matter, sediments	Uneaten feed, erosion, runoff	Gill clogging, reduced respiration, stress, lower growth
Disinfectants & Chemicals	Chlorine, Formalin, Hydrogen peroxide	Water treatment, disease control	Tissue irritation, gill damage, toxicity at high doses
Microplastics	Plastic particles, fibers	Degraded plastic waste	Ingestion, gut blockage, reduced feeding, transfer of toxins

Bioaccumulation and Biomagnification in Aquatic Food Chains

Bioaccumulation significantly amplifies the risk of exposure to toxic substances at higher trophic levels, including top predators and ultimately humans (Newman, 2015). In aquatic ecosystems, contaminants initially enter at the lowest trophic levels, such as phytoplankton and zooplankton, through direct absorption from water. These primary producers and consumers serve as the foundation of the food chain and act as the first point of entry for many toxic substances. As small fish consume contaminated plankton, the accumulated toxicants are transferred and further concentrated within their tissues. Subsequently, larger predatory fish feed on these smaller fish, resulting in an even higher concentration of contaminants at each successive trophic level. This progressive increase in contaminant concentration is known as biomagnification and represents a critical ecological and toxicological concern in aquaculture and natural aquatic systems. Unlike bioaccumulation, which occurs within a single organism over time, biomagnification involves the transfer and amplification of contaminants across the food chain. This process is particularly significant for persistent, non-biodegradable, and lipophilic substances such as mercury, polychlorinated biphenyls (PCBs), and certain pesticides. These compounds resist metabolic breakdown and are stored in fatty tissues, allowing them to remain in the organism for extended periods and be passed on to predators during feeding. The implications of biomagnification are profound, as top predators, including commercially important fish species, often exhibit the highest concentrations of toxic substances. In aquaculture systems, especially those integrated with natural water bodies or

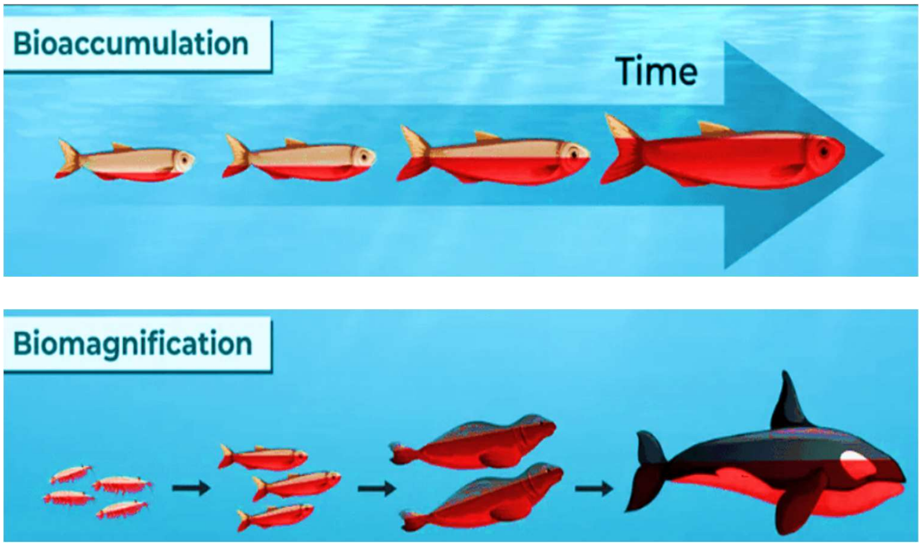

Figure 1. Bioaccumulation vs Biomagnification

dependent on external feed sources, this can lead to the accumulation of hazardous compounds in marketable fish. Consequently, the consumption of such contaminated fish poses significant health risks to humans, including neurological disorders, endocrine disruption, and other chronic health conditions.

Human Health Implications of Bioaccumulation and Toxicity

The consumption of fish and other aquatic products contaminated with toxic substances represents a major pathway for human exposure to environmental pollutants. In aquaculture systems, bioaccumulation and subsequent biomagnification of contaminants such as heavy metals, pesticides, antibiotics, and industrial chemicals can lead to the presence of hazardous residues in edible tissues. As fish occupy higher trophic levels in the food chain, they often accumulate significant concentrations of these toxic substances, thereby posing serious risks to human health upon consumption (Tchounwou *et al.*, 2012). Heavy metals such as mercury (Hg), cadmium (Cd), and lead (Pb) are among the most concerning contaminants due to their persistence, non-biodegradable nature, and high toxicity. Methylmercury, a highly toxic organic form of mercury, readily accumulates in fish tissues and can cause severe neurological disorders in humans, including impaired cognitive function, memory loss, and developmental defects in children. Cadmium exposure is associated with kidney damage, bone demineralization, and disruption of calcium metabolism, while lead toxicity can affect the nervous system, hematopoietic system, and cardiovascular health. Organic pollutants such as polychlorinated biphenyls (PCBs), dioxins, and certain pesticides are known for their lipophilic nature and ability to accumulate in fatty tissues. These compounds can disrupt endocrine function by mimicking or interfering with hormonal systems, leading to reproductive and developmental abnormalities. Long-term exposure to such substances has also been linked to carcinogenic effects and immune system suppression. Pesticide residues in fish may additionally cause neurotoxic effects, affecting the central and peripheral nervous systems in humans. The widespread use of antibiotics in aquaculture for disease prevention and treatment has raised concerns regarding the presence of antibiotic residues in fish products. Consumption of such residues can contribute to the development of antimicrobial resistance (AMR), a growing global public health issue. Resistant pathogens can reduce the effectiveness of therapeutic drugs in humans, making infections more difficult to treat. Additionally, antibiotics may disrupt the human gut microbiota, leading to potential digestive and metabolic disturbances.

Chronic Health Effects and Food Safety Concerns

Chronic exposure to low levels of contaminants through regular consumption of contaminated fish can result in cumulative health effects over time. These include increased risk of cancer, endocrine disorders, immune dysfunction, and metabolic diseases. Vulnerable populations such as pregnant women, children, and the elderly are particularly at risk due to their higher sensitivity to toxic substances. Moreover, contamination issues can undermine consumer confidence, affect marketability, and lead to economic losses in the aquaculture sector.

Prevention and Management of Bioaccumulation and Toxicity in Aquaculture Systems

The increasing concerns regarding bioaccumulation and toxicity in aquaculture systems necessitate the implementation of effective prevention and management strategies. These strategies aim to minimize the entry of contaminants into the culture system, reduce their accumulation within aquatic organisms, and ensure the production of safe and high-quality aquaculture products. Sustainable aquaculture practices, combined with scientific monitoring and regulatory frameworks, play a crucial role in mitigating the adverse effects of environmental contaminants. Regular monitoring of water quality parameters is one of the most critical approaches for controlling contamination in aquaculture systems. Parameters such as temperature, pH, dissolved oxygen, salinity, ammonia, nitrite, and nitrate levels must be continuously assessed to maintain optimal environmental conditions. Advanced monitoring techniques, including sensor-based systems and real-time data analysis, enable early detection of contamination and allow timely corrective measures. Maintaining good water quality not only reduces the availability of toxic substances but also enhances the physiological resilience of cultured organisms. Feed is a major pathway through which contaminants enter aquaculture systems. The use of high-quality, contaminant-free feed ingredients is essential to prevent the introduction of heavy metals, pesticides, and other harmful substances. Proper feeding practices, including optimized feeding rates and schedules, help minimize the accumulation of uneaten feed and reduce organic waste in the system. Improved feed management enhances nutrient utilization efficiency and reduces the risk of internal contamination. The excessive use of chemicals, antibiotics, and disinfectants in aquaculture can contribute significantly to toxicity and the development of antimicrobial resistance. Therefore, the adoption of responsible and judicious use of these substances is essential. Alternative approaches such as probiotics, immunostimulants, and herbal treatments can be used to enhance disease resistance in fish without introducing harmful residues. Implementing biosecurity measures and maintaining optimal culture conditions can further reduce the need for chemical interventions.

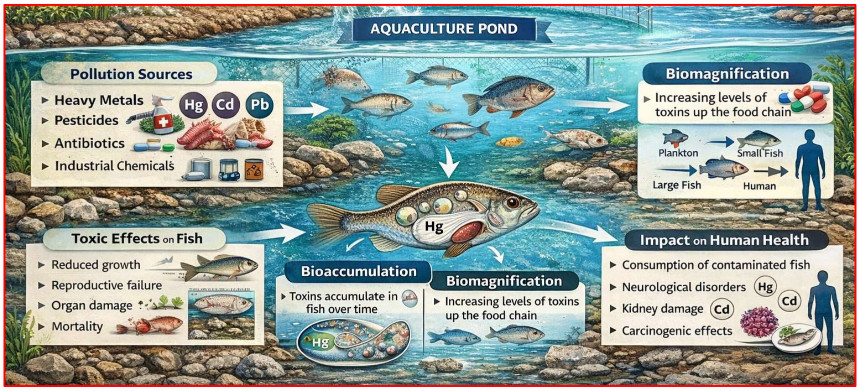

Figure 2. Conceptual Overview of Bioaccumulation and Toxicity in Aquaculture Systems

Conclusion

Bioaccumulation and toxicity are major concerns in aquaculture systems, affecting both aquatic organisms and human health. The continuous introduction of contaminants from agricultural, industrial, and aquaculture-related sources increases the risk of accumulation of toxic substances in fish tissues. These contaminants can disrupt physiological processes, reduce growth and reproduction, and ultimately impact the overall productivity of aquaculture systems. In addition to their effects on aquatic organisms, bioaccumulated toxic substances pose significant risks to human consumers through the food chain. The presence of heavy metals, pesticides, and other harmful compounds in edible fish tissues raises concerns regarding food safety and public health. Therefore, understanding the sources, mechanisms, and impacts of these contaminants is essential for developing effective management strategies. Future research and management efforts should focus on improving monitoring systems, reducing pollutant inputs, and promoting eco-friendly aquaculture practices. The adoption of sustainable techniques and strict regulatory measures will help minimize contamination risks and ensure the production of safe and high-quality aquaculture products. Overall, a balanced and integrated approach is necessary to achieve long-term environmental sustainability and food safety in aquaculture systems.

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INTEGRATION OF ROBOTICS IN FISH BREEDING: A MODERN APPROACH TO SUSTAINABLE AQUACULTURE

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Introduction

Aquaculture has become one of the fastest-growing food production sectors in the world, with fish breeding playing a crucial role in ensuring a continuous supply of quality fish seed. Traditional fish breeding methods, although widely practiced, are often labor-intensive and highly dependent on environmental conditions. In recent years, the integration of robotics and automated technologies has emerged as a significant advancement, offering improved efficiency, precision, and sustainability in fish breeding practices.

What is Robotics in Aquaculture?

Robotics in aquaculture refers to the use of automated machines, sensors, and intelligent systems to perform various fish farming activities with minimal human intervention. These technologies are designed to monitor, analyse, and control different aspects of the aquaculture environment.

In fish breeding, the integration of robotics helps maintain optimal environmental conditions, monitor fish health and behaviour, and automate routine operations. This leads to improved efficiency, greater consistency, and reduced dependence on manual labor in aquaculture systems.

Applications of Robotics in Fish Breeding

The integration of robotics in fish breeding has significantly improved the efficiency and precision of aquaculture operations. Various automated systems are used at different stages of the breeding process to ensure optimal conditions and better outcomes.

Robotic technologies play a crucial role in water quality monitoring, where sensors continuously measure parameters such as temperature, pH, dissolved oxygen, and salinity. These systems can automatically adjust environmental conditions, ensuring a stable and suitable habitat for breeding.

In addition, automated feeding systems provide feed at regular intervals and in controlled quantities, reducing wastage and promoting uniform growth. Robotics also assists in brood-stock monitoring through cameras and sensors that track fish behaviour, health, and stress levels.

Furthermore, robotic systems help in spawning operations and the careful handling of eggs and larvae, minimising physical damage and improving survival rates. Environmental control systems, including automated aeration and filtration, further support successful breeding by maintaining ideal conditions throughout the process.

Advantages of Robotics Integration in Fish Breeding

The integration of robotics in fish breeding offers several significant advantages, contributing to improved efficiency and productivity in aquaculture systems. One of the primary benefits is the reduction of manual labor, as automated systems can perform routine tasks such as monitoring, feeding, and environmental control with minimal human intervention. Robotics also enhances accuracy and consistency in breeding operations. Sensors and automated systems continuously monitor water quality parameters such as temperature, pH, and dissolved oxygen, ensuring that optimal conditions are maintained at all times. This leads to improved hatch ability and higher survival rates of eggs and larvae.

In addition, robotic systems enable real-time monitoring of fish behaviour and health, allowing early detection of stress, disease, or unfavourable conditions. This facilitates timely management and helps reduce potential losses. Another important advantage is efficient resource utilisation. Automated feeding systems minimise feed wastage, while controlled environmental systems help reduce water and energy consumption. Furthermore, the use of robotics minimises human error and supports data-driven decision-making, thereby improving overall farm management.

A practical example in the Indian context can be observed in initiatives by the Central Institute of Brackish water Aquaculture (CIBA) and Tamil Nadu Dr. J. Jayalalithaa Fisheries University (TNJFU), where sensor-based monitoring systems and automated aeration units are promoted in hatcheries and aquaculture farms. These technologies assist farmers in maintaining optimal water quality and feeding schedules, resulting in improved breeding efficiency, higher larval survival rates, and enhanced productivity. Sensor-based smart hatchery monitoring systems are widely used in modern aquaculture systems across India, Norway, and China. These systems monitor parameters such as pH, dissolved oxygen, and temperature, and are connected to mobile or computer dashboards for real-time tracking. This enables instant alerts and helps maintain stable breeding conditions.

Practical Applications in Fish Breeding

Sensor-Based Smart Hatchery Monitoring (IoT Systems)

Used in: Modern hatcheries (India, Norway, China)

- Sensors track:
- pH, dissolved oxygen, and temperature
- Connected to mobile/PC dashboards
- Provides instant alerts and stable breeding conditions

Result:

- Instant alerts
- Stable breeding conditions

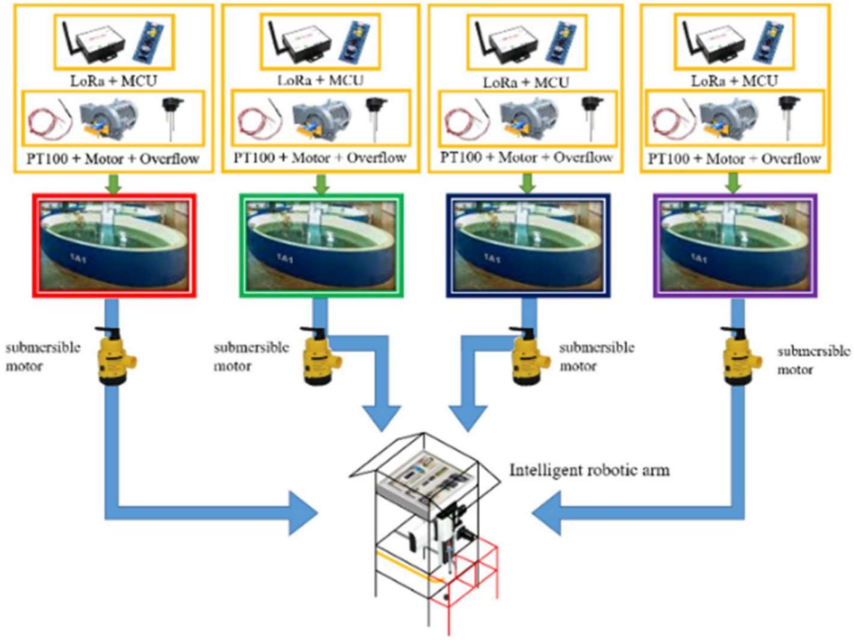

Figure 1: IoT-Based Smart Hatchery Monitoring System

Robotic Fish Monitoring (AI + Camera Systems)

Used in: Advanced farms (Norway, Japan)

- Underwater cameras + AI:
- Track fish movement
- Detect stress/disease

Result:

- Early disease detection
- Better brood stock selection

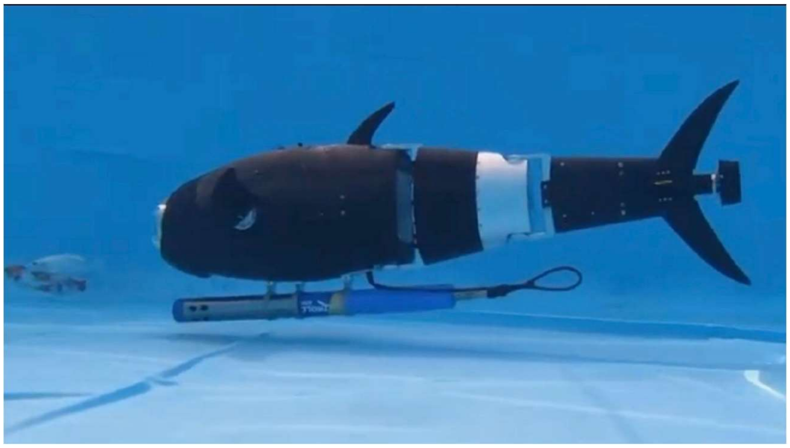

Figure 2: Robotic Fish Monitoring System

Challenges and Limitations

Despite its numerous advantages, the integration of robotics in fish breeding also presents several challenges. The high initial cost of installation and maintenance can limit its adoption, particularly among small-scale farmers. In addition, the operation of automated systems requires technical knowledge and skilled personnel.

Dependence on electricity and advanced infrastructure is another major limitation, especially in rural areas where power supply may be unreliable. Furthermore, the lack of awareness and adequate training among farmers can hinder the effective utilisation of such technologies.

Environmental and Sustainability Benefits

The use of robotics in fish breeding contributes significantly to sustainable aquaculture practices. Automated systems enable efficient utilisation of resources such as water, feed, and energy. By maintaining optimal environmental conditions, these systems reduce stress on fish and help minimise mortality rates.

In addition, precise feeding and effective waste management reduce environmental pollution, making aquaculture more eco-friendly. Such technologies support the development of sustainable and responsible fish farming systems.

Future Prospects

The future of fish breeding is closely linked to advancements in technologies such as artificial intelligence (AI) and the Internet of Things (IoT). These innovations will enable predictive monitoring, automated decision-making, and improved farm management.

As these technologies become more affordable and accessible, their adoption is expected to increase, leading to more efficient, productive, and sustainable aquaculture systems.

Conclusion

The integration of robotics in fish breeding represents a significant advancement in modern aquaculture. It improves efficiency, accuracy, and sustainability while reducing manual labor and human error. Although certain challenges remain, the continued development and adoption of these technologies will play a crucial role in the future of sustainable fish production.

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INTEGRATING CLIMATE-RESILIENT BREEDING STRATEGIES IN OKRA FOR AGRICULTURAL SUSTAINABILITY AND VIKSIT BHARAT 2047

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Abstract

As India marches towards the vision of 'Viksit Bharat 2047', ensuring food and nutritional security amidst escalating climate uncertainties remains a paramount challenge. Okra (*Abelmoschus esculentus* L. Moench), a vital vegetable crop for small and marginal farmers, is increasingly threatened by abiotic stresses like heat and drought, alongside devastating biotic pressures such as Yellow Vein Mosaic Virus (YVMV). This study explores the significant potential of climate-resilient breeding strategies to safeguard okra productivity. It emphasizes the integration of traditional quantitative genetics, such as Line x Tester analysis and heterosis breeding, with modern biotechnological tools including Marker-Assisted Selection (MAS) and genomic interventions. By harnessing genetic diversity from wild relatives and utilizing precision phenotyping, breeders can develop "smart" okra varieties that thrive in fluctuating environments. Furthermore, aligning breeding objectives with 'Mission LiFE' and Sustainable Development Goal 2 (Zero Hunger), this paper highlights how innovative seed systems and digital breeding tools can empower farmers. Ultimately, the transition from conventional to climate-smart breeding is not just an academic necessity but a strategic pillar for achieving a self-reliant and developed agricultural landscape in India by 2047.

Keywords: Climate-Resilient Breeding, Okra (Abelmoschus esculentus), Viksit Bharat 2047, Genetic Improvement, Biotic Stress, Sustainable Agriculture, Mission LiFE, Hybrid Vigour.

Introduction

Agriculture is the backbone of the Indian economy, and as the nation strives to achieve the "Viksit Bharat 2047" vision, the vegetable sector emerges as a critical driver for both economic growth and nutritional security. Among various vegetables, Okra (*Abelmoschus esculentus* L. Moench), popularly known as 'Bhindi,' holds a pre-eminent position due to its high export value, year-round cultivation, and rich nutritional profile, including dietary fiber, Vitamin C, and essential minerals. However, the path to a developed India by 2047 is challenged by the intensifying footprints of climate change. Rising global temperatures, unpredictable rainfall patterns, and the emergence of virulent strains of Yellow Vein Mosaic Virus (YVMV) and Enation Leaf Curl Virus (ELCV) have started to stagnate okra productivity across major growing belts.

To transform Indian agriculture into a sustainable and resilient powerhouse, a shift from traditional cultivation to "Climate-Smart Breeding" is no longer optional—it is a necessity. The core of this transformation lies in the genetic architecture of the crop. Developing climate-resilient okra varieties requires a multi-pronged approach that integrates classical breeding techniques, like Line x Tester analysis for exploiting heterosis, with cutting-edge genomic tools. Aligning with the government's "Mission LiFE" (Lifestyle for Environment) and Sustainable Development Goals (SDG 2: Zero Hunger & SDG 13: Climate Action), breeding programs must now prioritize genotypes that exhibit high water-use efficiency, heat tolerance, and robust resistance to biotic stresses.

This article reviews the strategic roadmap for okra breeding over the next two decades. By leveraging indigenous genetic resources and modern biotechnological interventions, we can ensure that okra remains a profitable crop for farmers and an affordable, nutritious choice for the masses. Achieving excellence in okra breeding will not only boost domestic production but also position India as a global leader in the high-quality seed system, fulfilling a vital component of the Viksit Bharat 2047 mission.

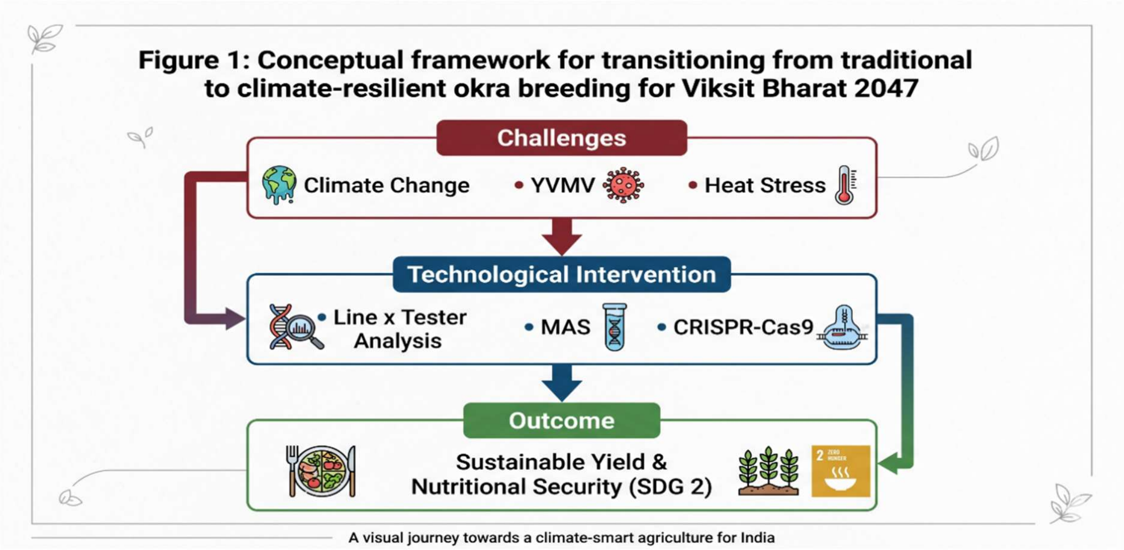


Figure 1: Conceptual framework for transitioning from traditional to climate-resilient okra breeding for Viksit Bharat 2047

A visual journey towards a climate-smart agriculture for India

Strategic Breeding Approaches for Climate Resilience

To achieve the 2047 productivity targets, okra breeding must evolve into a precision-driven science. The following strategies are pivotal for developing varieties that can withstand the vagaries of climate change:

1. Exploiting Genetic Architecture through Line × Tester Analysis

The foundation of any successful breeding program lies in understanding the combining ability of parents. By utilizing the Line × Tester (L×T) mating design, breeders can effectively evaluate a large number of lines for their General Combining Ability (GCA) and Specific Combining Ability (SCA). This approach is instrumental in identifying superior parents and high-yielding hybrids that exhibit "Heterotic stability under stress"—the ability of a hybrid to maintain stable yields even under environmental stress. For a developed India, focusing on hybrids that combine high fruit yield with tolerance to heat and drought is essential.

"The genetic variability and heritability studies (as shown in Table 1) indicate a significant scope for selection in traits like fruit yield."

Trait	Mean	Range (Min–Max)	GCV (%)	PCV (%)	h^2 (%)	GA	GAM (%)
PH	117.28	75.10–163.30	17.52	17.85	96.40	41.57	35.44
NPBPP	2.50	1.00–4.70	34.84	37.61	85.79	1.66	66.47

Trait	Mean	Range (Min–Max)	GCV (%)	PCV (%)	h² (%)	GA	GAM (%)
NOMS	17.85	12.00–25.00	13.87	15.14	84.01	4.68	26.20
DFF	44.52	34.70–54.30	8.81	9.10	93.80	7.83	17.58
NFA	5.90	2.94–9.50	21.85	23.77	84.51	2.44	41.37
DTEFM	50.38	38.14–58.50	8.42	8.65	94.82	8.51	16.89
FL	11.79	7.65–15.45	12.10	14.18	72.81	2.51	21.26
FW	1.47	0.96–2.00	8.53	14.69	33.69	0.15	10.20
AFW	12.52	8.50–16.05	10.04	11.98	70.21	2.17	17.33
NFPP	15.27	8.22–23.44	22.89	23.91	91.66	6.89	45.15
NSPF	55.87	32.00–82.80	19.15	19.29	98.48	21.87	39.14
100SW	6.20	4.20–8.50	12.42	13.10	89.98	1.50	24.28
SYPPG	21.64	9.42–39.86	29.37	30.14	94.93	12.76	58.94
SYPHQ	14.24	7.00–25.32	27.26	28.22	93.34	7.73	54.26
FYPPG	197.73	80.90–313.30	26.21	26.49	97.89	105.61	53.41
FYPHQ	131.21	57.20–200.70	25.73	25.86	99.04	69.22	52.76

(Source: Based on research findings from my research trial)

PH = Plant Height, NPBPP = Number of Primary Branches per Plant, NOMS = Number of Nodes on Main Stem, DFF = Days to First Flowering, NFA = Number of Fruits per Axil, DTEFM = Days to Edible Fruit Maturity, FL = Fruit Length, FW = Fruit Width, AFW = Average Fruit Weight, NFPP = Number of Fruits per Plant, NSPF = Number of Seeds per Fruit, 100SW = 100 Seed Weight, SYPPG = Seed Yield per Plant (g), SYPHQ = Seed Yield per Hectare (q), FYPPG = Fruit Yield per Plant (g), FYPHQ = Fruit Yield per Hectare (q), GCV = Genotypic Coefficient of Variation, PCV = Phenotypic Coefficient of Variation, h² = Broad Sense Heritability, GA = Genetic Advance, GAM = Genetic Advance as Percent of Mean.

Lines/Testers	**T1**	**T2**	**T3**	**T4**
L1	L1 x T1	L1 x T2	L1 x T3	L1 x T4
L2	L2 x T1	L2 x T2	L2 x T3	L2 x T4
L3	L3 x T1	L3 x T2	L3 x T3	L3 x T4
L4	L4 x T1	L4 x T2	L4 x T3	L4 x T4
L5	L5 x T1	L5 x T2	L5 x T3	L5 x T4
L6	L6 x T1	L6 x T2	L6 x T3	L6 x T4
L7	L7 x T1	L7 x T2	L7 x T3	L7 x T4
L8	L8 x T1	L8 x T2	L8 x T3	L8 x T4
L9	L9 x T1	L9 x T2	L9 x T3	L9 x T4
L10	L10 x T1	L10 x T2	L10 x T3	L10 x T4

Figure 2: *Mating design involving 14 parents (10 Lines and 4 Testers) to identify superior hybrids with high Specific Combining Ability (SCA).*

Figure 3: *Comparative response of susceptible and resistant okra genotypes against Yellow Vein Mosaic Virus (YVMV) under natural field conditions.*
(Source: SVPUAT, Meerut)

2. Pre-Breeding and Crop Wild Relatives (CWRs)

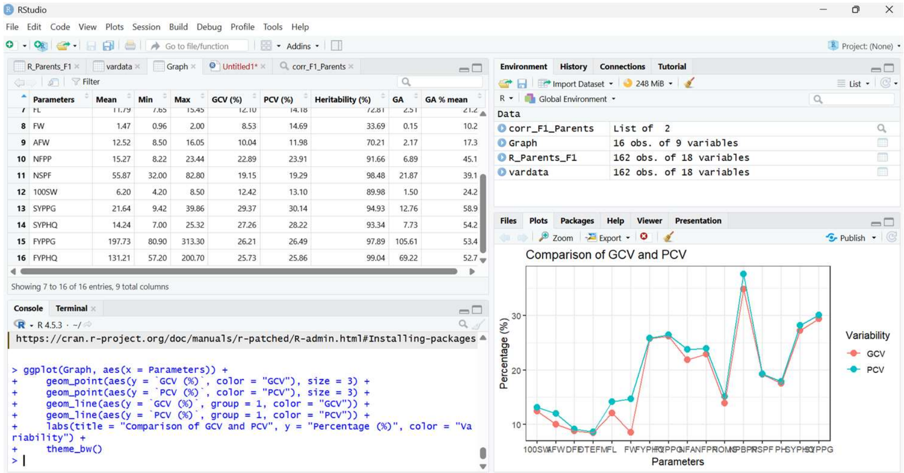
Broadening the genetic base is crucial for long-term resilience. Wild relatives of okra, such as *Abelmoschus tetraphyllus* and *A. ficulneus*, are natural reservoirs of resistance genes against YVMV and drought. Incorporating these genes into the cultivated *A. esculentus* through pre-breeding efforts will create a "Genetic resistance reservoir" for future varieties.

3. Integration of Biotechnology and Marker-Assisted Selection (MAS)

Traditional breeding is time-consuming. To accelerate the development of varieties for 2047, the integration of molecular markers is vital. Marker-Assisted Selection (MAS) allows for the early-stage identification of stress-tolerant genotypes without waiting for natural stress cycles. This precision breeding ensures that only the most resilient lines move forward in the selection pipeline.

4. Digital Phenotyping and Precision Farming

Under the "Digital & Precision Farming" focus area of Viksit Bharat, the use of automated sensors and R-based statistical tools (like RStudio) for data analysis is transforming breeding. High-throughput phenotyping allows breeders to monitor plant response to heat stress in real-time, enabling the selection of genotypes with better water-use efficiency and canopy temperature management.



	Parameters	Mean	Min	Max	GCV (%)	PCV (%)	Heritability (%)	GA	GA % mean
7	FL	11.79	7.65	15.45	12.10	14.18	72.81	2.51	21.2
8	FW	1.47	0.96	2.00	8.53	14.69	33.69	0.15	10.2
9	AFW	12.52	8.50	16.05	10.04	11.98	70.21	2.17	17.3
10	NFPP	15.27	8.22	23.44	22.89	23.91	91.66	6.89	45.1
11	NSPF	55.87	32.00	82.80	19.15	19.29	98.48	21.87	39.1
12	100SW	6.20	4.20	8.50	12.42	13.10	89.98	1.50	24.2
13	SYPPG	21.64	9.42	39.86	29.37	30.14	94.93	12.76	58.9
14	SYPHQ	14.24	7.00	25.32	27.26	28.22	93.34	7.73	54.2
15	FYPPG	197.73	80.90	313.30	26.21	26.49	97.89	105.61	53.4
16	FYPHQ	131.21	57.20	200.70	25.73	25.86	99.04	69.22	52.7

Showing 7 to 16 of 16 entries, 9 total columns

```
Data
corr_F1_Parents   List of  2
Graph             16 obs. of 9 variables
R_Parents_F1      162 obs. of 18 variables
vardata           162 obs. of 18 variables
```

```
https://cran.r-project.org/doc/manuals/r-patched/R-admin.html#Installing-packages

> ggplot(Graph, aes(x = Parameters)) +
+     geom_point(aes(y = `GCV (%)`, color = "GCV"), size = 3) +
+     geom_point(aes(y = `PCV (%)`, color = "PCV"), size = 3) +
+     geom_line(aes(y = `GCV (%)`, group = 1, color = "GCV")) +
+     geom_line(aes(y = `PCV (%)`, group = 1, color = "PCV")) +
+     labs(title = "Comparison of GCV and PCV", y = "Percentage (%)", color = "Va
riability") +
+     theme_bw()
> |
```

Figure 4: *Application of R-based statistical tools for precise genetic evaluation of yield-contributing traits.*

Challenges and Future Opportunities in Okra Research

While the potential for improving okra is vast, several bottlenecks must be addressed to reach the goals of 2047:

- **Genetic Erosion:** Continuous cultivation of a few popular hybrids is leading to a narrow genetic base. For a 'Viksit Bharat,' we must prioritize the conservation and utilization of landraces and indigenous germplasm.
- **The Yield-Stability Trade-off:** Often, high-yielding varieties are more sensitive to environmental fluctuations. Future breeding programs must focus on "Stability Breeding" using multi-environment trials (MET) to ensure consistent performance across diverse agro-climatic zones of India.
- **Viral Evolution:** The rapid mutation of the Yellow Vein Mosaic Virus (YVMV) requires constant vigilance. Developing "Broad-Spectrum Resistance" using advanced techniques like Gene Editing (CRISPR-Cas9) could be a game-changer for the next generation of okra breeders.
- **Seed System Infrastructure:** Innovation in the lab must reach the land. Strengthening the FPO (Farmer Producer Organization) networks to distribute high-quality, climate-resilient seeds is essential to fulfill the "Mission LiFE" objectives.

Policy Interventions and the Way Forward

To translate breeding research into field-level success by 2047, a robust policy framework is essential. The following interventions are recommended:

- **Strengthening Seed Systems:** Government policies should encourage the development of "Seed Hubs" specifically for climate-resilient vegetable crops. This aligns with the 'Viksit Bharat' goal of making India a global seed provider.
- **Support for Agri-Startups:** Promoting startups that focus on digital breeding tools and AI-based disease forecasting can accelerate the adoption of new okra varieties.
- **Incentivizing Mission LiFE:** Farmers adopting climate-resilient varieties and regenerative practices (like using less chemical pesticide due to virus-resistant seeds) should be recognized through carbon credits or green incentives.
- **Capacity Building:** Continuous training of youth and women in modern grafting and seed production techniques will ensure that rural entrepreneurship thrives alongside scientific advancement.

Alignment with Sustainable Development Goals (SDGs)

Our research on climate-resilient okra breeding directly contributes to the United Nations' Sustainable Development Goals (SDGs):

- SDG 2 (Zero Hunger): By developing high-yielding and virus-resistant okra hybrids through Line x Tester analysis, we ensure a stable food supply and enhance the income of smallholder farmers.
- SDG 12 (Responsible Consumption and Production): Climate-smart varieties reduce crop failure risks, leading to more efficient use of agricultural inputs and less wastage in the production cycle.
- SDG 13 (Climate Action): Focus on heat and drought-tolerant genotypes prepares the agricultural sector to adapt to the adverse effects of global warming, ensuring long-term crop resilience.

Mission LiFE: Lifestyle for Environment

This article strongly advocates for the principles of Mission LiFE (Lifestyle for Environment) by promoting a shift towards ecologically conscious agriculture:

- Reduction in Chemical Footprint: The development of YVMV and ELCV resistant seeds significantly reduces the farmer's dependence on chemical pesticides and insecticides. This leads to a healthier ecosystem and cleaner groundwater, fulfilling the "Pro-Planet People" (P3) vision.
- Resource Efficiency: By breeding for high water-use efficiency, we promote a lifestyle of "saving water" at the production level, ensuring that every drop produces more food.
- Sustainable Seed Choice: Encouraging the use of indigenous genetic resources and resilient hybrids empowers farmers to adopt sustainable farming practices that are in harmony with nature.

Conclusion: The Vision for 2047

The transformation of Indian agriculture into a global leader by 2047 hinges on our ability to adapt our crops to a changing climate. Okra, with its immense genetic potential and economic significance, stands at the forefront of this revolution. By integrating robust statistical designs like Line × Tester analysis with modern genomic tools and digital platforms, we can develop "Climate-resilient okra hybrids" varieties that offer high yields, superior nutrition, and climate resilience.

As we move forward, the synergy between research scholars, policymakers, and farmers will be the ultimate catalyst. A climate-resilient okra breeding program is not merely a scientific pursuit; it is a commitment to a hunger-free, prosperous, and developed India.

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REGIONAL ROOTS, GLOBAL RESONANCE: CCS HAU'S IMPACT ON AGROMETEOROLOGICAL RESEARCH

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The discipline of Agricultural Meteorology at Chaudhary Charan Singh Haryana Agricultural University, Hisar, emerged not as a routine academic expansion but as a visionary response to the deep-rooted vulnerabilities of Indian agriculture. Conceived in the early 1970s under the leadership of late Dr SM Virmani, then Chief Scientist of the Dryland Research Program, it marked a transformative shift in thinking. At a time when farming remained largely at the mercy of uncertain monsoons, Dr Virmani challenged the prevailing fatalism surrounding rainfed agriculture. He envisioned weather not as an uncontrollable hazard, but as a resource that could be understood, analyzed and strategically managed. By emphasizing the rigorous interpretation of long-term climatic data, he laid the foundation for a scientific approach to crop planning. This pioneering effort redefined agricultural decision-making, transforming the 'gamble' of monsoon-dependent farming into a more predictable and resilient system grounded in data-driven insights.

The Foundation: Dr SM Virmani's Vision

Dr Virmani's pioneering philosophy was grounded in the belief that weather is a resource to be managed rather than a hazard to be endured. He spearheaded the idea that understanding historical climatic patterns - such as rainfall probability, the onset of the growing season, and thermal indices - was a prerequisite for scientific crop planning. By integrating meteorology with agronomy, CCS HAU began providing farmers with a 'climate-smart' blueprint, shifting the focus from reactive farming to proactive, data-driven management. This paradigm shift was revolutionary, transforming meteorology from a descriptive science into a predictive, decision-support tool for the semi-arid tropics.

Institutional Growth and Global Leadership

As the department matured, its influence rippled far beyond the borders of Haryana. CCS HAU became a cornerstone of Research Project on Agrometeorology providing the intellectual framework for national-level climate-resilient strategies. The university's research didn't just stay in academic journals; it influenced global methodologies. Dr Virmani's subsequent shifting to ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) served as a bridge, exporting the rigorous agrometeorological standards developed at CCS HAU to international dryland research hubs in Africa and Southeast Asia.

Scaling New Heights: The Institutionalization and Expansion of Agricultural Meteorology at CCS HAU

While the seeds of agrometeorology were sown by Dr SM Virmani, the structural evolution of the discipline into a powerhouse of research and education was the result of a second wave of visionary leadership. Dr OP Bishnoi, a close associate of Dr Virmani within the Dryland Research Project, emerged as the torchbearer of this transition. Recognizing that meteorology could no longer remain a subset of dryland studies if it were to address the complexities of modern agriculture, Dr Bishnoi was instrumental in the formal establishment of a dedicated Department of Agricultural Meteorology in the early 1980s at CCS HAU, Hisar.

The Institutional Catalyst: AICRP on Agricultural Meteorology
The department's growth trajectory received its most significant 'fillip' or momentum with the establishment of the Cooperating Centre of the All India Coordinated Research Project on Agricultural Meteorology (AICRPAM). This was a watershed moment; it integrated CCS HAU into a national network of excellence, providing the financial, intellectual, and structural resources required to conduct multi-location, high-impact research.

With the advent of AICRP on Agricultural Meteorology, a new generation of dynamic young scientists, most notably Dr VUM Rao and Dr Diwan Singh joined the fray. These researchers were tasked with a dual mandate: fulfilling the national requirements set by the Indian Council of Agricultural Research (ICAR) while simultaneously addressing the hyper-local, regional specificities of Haryana in both the diverse agro-climatic zones.

Innovations in Research and Extension
Under this new leadership, the research programs moved from purely observational data to sophisticated, applied science. Key areas of focus included:

Micro-climate Modifications: Scientists began to move beyond observation toward intervention, investigating how cropping patterns and irrigation strategies could be deliberately designed to modify the canopy microclimate. By manipulating plant density, crop geometry, and water application, they demonstrated the potential to buffer crops against extremes of frost and heat stress. These efforts marked a shift toward microclimate management as a protective tool, where the field itself became an active regulator of temperature and moisture. In doing so, agrometeorology evolved from a diagnostic science into a practical, adaptive strategy for enhancing crop resilience.

Agromet Advisory Services: In its formative phase in early 1990s, the National Centre for Medium Range Weather Forecasting (NCMRWF) launched Experimental Agromet Advisory Services (EAAS) on a pilot scale across five State Agricultural Universities *viz*., Anand, Hisar, Ludhiana, Pantnagar and Thrissur. Among the earliest contributors, Dr Surender Singh served as the first regular appointee to this pioneering initiative in the country. This carefully designed rollout sought to rigorously evaluate the practical utility of medium-range weather forecasts under real farming conditions. Building on the success of these early efforts, Dr Singh, Dr Rao and their colleagues emerged as key architects in shaping the evolution of agrometeorological advisory services into their present operational form - Gramin Krishi Mausam Seva (GKMS) under the India Meteorological Department. Their work marked a decisive shift from generic weather bulletins to impact-based advisories, empowering farmers not only with forecasts but with clear, actionable guidance on how to respond - thereby transforming weather information into a practical tool for risk management and improved farm decision-making.

Thermal Indices and Crop Phenology: Extensive research on agrometeorological indices *viz*., **Growing Degree Days (GDD) and Photo-Thermal Units (PTU)** enabled a more refined understanding of crop development in relation to heat and light regimes. These thermal indices provided a scientific basis for predicting key phenological stages with greater accuracy. In the wheat–rice belt, such insights proved invaluable for optimizing the timing of harvests and subsequent sowing operations. As a result, farmers could better align their practices with climatic conditions, enhancing both productivity and resource-use efficiency.

Global Contributions and Educational Legacy

The department did not just serve the farmers of Haryana; it became a training ground for the world. The academic rigor introduced by Dr Bishnoi and refined by Dr VUM Rao and Dr Diwan Singh turned CCS HAU into a destination for international scholars. The research methodologies developed here - particularly in water-use efficiency and radiation interception, efficient cropping zones, forecasting aphids on mustard crop based on movement of western disturbances found their way into reputed scientific journals.

The era of Dr Bishnoi, Dr VUM Rao and Dr Diwan Singh marked the transition of agricultural meteorology at CCS HAU from a nascent research interest into a robust, nationally important department. By successfully executing the AICRP on Agrometeorology mandate, they proved that a regional center could lead national and global discourse. Their efforts ensured that the university became a primary node for climate-resilient agriculture, bridging the gap between atmospheric physics and the practicalities of the farmer's field.

Breaking the Glass Ceiling: Global Recognition and the WMO Milestone

The trajectory of a scientific department is often defined by the moments its research transcends national boundaries. For the Department of Agricultural Meteorology at CCS Haryana Agricultural University (CCS HAU), Hisar; this global breakthrough was personified by the accomplishments of Dr Surender Singh, while the department had already established a formidable reputation within India, Dr Singh’s career reflects a gradual transition from regional contributions to a broader international engagement, accompanied by a quiet rethinking of established institutional norms and hierarchies.

A Scholar in Global Demand*:* Impressed by the depth and practical utility of his early contributions—particularly in the realms of teleconnections and regional monsoonal climate, crop-weather interactions/modeling and climate-resilient strategies - the international scientific community sought Dr Singh’s expertise. His work resonated with diverse agro-climatic regions, leading to prestigious invitations as a visiting scholar in countries such as Italy, Brazil, Austria and Switzerland.

In Italy, a hub for European agricultural research; Brazil, a global leader in tropical agriculture & networking of weather based services; in Austria, a nucleus of precision, operational agrometeorology and alpine agriculture; and in Switzerland, a global leader in climate science, GHGs studies and sustainable mountain ecosystems, Dr Singh’s presence served a dual purpose: he exported the robust ‘Lab-to-Land’ methodologies perfected in the fields of province of Haryana while simultaneously absorbing global best practices in operational meteorology and precision farming. These international stints were not merely academic exchanges; they were diplomatic missions for Indian agricultural science, proving that the expertise housed within India’s State Agricultural Universities (SAUs) was of a world-class caliber.

Broadening Institutional Representation: Recognition by the WMO: Perhaps the most significant milestone in Dr Surender Singh*’*s career - and a ‘rare distinction’ for the Indian academic community - was the formal recognition of his accomplishments by the World Meteorological Organization (WMO). Historically, the engagement of the World Meteorological Organization with India has been largely anchored through the India Meteorological Department, the country’s nodal agency for meteorological services. Given its mandate, IMD has played a central and commendable role in representing India in international forums, with relatively limited participation from academic and agricultural institutions. The recognition of Dr Surender Singh by the WMO marks a significant and positive broadening of this engagement. It reflects an evolving global appreciation of agricultural meteorology as a discipline that integrates atmospheric science with field-level applications. This milestone highlights the importance of interdisciplinary approaches, where climate science is closely aligned with crop systems, farmer needs and on-ground realities - an area where institutions like CCS Haryana Agricultural University have made notable contributions. By contributing to global discussions, Dr Singh brought a valuable farmer-centric perspective, enriching the discourse and underscoring the role of applied agrometeorology in advancing climate-resilient agriculture.

A Legacy of Institutional Pride*:* This distinction brought immense prestige to CCS HAU, elevating its status from a premier regional university to a globally recognized center of excellence. It proved that with commitment and rigorous research, a researcher from an SAU could compete with and excel alongside peers from the world's most elite national and international organizations.

For the students and junior faculty at the department, Dr Surender Singh**'**s global journey served as a powerful inspiration. He demonstrated that the ‘roots’ planted in Hisar could indeed ‘reach’ the highest corridors of global science. Today, his legacy remains a cornerstone of the department's identity, representing a period where CCS HAU didn't just follow global standards - it helped set them.

Success through Continuity: The Legacy of Excellence

The trajectory of the Department of Agricultural Meteorology at CCS Haryana Agricultural University (CCS HAU) serves as a master class in institutional building. It underscores a fundamental truth in academia and governance: continuity in leadership creates excellence, while the erosion of leadership can destroy a hard-earned image built over decades. The global presence established by this department was not an accident of history, but the result of a deliberate, multi-generational nurturing of merit and professionalism.

The Chain of Excellence

The department’s success is rooted in a seamless ‘relay race’ of leadership. It began with the foundational vision of Dr SM Virmani, whose foresight in the 1970s identified weather data as the bedrock of rainfed farming. This vision did not wither upon his departure; it was adopted and expanded by Dr OP Bishnoi, who institutionalized the discipline. The momentum was then carried forward by the technical rigor of Dr VUM Rao and Dr Diwan Singh and eventually reached global heights through the scholarly brilliance of Dr Surender Singh.

This chain remained unbroken because each leader viewed themselves as a custodian of a larger mission rather than a temporary occupant of an office. By prioritizing the identification of high-caliber talent - such as persuading an Outstanding Scholar & Dual Gold Medalist like Dr Surender Singh to choose his alma mater over national agencies - the department ensured that the ‘intellectual capital’ remained within its walls.

Professionalism as a Global Currency

The ‘CCS HAU Model in Agrometeorology’ demonstrates that when merit and academic excellence are consistently upheld, a regional State Agricultural University can make significant contributions alongside leading national institutions. The department’s recognition by the World Meteorological Organization—an achievement traditionally associated with national agencies such as the India

Meteorological Department and Indian Institute of Tropical Meteorology - highlights the growing acknowledgment of excellence within academic systems.

This accomplishment conveys a broader message; when professionalism, scientific rigor, and institutional commitment are nurtured over time, they enable institutions to contribute meaningfully at both national and global levels.

A Lesson for the Future

The history of this department offers a profound lesson: institutions, no matter how strong, remain inherently delicate and must be continuously nurtured. The 'good image' of an organization is an invaluable yet intangible asset, sustained not by rhetoric but by consistent ethical leadership and a deep commitment to the science of effective delivery. It is through integrity in action and excellence in execution that credibility is built and preserved.

When leadership is anchored in the H5 principles - Honesty, Health, Hard work, Humility, and Humbleness - excellence ceases to be an aspiration and becomes an enduring institutional culture. Such values create an environment where merit flourishes and collective purpose drives progress. Over time, this culture transforms organizations into centers of trust, innovation, and impact.

Today, CCS Haryana Agricultural University stands as a beacon of this philosophy, illustrating how sustained regional commitment can achieve global relevance. Its journey reaffirms that when roots are strong and values are steadfast, the outcomes can meaningfully contribute to and enrich the global scientific discourse.

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