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INSECT SUPPLEMENTATION: BALANCING NUTRIENT LIMITATIONS IN PLANT-BASED FEED INGREDIENTS

Abstract

Fish farming has increasingly shifted from fertilized pond-based systems to intensive culture practices, where reliance on artificial feed is essential. This transition is particularly challenging in carp-based farming where commercial feed is not cost-effective, and farm-made feeds based on agro-industrial by-products form the primary components of fish diets. The increasing dependence on plant-based feed ingredients has highlighted several nutritional limitations, including low digestibility and deficiencies in essential nutrients. In this context, insect-based ingredients have emerged as a promising alternative due to their high protein content, balanced amino acid composition, and rich supply of lipids and micronutrients. Insects not only complement the nutritional deficiencies of plant-based feeds but also align with the natural feeding behavior of fish, enhancing feed acceptability and utilization. In addition, insect supplementation can reduce feed costs by utilizing locally available organic resources.

Introduction

Modern aquaculture is increasingly driven by artificial feeds application, which plays a central role in determining fish production, and overall farm profitability. In low to medium value fish culture, farmers still largely depend on agro-industrial by-products as feed or feed ingredients, with only limited or irregular inclusion of fishmeal. However, the availability, quality, and affordability of fishmeal remain inconsistent, creating challenges in its inclusion in feed formulation. Although plant-based ingredients are economical and readily available, they are often constrained by poor palatability, lower digestibility, deficiencies in essential nutrients, poor nutrients quantity and quality required for optimal fish growth, physiological processes, and proper tissue development (Daniel, 2018). Feed nutritional limitations reduce efficiency and can adversely affect growth performance and production outcomes, especially intensive culture systems such as recirculating aquaculture systems, and raceways. In contrast, in fertilized pond systems, natural productivity including plankton and insects can partially compensate for these nutritional deficiencies, particularly in carp farming (Manam and Quraishi, 2023). Therefore, there is a growing need to identify alternative, nutrient-rich feed sources that can effectively supplement plant-based diets and address their inherent limitations, thereby supporting more efficient and sustainable aquaculture practices. Various alternatives such as insect, algal and crustacean-based ingredients, animal by-products, and fishery by-products, have been explored; however, factors such as cost, availability, and sustainability influence their practical adoption. Among these, insects emerge as a particularly promising and accessible option due to their nutritional value, ease of production, adaptability, and compatibility with natural fish feeding behavior.

Present Feeding Practices

The use of commercial feed is often limited, depending on the species and culture system. In intensive aquaculture systems, such as tank-based catfish culture, RAS-based trout farming, and shrimp culture, where stocking density is high and natural food requirement is minimal or availability is insufficient to meet nutritional requirements, there is a heavy reliance on commercial feeds (Tacon & Metian, 2015). In contrast, semi-intensive aquaculture systems, farmer depend partly on natural productivity, and partly on supplementary artificial feeds that need not be nutritionally balance, as natural productivity can compensate for certain nutrient limitations. Farmers in such systems rely heavily on farm-made feeds such as wet mixtures, mash, and occasionally simple pellet feeds prepared using locally available ingredients such as oil cakes, bran, de-oiled soybean meal, and maize as the primary components of fish diets (Giri, 2024). The adoption of commercial feeds is frequently constrained by their high cost and uncertain economic returns, making low-cost alternatives more practical for farmers. These ingredients are widely used due to their easy availability, affordability, and familiarity, allowing feed preparation with minimal investment and technical input. Such plant-based feeding practices can support basic fish production, particularly in resource-limited systems, without the need for intensive feeding strategies.

Nutritional Limitations of Plant-Based Feed Ingredients

Plant-based feed ingredients, although widely used due to their affordability and availability, exhibit several nutritional limitations that can compromise fish growth and feed efficiency. The protein quantity of these ingredients is often lower compared to fishmeal or other animal-based ingredients, and the protein quality is also inferior due to imbalanced essential amino acid profiles, with deficiencies not only in lysine and methionine but also in other amino acids such as threonine and tryptophan, which are critical for optimal growth (Macusi *et al.*, 2023). In addition, plant-derived lipids are typically deficient in long-chain polyunsaturated fatty acids, particularly EPA and DHA, which are essential for fish health and development. High fiber content further reduces nutrient digestibility, as many fish species have limited ability to utilize complex carbohydrates efficiently (Daniel, 2018). Mineral availability is also compromised due to the presence of compounds such as phytate, which binds essential minerals and reduces their bioavailability. Moreover, plant ingredients contain various anti-nutritional factors, including tannins, protease inhibitors, and non-starch polysaccharides, which interfere with digestion and nutrient absorption (Ghosh *et al.*, 2018). These combined nutritional constraints lead to reduced feed intake, poor nutrient utilization, and ultimately lower growth performance and feed efficiency in cultured fish.

Insect as a food

Insects constitute a natural component of the diet of many fish species, making them a biologically suitable and highly acceptable feed resource. A wide range of wild and culture-based insect and invertebrate resources have been utilized across different stages of aquaculture, from hatchery and grow-out systems to use as fish bait. These include tubifex worms, bloodworms, earthworms, ant larvae, maggots, termites, silkworm pupae, hornet larvae, black soldier fly larvae, mealworms, etc. (Alfiko *et al.*, 2022) These organisms are rich in protein, lipids, and essential nutrients, and many of them can be raised using organic waste substrates, making them both economical and environmentally sustainable (Nogales-Mérida *et al.*, 2019). The relevance of insect inclusion is further supported by the natural feeding behavior of fish, as many species actively consume insects and benthic invertebrates in their natural habitats.

Nutritional Profile of Insects

Insects are increasingly recognized as a nutrient-dense feed resource, offering a balanced composition of protein, lipids, and essential micronutrients that make them highly suitable for aquafeed supplementation. One of the most notable features of insects is their high crude protein content, which typically ranges from 40 to 60% on a dry matter basis depending on the species and rearing conditions (Nogales-Mérida *et al.*, 2019). In addition to quantity, the quality of protein is also significant, as insect proteins are rich in essential amino acids, including lysine, methionine, threonine, and tryptophan, which are often limiting in plant-based feed ingredients (Alfiko *et al.*, 2022). Insects also contribute valuable lipids, including essential fatty acids that support energy metabolism and physiological functions in fish, although the fatty acid profile may vary among species (Hameed *et al.*, 2022).

Table: Proximate Composition of Common Insects Used in Aquafeed (% Dry Matter Basis)

Insect	Crude Protein (%)	Lipid (%)	Crude Fiber (%)	Carbohydrate (%)	Crude Ash (%)
Tubifex worms	50-60	25-27	4-8	3-18	7-8
Bloodworms	54-55	5-6	1-5	5-8	19-20
Ant larvae	34-57	9-49	2-29	4-14	1-6
Maggots	42-55	20-29	6-7	-	6-6.3
Earthworm	30-63	3.7-5.9	1.1-1.9	9.8-11.8	8.9-43
Termites	35-55	14-50	6-9	5-7	2-3
Silkworm pupae	55-71	20-32	0.5-9	5-28	4-7
Hornet larvae	33-35	11-22	4-12	28-36	2.5-2.8
Black soldier fly larvae	40-50	15-35	6-10	5-10	14-28
Mealworms	45-60	25-43	5-8	5-10	3-4.5

Sources: Herawati *et al.*, 2016; Fernando *et al.*, 2025; Prakash *et al.*, 2024; Tevapawat & Tungpairojwong, 2024; Aniebo & Owen *et al.*, 2010; Khan, 2018; Tassoni *et al.*, 2022; Chakravorty *et al.*, 2016. Pereira *et al.*, 2023.

Furthermore, insects are a good source of micronutrients such as iron, zinc, and vitamins, which play important roles in metabolic processes and immune function. Another important advantage is their relatively high digestibility, as insect meals are generally well utilized by fish, leading to improved nutrient absorption and feed efficiency compared to many plant-based ingredients (Nogales-Mérida *et al.*, 2019).

Role of Insect Supplementation in Plant-Based Diets

Insect supplementation plays a crucial role in improving the nutritional quality and efficiency of plant-based aquafeeds by addressing multiple limitations simultaneously. One of the primary benefits is the correction of the quantity of protein and essential amino acid deficiencies commonly observed in plant ingredients. Insects provide a more balanced amino acid profile, particularly improving levels of lysine, methionine, and other limiting amino acids, thereby supporting better protein synthesis and growth (Luttenschlager *et al.*, 2026). In addition, insect inclusion enhances protein utilization efficiency, due to their favorable amino acid composition and relatively higher digestibility, insect proteins are more efficiently assimilated compared to plant proteins, resulting in improved feed conversion and reduced nutrient wastage (Lee *et al.*, 2022). The presence of functional components such as chitin may also contribute to gut health and immune stimulation, indirectly supporting nutrient utilization (Ragozzino-Paulino *et al.*, 2025). In hatchery systems, insect supplementation may improve feed acceptability and palatability during early larval stages, when acceptance of artificial feeds is often poor, as insects constitute a natural component of the diet of many fish species and can support feed intake and nutrient assimilation. Insects can serve as a viable alternative to fishmeal, as its inclusion in feed formulations is limited by availability and cost, while insect incorporation can balance the plant-based ingredient nutritional limitation and reduce dependency on conventional protein sources.

Constraints and Challenges

Despite the promising potential of insect supplementation in aquafeeds, several constraints and challenges need to be addressed for its wider adoption. One of the primary concerns relates to nutritional variability, as the composition of insects can vary significantly depending on species, developmental stage, and rearing substrate, leading to inconsistency in feed quality (Ragozzino-Paulino *et al*., 2025). In addition, certain components such as chitin, present in the exoskeleton, may limit digestibility when included at higher levels, while variations in lipid composition among insect species may also require careful formulation (Alfiko *et al*., 2022). There are also constraints related to insect body structure and chemical composition, as the presence of indigestible fractions and structural components may reduce nutrient availability if not properly processed (Meyer-Rochow *et al*., 2021). Furthermore, issues related to processing and hygiene are critical, as insects reared on organic waste substrates may carry microbial contamination if adequate processing, drying, or sterilization measures are not followed (Vandeweyer *et al*., 2021). Another major limitation is the lack of standardization in insect production and inclusion levels in aquafeeds. Variations in production methods, nutrient composition, and absence of clear feeding guidelines can hinder consistent application at the farm level. Additionally, there is limited awareness and technical knowledge among farmers regarding insect production, processing, and incorporation into feed formulations. Therefore, effective training programs, extension services, and the development of standardized protocols are essential to promote safe, efficient, and large-scale adoption of insect-based feed strategies in aquaculture.

Economic Benefits

The inclusion of insect-based ingredients in aquafeeds offers significant economic advantages, particularly for small- and medium-scale farmers relying on low-cost feeding systems. One of the primary benefits is the reduction in feed cost, as insects can be produced locally using low-value organic wastes, thereby decreasing dependence on expensive conventional ingredients such as fishmeal and commercial feed inputs. The use of locally available resources for insect production not only minimizes input costs but also enhances resource efficiency by converting waste materials into valuable protein. By partially replacing imported feed ingredients, insect-based feeds can also reduce reliance on external markets and price fluctuations, contributing to more stable and self-reliant aquaculture practices.

Conclusion

The use of insects as a feed ingredient or as a supplement presents a practical and sustainable approach to overcome the nutritional limitations of plant-based feed ingredients commonly used in aquaculture, particularly in regions where fishmeal or other nutritionally rich ingredients are limited. By providing a balanced profile of essential amino acids, lipids, and key micronutrients, insects effectively complement deficiencies associated with conventional plant ingredients such as oilseed cakes and cereal by-products. Their inclusion not only improves protein utilization, feed acceptability, and growth performance but also offers a viable strategy to partially replace fishmeal in low-cost feeding systems. In addition to nutritional benefits, insect-based feeds contribute to economic efficiency by reducing feed costs and promoting the use of locally available resources. However, challenges related to variability in nutrient composition, processing, and lack of standardization need to be addressed through targeted research, capacity building, and extension efforts. Overall, the integration of insect protein into aquafeeds holds strong potential to enhance productivity, sustainability, and resilience in aquaculture, particularly in resource-limited regions.

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EDIBLE VACCINES: WHEN FOOD BECOMES MEDICINE

For centuries, the single noble purpose of agriculture has been to feed people, which sustains life. As global challenges evolve, the role of agriculture is quietly expanding from food to disease protection. Vaccines have always required needles and trips to the doctor's office. But what if your next dose of protection against disease could be part of your breakfast? Scientists around the world are developing edible vaccines that are genetically modified plants that produce disease-fighting antigens you can eat, with remarkable promise.

What are Edible Vaccines?

These represent an innovative approach to immunisation, where scientists use genetic engineering to introduce disease-fighting genes into plants, enabling them to produce antigens in their edible tissue. When you eat these, your body mounts an immune response, just as it would with a traditional injection. Edible vaccines rely on plants as biofactories and delivery systems, eliminating the need for needles, expensive equipment, or refrigeration. Molecular farming leverages the natural biosynthetic capabilities of plants to produce complex biological molecules in a cost-effective, scalable manner. Only specific, non-infectious components are expressed, ensuring safety while maintaining immunogenicity. This technology isn't purely theoretical; a recent breakthrough involves a duckweed-based vaccine that protected chickens against the avian infectious bronchitis virus with 100% efficacy, exceeding some commercial vaccines.

Why Plants?

The advantages are transformative, particularly for developing nations. Compared to conventional vaccine systems, plant-based approaches offer several compelling advantages:

- **Cost-Effectiveness:** Plant-based vaccine production is remarkably inexpensive compared to the regular practices. Plants can be cultivated using existing agricultural systems, significantly reducing production costs.
- **Scalability:** Once the elite line is developed, it can be propagated on a large scale using regular farming practices, making it feasible to produce large quantities of vaccine material without the need for industrial expansion.
- **Reduced dependence on cold chains:** Traditional vaccines require cold-chain storage (maintaining temperature between 2-8ºC). Edible vaccines, when produced in stable plant tissues like seeds or fruits, have the potential to reduce the need for this logistics.
- **Needle-free delivery:** This is an oral route of administration that eliminates the need for injection and dependence on trained healthcare personnel. Highly beneficial for mass immunisation programs and paediatric populations.
- **Cultural compatibility:** These vaccines are embedded in food crops; they can be easily integrated into existing dietary habits, making them more accessible and culturally acceptable.

How do edible vaccines work in the body?

Edible vaccines can simulate mucosal immunity when consumed, as the antigens are delivered to specialised lymphoid tissue in the gastrointestinal tract called GALT (gut-associated lymphoid tissue), which contains both T cells and B cells. This triggers the immune system to produce antibodies that are not limited to the bloodstream but are also present at mucosal surfaces, such as the gut and respiratory tracts, which serve as primary entry points for many pathogens. This dual-layer immune response offers a significant advantage over traditional vaccines. Animals that received oral doses of plant-based vaccines produced neutralising antibodies and were fully protected against infection.

Real Success Stories:

This science has already progressed beyond laboratory experiments, as presented in Table 1:

Year	Plant	Result	Reference
1992	Tobacco	First successful expression of a vaccine against Hepatitis B Surface antigen (HBsAg) that showed similar physical properties as human-derived HBsAg	Manson *et al.*, 1992
1998	Potato	A transgenic plant encoding the *Escherichia coli* heat-labile enterotoxin B subunit (LT-B) induces an immune response to E. coli and is tested in Mice.	Mason *et al.*, 1998
2003	Cherry Tomatillo	Oral immunogenic property of recombinant HBsAg in animal immune tests	Gao *et al.*, 2003
2005	Banana	Vaccine against HBsAg with maximum expression in leaves	Kumar *et al.*, 2005
2005	Alfalfa	Vaccines for major cattle diseases like foot-and-mouth disease virus, Bovine rotavirus, and Bovine viral diarrhoea virus	Dus Santos *et al.*, 2005
2008	Tomato	Expression of the rabies virus nucleoprotein in tomato induced antibodies in mice when orally administered to them	Perea Arango *et al.*, 2008
2010	Tobacco	Expressed mycobacterial antigens fused with elastin-like peptides (ELP), which act as a vaccine against Tuberculosis (Ag85B-ESAT-6)	Floss *et al.*, 2010
2013	Rice	MucoRice-CTB, the first cold-chain-free and unpurified oral vaccine against cholera toxin B subunit (CTB)	Yuki *et al.*, 2013
2013-15	Various plant	Multiple veterinary vaccines mainly for Newcastle disease virus, Rotavirus, Rabbit haemorrhagic disease, Foot-and-mouth, and Bluetongue.	Rybicki *et al.*, 2013; Liew and Bejo, 2015.
2017	Lettuce	Successful production of the HCV E1E2 heterodimer, an important vaccine candidate, using *Agrobacterium*-mediated transfer technology	Clarke *et al.*, 2017
2018	Tobacco	Plant-made E2 glycoprotein single-dose vaccine provided complete protection against Classical Swine Fever in pigs	Laughlin *et al.*, 2019

2020	Duck Weed	Expression of the LamB Vaccine antigen in this plant against fish vibriosis, when orally administered into zebrafish, showed immunisation.	Heenatigala *et al.*, 2020
2021	Plant-based platforms (CoVLP, KBP-201)	Plant-based vaccine candidates in clinical trials with the CoVLP vaccine are showing 10 times more neutralising antibody responses	Maharjan and Choe, 2021
2023	Tomato	The TOMOVAC transgenic line stably synthesises an antigenic S1 protein of SARS-CoV-2. Early evidence of immunogenicity is observed in mice.	Abdurakhmonov *et al.*, 2023
2024	Orange juice (Plant-derived extracellular vesicles-EVs)	mRNA stably packed in plant EVs when orally administered to rats induced IgM, IgG, and mucosal IgA responses	Gai *et al.*, 2024
2025	Duck Weed	100% protection against the avian infectious bronchitis virus (IBV) that exceeded the commercial live attenuated H120 vaccine	Tan *et al.*, 2025

Challenges:

Edible vaccines face several scientific, regulatory, and social challenges that remove it from becoming mainstream. The biggest challenge is ensuring consistent dosing, as variability in plant growth can affect antigen expression level. The stability and bioavailability of the antigen are variable. From a regulatory perspective, edible vaccines present a unique challenge. They do not fit neatly into existing categories of pharmaceuticals or food products, making approval processes complex and time-consuming. Regulatory agencies worldwide are still developing appropriate frameworks to evaluate the safety, efficacy, and environmental impact. Additionally, some antigens are destroyed by stomach acid before reaching the immune system in the gut. Addressing these challenges through advances in biotechnology, regulatory clarity, and effective science communication will be essential for realising the full potential of edible vaccines.

Conclusion:

Edible vaccines may not replace conventional immunisation completely, but they compel us to rethink the relationship between agriculture and medicine. They represent a paradigm shift in how we think about immunisation from no cold chain, no needles to just nutritious and protective foods. It's a science in progress as research accelerates and regulatory frameworks mature; food becomes a shield.

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BETTER FARMING, BETTER INCOME

New Trends for Indian Farmers

Abstract

Agriculture is the backbone of the Indian economy, providing livelihood to a large section of the population. However, traditional farming practices, rising input costs, climate change, and market uncertainties have created challenges for farmers. In this context, adopting new and innovative agricultural trends has become essential for improving farm productivity and increasing farmers' income. This article focuses on recent trends in Indian agriculture that are simple, practical, and beneficial for farmers. The study highlights the importance of modern approaches such as precision farming, use of information and communication technologies (ICTs), organic farming, integrated farming systems, and climate-smart agriculture. These practices help in efficient use of resources like water, fertilizers, and energy, thereby reducing costs and increasing yields. The use of mobile applications, weather forecasting tools, and digital platforms enables farmers to make informed decisions regarding crop management, pest control, and market prices. Furthermore, diversification into allied activities such as dairy, poultry, and horticulture is emphasized as an important strategy for income enhancement. Government initiatives and schemes also play a significant role in promoting these trends and supporting farmers through subsidies, training, and access to markets. The article also stresses the role of agricultural extension services in creating awareness and building farmers' capacity to adopt these innovations.

Keywords: Indian agriculture, modern farming, precision farming etc.

1. Introduction

India is a land of farmers. From the fertile Gangetic plains of Uttar Pradesh to the sun-drenched fields of Punjab, and from the lush delta of Andhra Pradesh to the terraced farms of the North-East, agriculture is not merely an occupation for millions of Indians. It is a way of life, a culture, and the very backbone of our national economy. Yet today, the Indian farmer stands at a crossroads. On one side lies the age-old challenge of low income, unpredictable rainfall, rising input costs, and fragmented landholdings. On the other side, and this is what makes our times truly exciting — lies a revolution. A quiet but powerful transformation powered by technology, innovation, policy reform, and the indomitable spirit of India's farming community. This article, written for agriculture students, practising farmers, and academic professors alike, explores the most significant trends reshaping Indian agriculture in 2025. We examine current data, on-ground practices, government interventions, and futuristic technologies — all with the singular goal of answering one vital question: How can Indian farmers farm better and earn more?

2. Indian Agriculture: The Current Scenario (2025-26)

2.1 Agriculture's Role in the Indian Economy

Agriculture remains a pillar of India's economy, contributing approximately 17–18% of the national GDP in 2025, while employing over 43% of the workforce. The sector's scale is staggering — India is the second-largest producer of farm output in the world, and holds the distinction of having the highest net cropped area globally.

17–18% Agriculture's Share of GDP (2025)	**43%+** Workforce Employed in Farming	**354 MT** Record Foodgrain Output 2024-25	**₹10L Cr+** Agricultural Credit Disbursed

National foodgrain production reached a record 354 million tonnes in 2024-25, representing a remarkable 6.6% increase over the previous year. India's agricultural exports climbed 6.5% year-on-year to USD 37.5 billion for April–December 2024, signalling growing global demand for Indian farm produce. Meanwhile, the agri-tech market is on an explosive trajectory — projected to reach USD 24 billion by 2025, driven by rapid technology adoption across the farming value chain.

3. New Trends Transforming Indian Farming

3.1 Precision Agriculture — Farming Smarter, Not Harder

Precision agriculture is perhaps the most exciting revolution in Indian farming today. Using satellite imagery, drone surveillance, sensor networks, and Artificial Intelligence (AI), farmers can now monitor every square metre of their field — detecting crop stress, measuring soil moisture, and applying fertilisers only where needed. This 'site-specific' approach dramatically reduces input waste while improving yields.

India's smart agriculture market reached Rs. 6,033 crore (USD 714 million) in 2024 and is projected to grow at a CAGR of 20.54% to Rs. 33,325 crore by 2033. The government has allocated Rs. 6,000 crore for digital agriculture infrastructure — funding AI-based crop surveys, drone-enabled nutrient mapping, and app-based credit scoring that enables farmers to access formal loans within just 24 hours.

Key Technologies Driving Precision Agriculture:

- Drones and UAVs for aerial crop monitoring, pesticide spraying, and yield estimation
- Remote Sensing & Satellite Imaging to map soil health and crop conditions across large areas
- IoT-based soil sensors that provide real-time data on moisture, temperature, and pH
- AI-powered advisory apps (e.g., Kisan Suvidha, AgroStar, DeHaat) offering personalised crop advice
- Blockchain for transparent supply chains — from farm gate to market

Chart 1: Growth Drivers in Indian Agri-Tech (Projected Value, Rs. Crore)

Smart Agriculture Market	**Rs.33,325 Cr (2033)**
Agri Exports (2024)	**USD 37.5 B**
Food Processing Exports	**USD 49.4 B**
PM-KISAN Total Transferred	**Rs.3.9 Lakh Cr**
Agricultural Credit (KCC)	**Rs.10 Lakh Cr+**

3.2 Natural and Organic Farming — Back to Basics, Forward to Profits

Across India, a powerful movement is gaining momentum: farmers returning to natural and organic farming methods, inspired by both health consciousness among consumers and the long-term degradation of soil caused by excessive chemical use. Urban consumers are fuelling a projected 25.25% CAGR for certified organic products through 2027 — creating a massive market opportunity for farmers willing to make the switch.

Government initiatives like the National Mission on Natural Farming and the Paramparagat Krishi Vikas Yojana (PKVY) are actively promoting chemical-free cultivation. The Soil Health Card scheme has tested millions of soil samples, revealing nutrient deficiencies and guiding farmers toward balanced, sustainable nutrition management.

Practical Steps for Farmers — Transitioning to Organic:

1. Begin with a small plot (0.5–1 acre) to test organic methods before scaling up
2. Prepare Jeevamrit (fermented manure liquid) and Beejamrit (seed treatment solution) using locally available cow dung and urine
3. Stop chemical fertilisers gradually; replace with compost, vermicompost, and bio-fertilisers
4. Apply neem-based pesticides and Panchagavya as natural pest management
5. Get organic certification through APEDA or state agricultural departments to command premium prices
6. Partner with local FPOs (Farmer Producer Organisations) to collectively market organic produce

3.3 Diversification — Allied Sectors as Income Multipliers

One of the most transformative trends in Indian agriculture is the move beyond traditional crop cultivation into allied sectors. Dairy farming, fisheries, horticulture, apiculture (bee-keeping), mushroom cultivation, and poultry are emerging as powerful income multipliers that stabilise farmer earnings against the volatility of traditional cropping.

4. Government Schemes — The Farmer's Launchpad

The Government of India has introduced a comprehensive ecosystem of welfare schemes and financial instruments designed to protect and empower the farming community. Understanding and accessing these schemes is critical for every farmer and every agricultural professional.

Table 3: Key Government Schemes for Farmers — 2025

Scheme Name	Benefit	Current Status
PM-KISAN Samman Nidhi	₹6,000/year direct income support	₹3.90 Lakh Cr disbursed to 11 Cr+ farmers
Kisan Credit Card (KCC)	Collateral-free farm credit	₹10 Lakh Cr+ to 7.71 Cr farmers; limit raised to ₹5L
PM Fasal Bima Yojana	Crop loss insurance coverage	₹1.83 Lakh Cr claims paid since 2016
PM-KUSUM Scheme	Solar pumps & renewable energy on farms	Expanding solar coverage; ₹460M ADB support
PM Dhan-Dhaanya Krishi Yojana	Targets 100 low-productivity districts	₹35,000 Cr+; benefits ~1.7 Crore farmers
Mission for Aatmanirbharta in Pulses	Boost pulse production & reduce imports	₹11,440 Cr budget; launched Oct 2025
10,000 FPO Mission	Collective marketing & input procurement	Operational; especially helps women farmers
National Natural Farming Mission	Promote chemical-free farming	Bio-inputs support & AI nutrient guidance
Ethanol Blending Programme	Additional income for sugarcane farmers	19.05% blending achieved (July 2025)

5. Best Farming Practices — A Practical Guide

5.1 Soil Health Management

Healthy soil is the foundation of prosperous farming. Declining soil organic carbon across India — flagged by recent ICAR studies — demands urgent attention. Here is what every farmer should practice:

- Get your soil tested at the nearest Soil Health Card centre every 2 years

- Apply compost and vermicompost at 5–10 tonnes per acre to improve organic matter content
- Practise crop rotation — alternate cereals with legumes to restore nitrogen naturally
- Use green manuring crops like dhaincha or sunhemp before the main crop
- Avoid burning crop residue; instead, incorporate it into the soil or convert to compost

5.2 Water-Smart Farming

With over 85% of farmers having limited financial resilience against climate shocks, water conservation is no longer optional — it is survival. Micro-irrigation under the PM Krishi Sinchai Yojana (Per Drop More Crop) has been a game-changer.

- Install drip or sprinkler irrigation — save 30–50% water compared to flood irrigation
- Build farm ponds to harvest rainwater for use during dry spells
- Practise mulching to reduce soil moisture evaporation by up to 40%
- Use soil moisture sensors (now affordable under ₹2,000) to irrigate only when needed
- Explore solar-powered pumps under PM-KUSUM to eliminate electricity dependency

5.3 Crop Diversification Strategies

The risks of relying on a single crop are immense. Diversification into high-value crops and allied sectors provides income security and exponentially higher returns.

- Introduce oilseeds (mustard, sesame, nigerseed) which have received enhanced MSPs for 2024-25
- Grow pulses under the Dalhan Aatmanirbharta Mission to tap into government support
- Integrate horticulture (fruits and vegetables) — these grow at 7.42% CAGR and command better prices
- Start small-scale aquaculture or poultry alongside field crops for steady cash flow
- Explore contract farming with agri-food companies to guarantee market and reduce price risk

5.4 Post-Harvest Management

India loses 20–30% of perishable produce annually due to poor post-harvest practices. Fixing this could add lakhs of rupees to farmer incomes without a single seed being changed.

1. Harvest at the right maturity stage — early or delayed harvest increases losses significantly
2. Use crates instead of gunny bags for fruits and vegetables to prevent bruising
3. Access cold storage facilities through government-supported Agriculture Infrastructure Fund
4. Explore agro-processing — convert raw produce into value-added products (flour, jam, dried goods)
5. Leverage e-NAM (National Agriculture Market) portal to discover better prices across markets

6. Technology as the New Bullock — Digital Farming in 2025-26

From the smartphone in a farmer's pocket to satellites orbiting thousands of kilometres above — technology is now embedded in every layer of Indian agriculture. The government's Rs. 6,000 crore allocation for digital agriculture infrastructure is transforming the landscape at unprecedented speed.

6.1 Artificial Intelligence in Farming

AI-powered tools are assisting Indian farmers in ways that were unimaginable just a decade ago. From disease detection to market price prediction, AI is becoming the farmer's most trusted advisor.

- AI-based crop health apps: Upload a photo of diseased leaves — receive instant diagnosis and remedy
- AI crop surveys replacing manual field counting with drone-enabled automated assessment
- Predictive analytics for market prices, helping farmers decide when and where to sell
- App-based credit scoring enabling formal loans within 24 hours — replacing traditional collateral requirements

6.2 Drones — The Farmer's Eye in the Sky

- Drone-enabled pesticide spraying covers 10 acres in 30 minutes vs. 2 days manually
- Nutrient mapping by drones identifies deficient zones to apply targeted fertiliser
- Regular aerial monitoring detects crop stress 2–3 weeks before it becomes visible to the naked eye
- Government subsidies available under SMAM scheme for agricultural drone purchase

6.3 Digital Market Access

The e-NAM portal has connected farmers to buyers across 1,361 markets in 23 states and 4 Union Territories. Farmers can now upload produce quality photos, receive competitive bids, and sell — all without ever leaving their village. Digital Farmer IDs are streamlining loan disbursement and subsidy delivery, eliminating the red tape that previously robbed farmers of time and money.

Chart 2: Approximate Annual Income Comparison — Traditional vs. New Farming (per acre)

Traditional Wheat/Rice			**~₹25,000/yr**
Horticulture (Tomato)			**~₹80,000/yr**
Organic Vegetables			**~₹1.2 Lakh/yr**
Aquaculture (Fishery)		**~₹2 Lakh/yr**	
Mushroom Cultivation			**~₹1.5 Lakh/yr**
Contract Farming (HVC)			**~₹1 Lakh/yr**

7. Inspiring Success Stories — Farmers Leading the Way

7.1 The FPO Revolution

Farmer Producer Organisations have emerged as perhaps the most powerful institutional reform in Indian agriculture. Across India, 10,000 FPOs have been formed and strengthened, enabling small and marginal farmers to collectively negotiate better input prices, access credit, and market produce at premium rates. Women farmers, who constitute over 30% of India's agricultural workforce, have been particular beneficiaries — gaining formal recognition, access to finance, and decision-making power within these collectives.

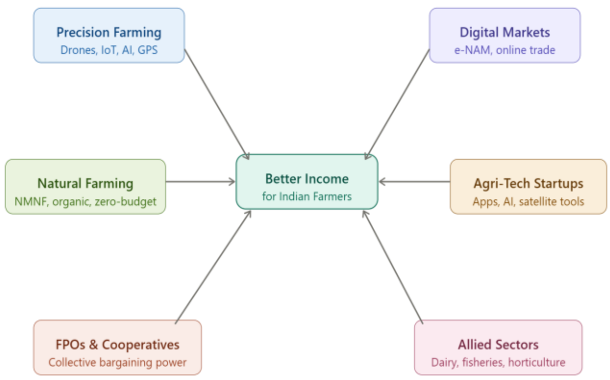
7.2 Solar-Powered Sugarcane Farmers

Through the ethanol blending programme, sugarcane farmers across Maharashtra, UP, and Karnataka are now earning additional income by supplying ethanol to oil companies. The programme reached 19.05% blending levels by July 2025, generating substantial supplementary income for millions of sugarcane growers. Simultaneously, PM-KUSUM solar pumps are eliminating electricity bills and enabling reliable irrigation — effectively giving farmers a dual income from their land: crops and solar energy.

9. The Road Ahead — Agriculture's Golden Decade

India's agriculture sector is projected to reach INR 2,51,993 billion by 2034, growing at an impressive CAGR of 9.68%. The sector's evolution toward data-driven, resource-efficient management systems, supported by private sector investment and FDI — positions Indian agriculture for sustained productivity growth and improved farmer incomes.

The next decade will be defined by several transformative forces. Agri-tech startups — already attracting USD 30–35 billion in investment by 2025 — will bring affordable precision tools to the last-mile farmer. Organic and natural farming will tap into a rapidly growing domestic and export market. Allied sectors will provide income diversification and resilience. And an empowered, educated farming community will leverage digital platforms to command better prices, access better credit, and make better decisions.



11. Conclusion

India's farming story is at its most pivotal juncture in generations. The challenges are real — climate uncertainty, fragmented holdings, market volatility, and soil degradation cast long shadows over millions of farming households. Yet, the opportunities have never been brighter or more accessible.

The convergence of technology, policy support, institutional innovation, and a changing market is creating conditions for a genuine agricultural renaissance. A student of agriculture today must understand not just the science of crops, but the economics of farming, the power of digital tools, and the importance of community organization. A farmer today must be willing to innovate, to diversify, and to demand and access the schemes and infrastructure that rightfully belong to him or her. A professor or researcher must bridge the gap between laboratory discovery and field-level adoption, because knowledge that does not reach the farmer's hand is knowledge wasted. Better farming begins with better information. Better income follows better decisions. And a better India grows from better-supported, better-educated, and better-empowered farmers. The seeds of change have already been sown, it is time to water them well.

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BEEJAMRIT: A NATURAL SEED TREATMENT FOR SUSTAINABLE AGRICULTURE

Introduction

In recent years, farmers across India have increasingly adopted **sustainable and chemical-free farming practices** to protect soil health, human well-being, and the environment. This shift has encouraged a return to **traditional agricultural wisdom**, blended with scientific understanding — a movement commonly referred to as **Natural Farming**.

The concept of natural farming was popularized by **Masanobu Fukuoka**, a Japanese farmer and philosopher, celebrated for his pioneering work in re-vegetating desertified lands. He advocated **no-till, herbicide-free, and pesticide-free cultivation**, creating an approach widely known as "natural farming" or "do-nothing farming."

The **four pillars of natural farming** are:

1. **Beejamrit**
2. **Jivamrit**
3. **Acchadana** (mulching/covering)
4. **Whapasa** (natural moisture management)

This article emphasizes solely on **Beejamrit**, often referred to as the **"life-saving nectar."** Beejamrit acts as a **natural seed tonic**, enhancing seed vitality, disease resistance, and germination, ensuring healthier crop growth. While **seed quality** is primarily determined by genetics, it can be further enhanced through treatments. Beejamrit combines the beneficial properties of **fungicides, insecticides, biopesticides, and plant growth stimulants**, but is completely safe, exerting **no adverse effects on seeds, soil, or the environment**.

What is Beejamrit?

Beejamrit is a **liquid organic formulation** extensively used for seed treatment in **organic and natural farming systems**. The term Beejamrit translates to **"nectar for seeds."**

When applied to seeds prior to sowing, Beejamrit:

- Forms a **protective bio-coating** against fungal and bacterial infections
- Enriches seeds with **vital nutrients**, promoting rapid germination and vigorous early growth
- Provides a **sustainable alternative** to costly chemical seed treatments

Composition and functional role of ingredients in Beejamrit

Beejamrit is **eco-friendly, effective, and economical**, using ingredients that are often sourced directly from the farm.

Table 1: Key ingredients and their functional roles in Beejamrit

Ingredient	Function in Beejamrit
Indigenous Cow dung	Serves as a rich source of essential macro- and micronutrients, while also introducing a robust consortium of beneficial microorganisms that support soil vitality and plant growth.
Indigenous Cow urine	Possesses natural antifungal and antibacterial properties, offering protection against seed-borne pathogens. Additionally, it supplies bioavailable nitrogen and vital minerals that enhance overall plant health.
Lime (Calcium Carbonate)	Used sparingly to moderate the pH of the solution, lime helps neutralize excess acidity and plays a role in suppressing certain soil-borne pathogens.
Soil (from a bund or forest)	A small quantity of soil, preferably from ecologically undisturbed areas such as forest floors or bunds, introduces a diverse and native population of beneficial microorganisms, enriching the microbial composition of the formulation.
Water	Functions as the solvent medium, facilitating the dissolution, activation, and uniform blending of all ingredients to form a cohesive, bioactive liquid solution.

Preparation of Beejamrit formulations for different crop categories

Table 2: Beejamrit solution for 10 kg cereal crop seeds (Wheat, Rice)

Ingredient	Quantity
Water	2 Litre
Indigenous Cow dung	500 g
Indigenous Cow urine	500 ml
Lime (Calcium Carbonate)	A pinch (~5 g)
Soil (from a bund or forest)	A pinch (~5 g)

Table 3: Composition of Beejamrit solution for treating 2 kg of leguminous crop seeds

Ingredient	Quantity
Water	400 ml
Indigenous Cow dung	100 g
Indigenous Cow urine	100 ml
Lime (Calcium Carbonate)	1 g
Soil (from a bund or forest)	1 g`

Table 4: Beejamrit solution for 20 kg seed treatment (Tubers, Rhizomes, and Setts)

Ingredient	Quantity
Water	8 Litre
Indigenous Cow dung	2 kg
Indigenous Cow urine	2 litre
Lime (Calcium Carbonate)	20 g
Soil (from a bund or forest)	20 g`

Preparation procedure for Beejamrit formulation

1. Pour **water** into a clean plastic tub.
2. Gradually add all other ingredients while stirring.
3. Stir the mixture **clockwise for 2–3 minutes** to achieve thorough homogenization.
4. Cover the container with a **jute sack** and allow **fermentation overnight**.
5. The next morning, stir again clockwise for 2–3 minutes.
6. The solution is now ready for **seed or cutting treatment**.

Application method for seed and planting material treatment

Monocot seeds

1. Spread seeds evenly on a clean tarpaulin sheet.
2. Pour **adequate Beejamrit** to moisten all seeds thoroughly.
3. Gently rub seeds with both hands for uniform coating.
4. Allow seeds to **air-dry under shade** for ~1 day.
5. Seeds are now ready for sowing.

Dicot seeds

1. Spread seeds evenly on a clean tarpaulin sheet.
2. Spray Beejamrit uniformly, ensuring seeds are adequately moistened.
3. **Do not rub seeds** with hands; instead, gently **agitate using fingers** in an up-and-down motion.
4. Air-dry seeds in **partial shade**, avoiding direct sunlight.
5. After ~1 day, seeds are ready for sowing.

Tubers, rhizomes, and sugarcane setts

1. Prepare **at least 20 L Beejamrit** for larger seed/tuber volumes.
2. Place seeds/tubers in a **bamboo basket**.
3. Immerse the basket in Beejamrit for **15–20 seconds** for uniform coating.
4. Air-dry in **partial shade** near sunlight.
5. Seeds/tubers are ready for planting.

Fruit cuttings

1. Select **healthy, disease-free cuttings** from fruit plants, grapevine, black pepper, sweet potato, or drumstick (Moringa).
2. Immerse cuttings in Beejamrit for **10–15 seconds**.
3. Air-dry in **partial shade** to remove excess moisture.
4. Plant cuttings for propagation.

Mode of action of Beejamrit

Beejamrit imparts a **biologically active coating** on seeds, providing:

- **Disease Suppression:** Natural barrier against seed- and soil-borne pathogens.
- **Improved Germination Efficiency:** Enhances enzymatic activity, accelerating and uniforming germination.
- **Stronger Root Growth:** Promotes extensive and resilient root systems for optimal nutrient and water uptake.
- **Augmented Plant Immunity:** Activates innate defense mechanisms against pests, diseases, and environmental stress.
- **Stimulation of Beneficial Microbiota:** Supports growth of nitrogen-fixing and phosphate-solubilizing bacteria, improving soil fertility.

Conclusion

Beejamrit exemplifies the integration of **traditional agricultural knowledge** with modern **sustainable farming practices**. It ensures:

- Healthy seed germination and vigorous early plant growth
- Enrichment of soil with beneficial microbes
- Safe, chemical-free cultivation

By replacing costly chemical seed treatments, Beejamrit enables farmers to cultivate **safe, environmentally friendly crops**, promoting **self-reliance, ecological balance, and agricultural regeneration**. Beejamrit is not merely a seed treatment—it is a **symbol of India's return to its agricultural roots** and a vital step toward **sustainable farming**.

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POTENTIAL OF UNDERUTILIZED FRUIT CROPS IN EMPOWERMENT OF TRIBAL WOMEN FARMERS

India possesses a rich diversity of fruit crops, of which several are widely cultivated and commercialized, while many others remain confined to specific regions with limited recognition and market presence. These lesser-known crops, referred to as underutilized horticultural crops, are often abundant, inexpensive, and seasonally available, yet remain underexploited. Despite their low popularity, they are rich sources of vitamins, minerals, antioxidants, and other essential nutrients, and are increasingly recognized as "future fruit crops" due to their nutritional and medicinal importance. However, their limited adoption is attributed to factors such as restricted cultivation areas, lack of awareness regarding their food value, non-availability of quality planting materials, prolonged gestation periods, technological gaps, weak marketing systems, and inadequate processing and value addition. In the context of growing concerns over nutritional security, particularly among rural and economically weaker populations, underutilized fruits offer a viable and sustainable solution. While India has achieved self-sufficiency in food grain production, access to nutritious and balanced diets remains a challenge, especially due to the high cost of commercially cultivated fruits. In contrast, underutilized fruits such as aonla, bael, jamun, karonda, tamarind, custard apple, and others are locally available and affordable, making them highly relevant for improving dietary diversity and nutrition security.

Importantly, these crops also hold significant potential for women empowerment. Rural and tribal women, who are traditionally involved in the collection, processing, and utilization of these fruits, can play a central role in their promotion and commercialization. With appropriate support in terms of skill development, value addition, and market linkages, underutilized fruit crops can serve as a foundation for women-led micro-enterprises, enhancing income generation, livelihood security, and decision-making capacity. Thus, promoting underutilized fruit crops not only contributes to nutritional security but also offers a sustainable pathway for empowering women and strengthening rural livelihoods.

Properties of underutilized fruits:

Custard apple (*Annona squamosa*): Custard apple is an important minor fruit crop of the eastern tropical regions of India, cultivated sporadically across diverse agro-climatic conditions. In recent years, its market potential has increased due to growing recognition of its nutritional value and its use in processed products such as ice cream and beverages. The fruit is a rich source of essential minerals, including calcium, potassium, magnesium, iron, and copper, and is also abundant in vitamins A and C. Owing to its high calorific value and pleasant taste, it is widely appreciated as a nutritious fruit. Custard apple pulp can be utilized as a milk substitute in the preparation of various beverages, enhancing its functional importance. In addition to its nutritional benefits, the crop possesses medicinal properties and is traditionally used in the treatment of ailments such as diarrhoea and dysentery. The bark of the tree is also valued in herbal medicine due to the presence of astringents and tannins, further highlighting its therapeutic significance.

1. **Jackfruit (*Artocarpus heterophyllus*):** It is an important minor fruit crop used in both tender and ripe form. It is cultivated in the backyard homestead garden and in small pockets. It also forms an integral part of agroforestry system. The tender fruits are used as vegetable and have good market potential. It is a rich source of vitamin A, C, riboflavin, niacin, thiamine, and foliate. It also contains important minerals like magnesium, calcium, iron, potassium, phosphorous, copper, zinc, manganese and selenium. Jackfruit is low in sodium, and saturated fats. It is a rich source of dietary fiber and provides almost 11% of the daily fiber requirement. The nutrients found in it have powerful anti-cancer, anti-ageing, anti-ulcerative, and anti-hypersensitivity properties that are valuable in treatment of several diseases. Consumption of jackfruit leaves helps in improving glucose tolerance in diabetes patients. It has powerful laxative properties. The root extracts of jackfruit are effective in controlling asthma.

2. **Jamun (*Syzygium cumini*):** The eastern region of India is rich in the biodiversity of jamun (black plum), a nutritionally important underutilized fruit crop. It is a good source of minerals such as calcium, iron, magnesium, phosphorus, and sodium, along with vitamins like vitamin C, thiamine, riboflavin, niacin, carotene, and folic acid, as well as fiber and protein. Jamun is well known for its medicinal properties, particularly in diabetes management. Studies, including those from the Central Drug Research Institute, Lucknow, have reported that seed extracts and bark decoctions exhibit hypoglycemic effects, helping to reduce blood sugar levels and glycosuria. The presence of jamboline in the seeds aids in regulating the conversion of starch into sugar. Additionally, the fruit supports digestive health due to its cooling and astringent properties and is also beneficial for maintaining healthy skin.

3. **Bael (*Aegle marmelos*)**: Wood apple (bael) is an important minor fruit crop of the eastern region of India. It is a rich source of minerals such as calcium, phosphorus, and iron, along with vitamins A and C, fiber, protein, and bioactive compounds like tannins. The fruit is known for its digestive benefits, acting as an energy booster and natural laxative, and is effective in treating intestinal worms. Various parts of the tree possess medicinal properties. The gum obtained from the trunk and branches is used in the treatment of diarrhoea, dysentery, and diabetes. Leaves, rich in tannins, help reduce inflammation, while roots are used in managing ear ailments. The fruit also supports liver and kidney health. In traditional medicine, different parts of the plant are used for treating snakebites, and in some regions, fruit pulp is applied for protection against infections such as malaria, highlighting its diverse therapeutic potential.

4. **Aonla (*Phyllanthus emblica*)**: Aonla (Indian gooseberry) is a highly nutritious fruit and one of the richest natural sources of vitamin C (500–700 mg/100 g). It holds significant importance in Ayurvedic medicine due to its wide range of therapeutic properties. The presence of tannins such as gallic acid and ellagic acid helps prevent the oxidation of vitamin C, enhancing its stability and efficacy. The fruit exhibits laxative and diuretic properties and is beneficial in managing digestive disorders, jaundice, and cough. It is a key ingredient of the well-

known Ayurvedic formulation *Triphala*. Aonla also possesses antiseptic properties useful in wound healing and is traditionally used in treating snakebites and scorpion stings. Owing to its medicinal value, it is considered effective against various ailments, including respiratory disorders, diabetes, heart diseases, diarrhoea, dysentery, eye disorders, and rheumatism.

5. **Ber (*Zizyphus marutiana*)**: Ber commonly referred to as Indian plum is a well-known economical and medicinal tree. The fruit contains Vitamin B, C, carotene, protein, sugar, minerals, mainly calcium, iron and phosphorus. It improves muscular strength and act as an immune stimulant to increase physical stamina. It has antipyretic, diuretic, expectorant and sedative properties. The pulp of dried fruit is recommended in Ayurveda for treating burning sensation, blood impurities, excessive thirst and anorexia. It is also used to cure rheumatism, vomiting and eye diseases.

6. **Tamarind (*Tamarindus indicus*):** Tamarind is an important minor fruit crop in India, valued for its rich nutritional and medicinal properties. It contains several bioactive compounds such as limonene, geraniol, cinnamic acid, methyl salicylate, and other volatile constituents that contribute to its therapeutic potential. The fruit is also a good source of essential vitamins, including vitamins A, C, thiamine, riboflavin, niacin, and folic acid, along with minerals like potassium, calcium, iron, magnesium, zinc, copper, and selenium. The pulp is rich in non-starch polysaccharides (dietary fiber) such as pectin, mucilage, hemicellulose, and tannins, which impart natural laxative properties and support digestive health. Additionally, the presence of tartaric acid gives tamarind its characteristic sour taste and enhances its antioxidant capacity.

7. **Karonda (*Carissa carandas*):** Karonda is a hardy, evergreen, spiny, and indigenous shrub widely grown in India. Its fruits are a rich source of iron and have long been valued in traditional medicine. Tribal communities, particularly in the Western Ghats, use the fruit to help regulate blood sugar levels and protect against liver disorders. Karonda extracts exhibit strong antimicrobial properties, while the root bark possesses significant anthelmintic activity comparable to albendazole. Additionally, root extracts are known for their effective wound-healing properties, highlighting the plant's diverse therapeutic potential.

8. **Star gooseberry (*Phyllanthus acidus*):** Though star gooseberries do not receive as much attention as aonla but these fruits may still be considered as super fruits for their incredible health benefits. The antioxidants in star gooseberry fruit have a hepatoprotective effect on the liver. The plant extracts provide treatment against cystic fibrosis of the lungs. The leaf extracts exhibit strong anti-microbial, anti-inflammatory, analgesic and antioxidant properties, also reduces blood pressure, thereby suggesting potent hypotensive properties.

9. **Kendu (*Diospyros melanoxylon*)**: Kendu is commonly referred to as Coromandel ebony or East Indian ebony and is native to India and Sri Lanka. The seeds have intoxicating properties and have been prescribed in India as a cure for mental disorders, nervous breakdowns and palpitations of the heart. The fruits have a cooling and an astringent effect. The dried flowers are reportedly useful in urinary, skin and blood diseases. The bark is astringent and used in the treatment of diarrhoea. Recent researches reported the presence of anti-plasmodial properties in *Diospyros.*

Potential of Underutilized fruit crops

S.No.	Fruit crop	Nutritive value	Medicinal properties	Popular Value-added products
1.	Aonla	Vit. C (500–700 mg/100g) anti-oxidative property	Constituent of Triphala Laxative properties	Candy, murabba, juice, pickle, chyawanprash, powder
2.	Star Gooseberry	Vit. C (150-200 mg/100g), anti-oxidative property	Protects liver	Pickle, candy, chutney, salted preserve
3.	Bael	Rich in Vit B, and minerals	Laxative and diuretic effect due to presence of marmelosin (0.2-0.4 per cent)	Squash, sherbet, pulp powder, jam, toffee
4.	Custard apple	Rich in potassium, calcium	Good for hair, eyes and skin.	Pulp, ice cream, frozen pulp, milkshake, desserts
5.	Jackfruit	Vitamin A 110 IU Potassium	Laxative effect (Dietary fibre content1.5 g)	Chips, flour, pickles, ready-to-eat curries, jam, nectar
6.	Karonda	Rich in iron	Antimicrobial properties	Pickle, chutney, jelly, jam, squash
7.	Jamun	Rich source of magnesium anti-oxidative property	Reduces blood sugar level	Squash, juice, vinegar, wine, jam, seed powder
8.	Ber	Rich source of Potassium, calcium, phosphorus	Antipyretic, diuretic and expectorant properties	Candy, dehydrated fruit, pickle, powder, chutney
9.	Tamarind	Rich in potassium, phosphorus, magnesium, calcium	Carminative and laxative Contains health benefiting essential Phytochemicals	Pulp concentrate, candy, chutney, sauce, ready-to-use paste

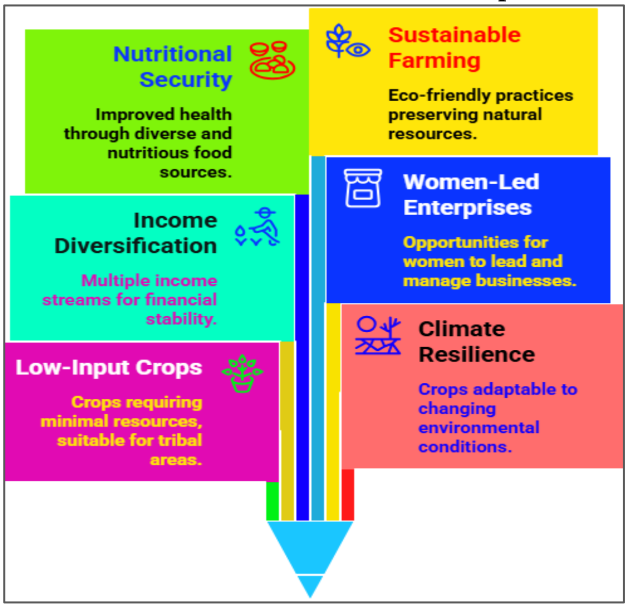
Scope of Underutilized Fruit Crops for Women Empowerment and Livelihood Security

- **Accessible and low-risk enterprise for women farmers:** Underutilized fruit crops such as aonla, ber, tamarind, custard apple, and jackfruit can be grown on marginal and wastelands with minimal inputs. Their hardy nature and adaptability reduce production risks, making them suitable for resource-poor tribal and rural women.
- **Opportunities for women-led nursery and planting material production:** The lack of quality planting material and improved cultivars creates scope for women to engage in nursery raising, vegetative propagation, and distribution of elite planting materials as income-generating activities.
- **Scope for skill development and capacity building:** Training in improved cultivation practices, propagation techniques, and orchard management can enhance women's technical knowledge, enabling them to actively participate in commercial horticulture.
- **Strong potential for value addition and micro-enterprises:** Due to their perishable nature, these fruits offer immense scope for processing into products such as candies, pickles, juices, jams, squashes, powders, and ready-to-eat items. These activities can be efficiently managed by women through Self-Help Groups (SHGs), promoting entrepreneurship.
- **Reduction of post-harvest losses through women-led interventions:** Women can play a crucial role in adopting improved storage, processing, and preservation techniques, thereby reducing losses and increasing the shelf life and market value of fruits.
- **Income generation and livelihood diversification:** Processing, packaging, and marketing of underutilized fruit products provide multiple income streams, reducing dependency on seasonal agriculture and enhancing household economic stability.
- **Enhanced market participation and collective action:** Formation of women-based SHGs,

cooperatives, and Farmer Producer Organizations (FPOs) can strengthen collective marketing, improve bargaining power, and facilitate access to local, national, and niche markets.

- **Promotion of nutrition and household food security:** These fruits are rich in vitamins, minerals, and medicinal compounds. Their cultivation and consumption improve family nutrition, particularly benefiting women and children.

Potential of Underutilized fruit crops



- **Preservation of indigenous knowledge and cultural practices:** Tribal women possess traditional knowledge related to the use, processing, and medicinal properties of these fruits. Promoting these crops helps conserve indigenous knowledge systems while enhancing women's social recognition.
- **Employment generation at local level:** Activities such as cultivation, harvesting, sorting, grading, processing, and marketing create employment opportunities within villages, reducing migration and supporting women's participation in the local economy.
- **Scope for integration with government schemes and institutional support** Programs related to rural livelihoods, horticulture, and tribal development can support women through training, financial assistance, infrastructure, and market linkages.
- **Potential for niche and export markets:** With increasing awareness of the nutritional and therapeutic value of these fruits, there is growing demand in health-conscious and international markets. Women-led enterprises can tap into these opportunities with proper branding and value addition.
- **Contribution to sustainable and climate-resilient livelihoods**: These crops support agroforestry and eco-friendly farming systems, ensuring long-term sustainability while empowering women economically and socially.

Conclusion

Underutilized tropical fruit crops present a promising yet largely untapped pathway for enhancing livelihood security and empowering tribal and rural women. Despite their current neglect due to long gestation periods, lack of improved planting material, and limited market visibility, these crops possess inherent advantages such as adaptability to marginal conditions, low input requirements, and rich nutritional and medicinal value. Their resilience to climatic variability further strengthens their relevance in sustainable farming systems. The real potential of these crops lies in their integration with women-led activities such as nursery development, cultivation, value addition, and small-scale processing enterprises. By reducing post-harvest losses and enhancing shelf life through appropriate technologies, these fruits can be transformed into a wide range of marketable products, thereby generating additional income and employment opportunities at the local level. Collective approaches through Self-Help Groups and farmer organizations can further improve market access and bargaining power for women. Effective extension through field demonstrations, strengthening market linkages, creating consumer awareness about the nutritional benefits of these fruits, and promoting value-added products are essential for the promotion of these crops. Additionally, Policy support and institutional backing will play a crucial role in conserving biodiversity while scaling up their commercial utilization. Strategic promotion of underutilized fruit crops can transform them from neglected resources into drivers of women empowerment, nutritional security, and sustainable rural livelihoods, contributing significantly to inclusive and resilient agricultural development.

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Miyawaki Gardens: A Green Revolution in Urban Landscapes

Introduction

Rapid urbanization, industrial growth and expanding infrastructure have drastically reduced natural green cover across the globe. Cities are increasingly facing environmental challenges such as air pollution, rising temperatures, biodiversity loss and declining soil health. In this context, innovative and sustainable approaches to urban greening are urgently needed. One such transformative solution is the Miyawaki method, developed by renowned Japanese botanist Akira Miyawaki.

The Miyawaki method offers a practical and efficient way to create dense, native forests in small urban spaces. These "mini-forests" not only beautify landscapes but also restore ecological balance, making cities healthier and more resilient.\

Origin and Concept of the Miyawaki Method

The Miyawaki method was pioneered in the 1970s by Akira Miyawaki, who aimed to restore natural vegetation in degraded landscapes. His approach was based on the principle of "potential natural vegetation" (PNV)—the type of vegetation that would naturally grow in a specific region without human interference.

Unlike conventional plantation methods that often rely on monoculture or ornamental species, the Miyawaki technique focuses on planting a diverse mix of native species. This creates a self-sustaining ecosystem that closely resembles a natural forest.

Principles of the Miyawaki Method

The success of Miyawaki forests lies in its scientific principles:

1. Use of Native Species - Only indigenous plant species adapted to local climate and soil conditions are selected. This ensures better survival and ecological compatibility.
2. High density planting - Saplings are planted densely (3–5 plants per square meter), encouraging competition for sunlight and nutrients. This results in faster growth and stronger plants.
3. Multi – layered structure

   The forest is designed with different vegetation layers:
   - Shrubs
   - Sub-trees
   - Trees
   - Canopy species

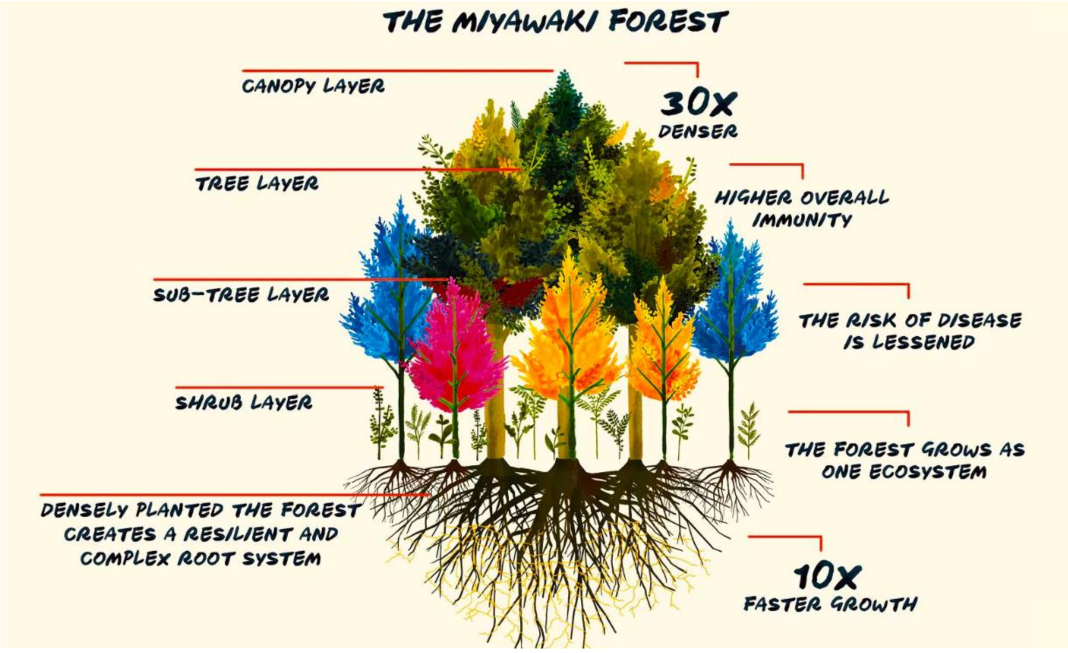
   This layered structure mimics natural forests and enhances biodiversity.
4. Soil enrichment - Soil is improved using organic materials such as compost, rice husk, cocopeat and mulch to enhance fertility, aeration and water retention.
5. Minimal long – term maintenance: After 2–3 years of initial care, the forest becomes self-sustaining, requiring little to no maintenance.

Step-by-Step Process of Creating a Miyawaki Garden:

1. Site Assessment - The first step involves analyzing soil type, water availability and climatic conditions.
2. Soil preparation – The soil is loosened and enriched with organic amendments to create a fertile growing medium.
3. Species selection – A mix of 20–40 native species is selected based on local ecology.
4. Plantation – Saplings are planted randomly and densely to simulate natural growth patterns.
5. Mulching – Organic mulch is applied to retain moisture and suppress weeds.
6. Maintenance – Regular watering and care are provided for the first 2–3 years.

Ecological Benefits of Miyawaki Gardens:

- Miyawaki forests attract birds, butterflies, insects, and microorganisms, thereby restoring ecological diversity.
- These forests help reduce urban heat islands by lowering surrounding temperatures.
- Dense vegetation acts as a natural filter, absorbing pollutants and improving air quality.
- Improved soil structure enhances water retention and groundwater recharge.



- Fast-growing trees absorb carbon dioxide at higher rates, helping mitigate climate change.

Social and economic benefits:

- Transforms barren land into lush green spaces – Urban beautification
- Encourages participation of local communities, schools, and organizations.
- Green spaces reduce stress and improve psychological well-being.
- Although initial costs are high, maintenance costs are minimal after establishment.

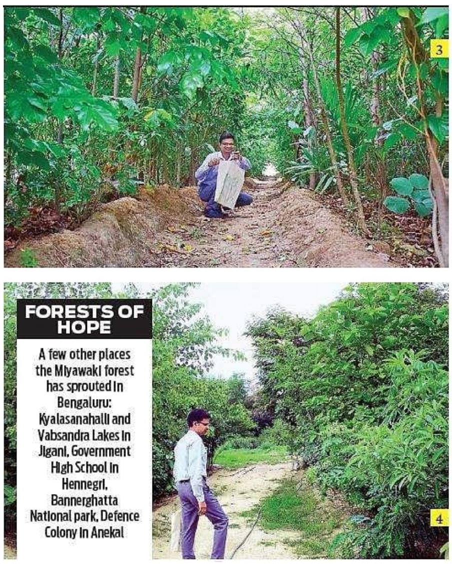
Miyawaki gardens in India:

The Miyawaki method has gained remarkable popularity in India in recent years. Several cities have embraced this technique to combat pollution and enhance urban greenery.

Notable Cities

- Bengaluru
- Hyderabad
- Delhi
- Mumbai

Municipal corporations, NGOs, and citizen groups are actively creating Miyawaki forests in parks, school campuses, and unused land parcels. In cities like Mumbai, small patches of land have been converted into thriving forests, demonstrating the feasibility of this method even in densely populated areas.



Miyawaki miracle in Bengaluru

A dense forest takes root in diesel loco shed premises in Bengaluru

The dense tree cover created on 1,250 square meters of space in the diesel loco shed in Krishnarajarapuram in the last three years is the reason these delightful creatures have opted to stop by. Altogether 4,100 trees find place in this limited space, thanks to the adoption of the unique Japanese style of forestry – Miyawaki. Tree experts swear this afforestation method as the healthiest option to counter the concrete, pollution -packed spaces our cities have transformed themselves into. (From a news clipping of The new Indian express)

Miyawaki Forest – Hyderabad (Kawaguda Urban Forest)

One of India's largest Miyawaki forests (~18 acres). Contains 4.2 lakh plants and 100+ bird species, making it a biodiversity hotspot.

Miyawaki Forest – Warangal (Institutional Campus)

- Example from educational institutions like NIT Warangal.
- Around 2,000 saplings planted to create layered vegetation.

Comparison with Conventional Afforestation

Feature	Miyawaki Method	Traditional Plantation
Growth Rate	Very fast	Moderate
Species Diversity	High	Often low
Maintenance	Low (after 3 years)	Continuous
Space Requirement	Small	Large
Ecological Value	High	Moderate

Future Prospects

The Miyawaki method has immense potential in addressing urban environmental challenges. With increasing awareness and policy support, it can be integrated into:

- Smart city projects
- Urban planning strategies
- School and institutional landscaping
- Corporate social responsibility (CSR) initiatives

Technological tools such as GIS and remote sensing can further enhance planning and monitoring of these forests.

Conclusion

Miyawaki gardens represent a powerful blend of science and sustainability. By recreating natural ecosystems in urban areas, they offer a practical solution to the growing environmental crisis. While they may not replace large natural forests, they serve as vital green lungs within cities. As urban populations continue to rise, adopting innovative approaches like the Miyawaki method can help restore ecological balance and improve quality of life. The success of these mini-forests lies not only in their rapid growth but also in their ability to reconnect people with nature.

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Chia Seed the super food of 21st Century: Nutritional Powerhouse and Functional Ingredient

Abstract

Chia (*Salvia hispanica* L.) is an ancient oilseed historically cultivated and consumed by the Mayan and Aztec populations. It is recognized as a valuable source of omega-3 fatty acids, particularly alpha-linolenic acid, along with soluble and insoluble dietary fibers and proteins. Furthermore, chia seeds are enriched with essential micronutrients, including vitamins, minerals and natural antioxidants. Owing to its nutritional composition, chia is classified as a functional food, contributing not only to basic nutrition but also to enhanced satiety and the prevention of chronic conditions such as cardiovascular diseases, inflammatory disorders, neurological dysfunctions, and diabetes. Presently, chia exhibits considerable potential across multiple sectors, including food, health, pharmaceuticals, animal feed and nutraceutical industries.

Keywords Chia seeds, Functional ingredients, Nutraceutical.

Introduction

Chia seeds are small edible seeds derived from the plant *Salvia hispanica L.*, a member of the Lamiaceae (mint) family, native to Central and South America. Historically, chia seeds were a staple food in ancient civilizations such as the Aztecs and Mayans, valued for their nutritional and medicinal properties. In recent years, chia seeds have gained significant attention as a functional food due to their high nutritional content and potential health benefits. From a nutritional perspective, chia seeds are rich in macronutrients and bioactive compounds. They contain high levels of dietary fiber (23–41%), protein (16–26%) and lipids (20–34%), particularly polyunsaturated fatty acids such as α-linolenic acid (omega-3) and linoleic acid (omega-6). Additionally, they are a good source of vitamins (especially B-complex) and essential minerals like calcium, phosphorus and potassium.

Scientific studies have highlighted that chia seeds possess various functional and therapeutic properties. Their bioactive components, including antioxidants (e.g., quercetin, caffeic acid and chlorogenic acid), contribute to anti-inflammatory, antihypertensive, hypoglycemic and cardioprotective effects. These properties make chia seeds beneficial in the prevention and management of chronic diseases such as diabetes, cardiovascular diseases, and obesity. Moreover, chia seeds are considered a promising ingredient in the development of functional foods due to their unique physicochemical characteristics. When hydrated, they form a gel-like mucilage, which can act as a thickening, stabilizing and emulsifying agent in food products. This characteristic enhances their application in modern food technology and plant-based diets. In summary, the growing scientific interest in chia seeds is attributed to their exceptional nutritional profile, health-promoting properties and versatility in food applications. These attributes position chia seeds as an important component of a balanced diet and a valuable subject of ongoing nutritional and clinical research.

Botanical and Taxonomic Classification

The scientific classification of chia is:

- **Kingdom:** Plantae
- **Subkingdom:** Tracheobionta (vascular plants)
- **Division:** Magnoliophyta (flowering plants)
- **Class:** Magnoliopsida (dicotyledons)
- **Order:** Lamiales
- **Family:** Lamiaceae
- **Genus:** Salvia
- **Species:** Salvia hispanica

Fig1. Chia seeds (optical images) (color figure available online).

Nutritional value of chia seed

Despite their tiny size, chia seeds (*Salvia hispanica L.*) are considered a "superfood" due to their exceptional density of omega-3 fatty acids, dietary fiber and high-quality protein. Below is a detailed breakdown of the nutritional value per 100g of dried chia seeds, based on 2024–2026 nutritional databases and clinical reviews.

1. Macronutrient Profile

Chia seeds are unique because they contain a balanced ratio of all three macronutrients, with a significant emphasis on healthy fats and fiber.

Nutrient	Amount per 100g	Key Note
Calories	486 kcal	High energy density from healthy fats.
Total Fat	30.7 g	~80% is polyunsaturated fat (PUFA).
Protein	16.5 – 17.0 g	Contains all 9 essential amino acids.
Total Carbs	42.1 g	Primarily complex; negligible sugars.
Dietary Fiber	34.4 g	Over 80% is insoluble fiber.
Net Carbs	~7.7 g	Highly keto-friendly due to fiber content.

2. Fatty Acid Composition

Chia is the richest plant-based source of Alpha-Linolenic Acid (ALA), an essential omega-3 fatty acid. Omega-3 (ALA): ~17.8 g per 100g (Approx. 60% of total fat). Omega-6 (Linoleic Acid): ~5.8 g per 100g. Omega-6 to Omega-3 Ratio: ~0.3:1 (Highly anti-inflammatory; most modern diets are 15:1). Saturated Fat: 3.3 g (Very low). Note on Bioavailability: While high in ALA, the human body's conversion of ALA to active EPA and DHA is relatively low (approx. 5–10% for EPA and <1% for DHA).

3. Micronutrients (Vitamins & Minerals)

Key Minerals (% Daily Value per 100g)- Manganese: 2.7 mg (118% DV) – Essential for metabolism and bone health. Phosphorus: 860 mg (123% DV) – Critical for cell repair and ATP production. Magnesium: 335 mg (80% DV) – Supports muscle function and nervous system. Calcium: 631 mg (63% DV) – 5x the calcium found in an equivalent weight of milk. Iron: 7.7 mg (97% DV) – High content, though absorption may be affected by phytates.Copper: 0.9 mg (103% DV) – Vital for iron absorption and heart health. Vitamins- Niacin (B3): 8.8 mg (55% DV). Thiamin (B1): 0.6 mg (52% DV). Folate (B9): 49 µg (12% DV).

4. Bioactive Phytochemicals

Beyond standard vitamins, chia contains potent antioxidants that prevent the seeds' fats from going rancid and provide cellular protection. Chlorogenic Acid: May lower blood pressure. Caffeic Acid: Known for anti-inflammatory effects. Quercetin & Kaempferol: Powerful antioxidants that may reduce the risk of chronic diseases like heart disease and certain cancers.

Uses and application of chia seed

Based on recent research papers (published between 2024 and 2026), the applications of chia seeds (*Salvia hispanica L.*) have expanded from general nutrition into targeted pharmaceutical delivery systems, advanced cosmeceuticals and sustainable industrial materials.

1. Pharmaceutical & Drug Delivery Research

Recent breakthroughs have identified chia mucilage as a "smart material" for medicine. pH-

Responsive Hydrogels: Research published in *Materials Advances* (2025) describes a novel glucoxylan-grafted hydrogel derived from chia mucilage. This material is designed for targeted drug delivery; it remains stable in the stomach's acidic environment but releases medication (specifically tested with *nicorandil* for heart conditions) in the neutral pH of the small intestine. Pharmaceutical Excipient: A 2023–2025 review in *Medical Sciences Forum* highlights the use of chia's sticky gel as a biodegradable binder and disintegrant in tablet formulations, offering a natural alternative to synthetic polymers.

2. Advanced Bioactive Peptides (Cosmeceuticals)

Research is now focusing on the specific molecules produced when chia proteins are broken down. Anti-Aging Enzymes: A major study in *Food Research International* (2025) isolated chia peptides (specifically those < 3 kDa) that inhibit the four primary enzymes responsible for skin aging: elastase, tyrosinase, hyaluronidase, and collagenase. Specific Sequences: Seven unique peptide sequences (e.g., *APHWYTN* and *GDAHWTY*) were identified via molecular docking as potent inhibitors that protect the skin's protein matrix from degradation.

3. Clinical Findings in Metabolic Health

Meta-analyses and randomized controlled trials (RCTs) from 2024–2025 have refined the clinical evidence for chia: Inflammation Biomarkers: A 2024 meta-analysis by *Karimi et al.* confirmed that chia supplementation significantly reduces C-reactive protein (CRP), a key marker of systemic inflammation, by an average of 1.18 mg/L. Hypertension: Recent trials show a significant reduction in systolic blood pressure (mean difference of -3.27 mmHg), though the effect on diastolic pressure is often reported as non-significant. Lipid Metabolism: While chia consistently lowers triglycerides and LDL cholesterol in animal models (by up to 21% and 38%, respectively), human trials in 2025 emphasize its role in increasing HDL-C (good cholesterol) when combined with other fibers like oatmeal.

4. Industrial & Sustainable Agriculture

Bio-Refinery & By-products: Research in the *European Journal of Medicinal Plants* (2025) explores using defatted chia cake (the leftovers from oil pressing) to create protein concentrates and phenolic extracts for fortifying bread and pasta. Sustainable Packaging: Chia gum is being researched as a base for biodegradable films and edible coatings to extend the shelf life of fruits and vegetables. Climate-Resilient Crops: Agronomic research in 2025 highlights chia as a drought-tolerant alternative to alfalfa in arid regions, requiring significantly less water for cultivation.

Conclusion

The review highlights various aspects of chia seeds, including their functional, nutritional, medical and physicochemical properties. Chia seeds hold significant potential as a source of valuable nutrients and nutraceuticals, which are of great interest to fields like medicine, science, technology and engineering. Notably, these gluten-free seeds are rich in antioxidants, dietary fiber and high-quality protein. The review emphasizes the need for further research, particularly focused on the protein content due to its importance in human nutrition, as well as more investigation into mucilage as a source of dietary fiber. The commercial cultivation of this oilseed as an alternative crop could be economically beneficial for both farmers and food formulators, allowing them to take advantage of the functional properties of this intriguing crop, which is both traditional and novel. The bioactive compounds found in chia seeds, along with the limited research on its health benefits, highlight its potential as a nutraceutical.

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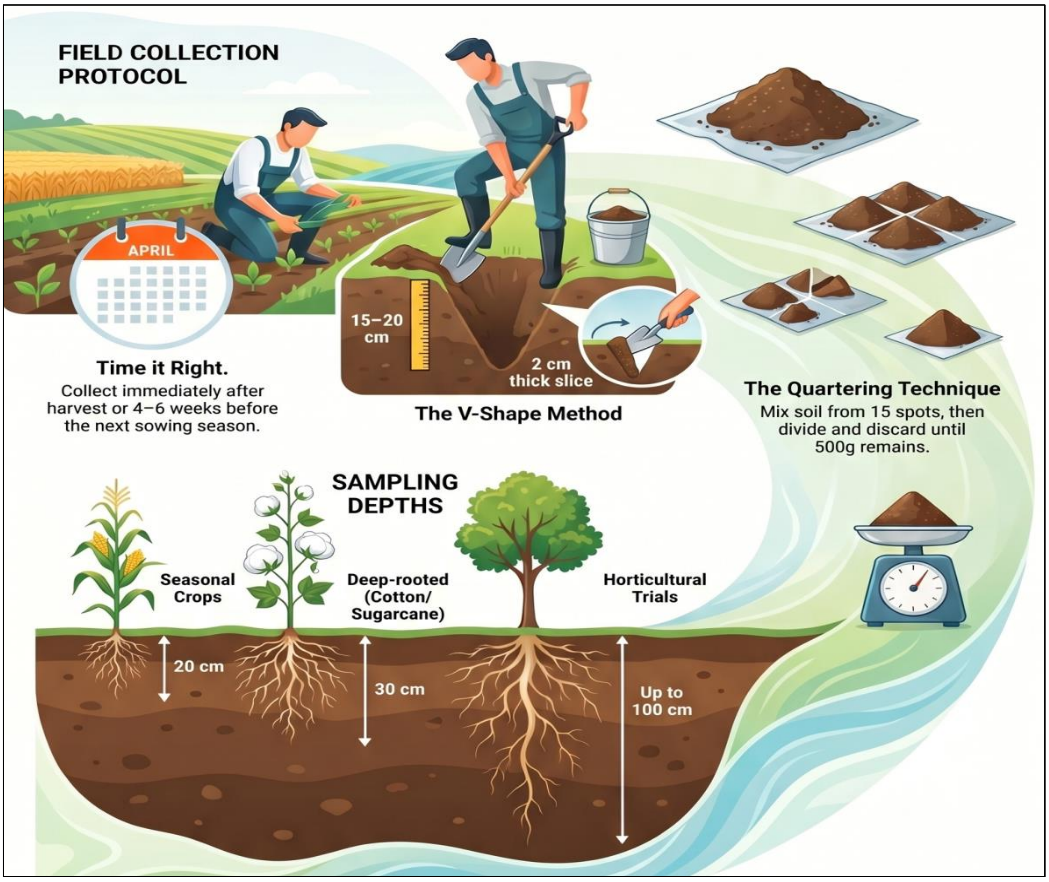
Preserving the Vitality of Our 'Mother Earth'

The Imperative of Scientific Soil Testing

Soil is the fundamental bedrock of our existence, the architect of our prosperity, and the ultimate guarantor of food security for future generations. For a farmer, soil is not merely a medium for plant growth; it is a living, breathing entity often referred to as 'Black Mother' in the Indian agrarian psyche. When we speak of soil, we conjure images of the golden sunrise over tilled ridges, the tireless labor of the *Baliraja* (the farmer king), and the evocative scent of the first rain hitting the parched earth. However, in our quest for immediate high yields, we have often forgotten a crucial question: What is the true physiological state of the soil we rely upon? Modern agriculture often focuses on the external variables high yielding seeds, sophisticated irrigation, and expensive fertilizers while neglecting the health of the womb in which these inputs are placed. Today, with 95% of global food production depending directly on soil, we stand at a critical crossroads where the degradation of this resource threatens our very survival.

A Historical Perspective: From Ancient Wisdom to Modern Science

The sanctity of soil is deeply embedded in our cultural heritage. Long before the advent of modern pedology, Indian civilization recognized soil as a divine maternal figure. The *Bhumi Sukta* of the **Atharvaveda** (circa 1500 BCE), considered the world's first hymn to the earth, poignantly declares: *"Mata Bhumiḥ Putro'ham Prithivyaḥ"*



The Earth is my mother, and I am the son of the Earth. Ancient scholars also attempted scientific classifications. Around 300 BCE, **Kautilya**, in his seminal work *Arthashastra*, categorized land into four functional types: *Urvara* (fertile), *Sthala* (dryland), *Anupa* (marshy), and *Jangala* (desert/fallow). Globally, the Mesopotamians judged fertility through taste and color, while the Egyptians understood the nutrient rich value of the Nile's flood silts an early form of empirical nutrient management. The transition to modern soil science began in 17th century Europe. **John Evelyn** authored *Terra* in 1679, the first English treatise on soil. However, the true "Father of Agricultural Chemistry," **Justus von Liebig** revolutionized the field in 1840 with his **'Law of the Minimum.'** This principle remains the cornerstone of modern fertilizer management, stating that plant growth is dictated not by total resources available, but by the scarcest nutrient. Later, in 1883, **V.V. Dokuchaev** published *Russian Chernozem*, establishing soil science as an independent discipline. In India, the institutional journey began with the establishment of the **IARI** in 1927, followed by the formalization of national soil surveys through **NBSS&LUP** in Nagpur in 1953.

The Anatomy of Soil: A Microscopic Universe

To the untrained eye, soil is just dirt. To a scientist, it is a dynamic, living natural resource. The **Food and Agriculture Organization (FAO)** defines soil as a complex ecosystem where minerals, organic matter, water, and air coexist in a delicate equilibrium. An ideal soil composition comprises:

- **Minerals (45%):** The structural skeleton of the soil, providing essential elements like Calcium, Magnesium, and Potassium.
- **Organic Matter (5%):** The "soul" of the soil. It regulates moisture retention, fuels biological activity, and buffers nutrient supply.
- **Water (25%):** The universal solvent that transports nutrients from the soil matrix to the plant roots.
- **Air (25%):** Essential for root respiration and the survival of aerobic microorganisms.

The biological density of soil is staggering. A single teaspoon of healthy soil contains over a billion bacteria, millions of fungi, and thousands of protozoa and micro arthropods. These organisms are the "silent workers" that decompose organic debris, fix atmospheric nitrogen, and maintain soil porosity, ensuring that rainwater infiltrates rather than runs off.

The Crisis: A Diagnostic Reality Check

Soil testing is effectively a "blood report" for the land. Just as a physician cannot treat a patient without a diagnosis, a farmer cannot manage a farm without knowing the soil's nutrient status. Unfortunately, the current data for Indian agriculture paints a sobering picture:

1. **Declining Fertility:** Approximately 30% of India's land is currently categorized as having 'low fertility' or being in a state of degradation.
2. **The Carbon Crisis:** In Maharashtra, the average **Organic Carbon (OC)** level has plummeted to **0.42%**, significantly below the ideal threshold of **0.75%**. This indicates that our soils are nearly 44% more "exhausted" than they should be.
3. **Micronutrient Deficiencies:** In regions like Vidarbha, nearly 81% of the soil is deficient in **Zinc**, a critical element for crop immunity and yield.
4. **Alkalinity and Salinity:** In the Marathwada region, 65% of the soil has a **pH exceeding 8.0**. This high alkalinity "locks" nutrients, meaning even if a farmer applies expensive fertilizers, the plants cannot absorb them.

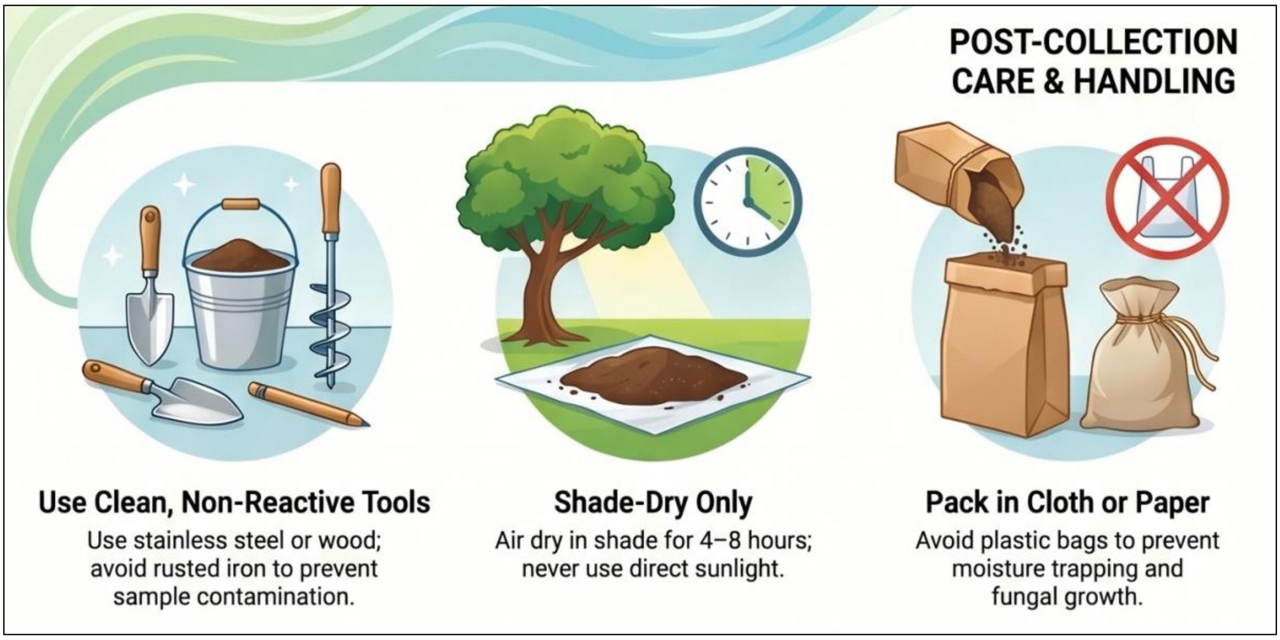
By adopting scientific soil testing, farmers can reduce unnecessary fertilizer expenditures by 30 40% while potentially increasing yields by 15 25%.

The Art and Science of Soil Sampling

The accuracy of a soil test depends entirely on the quality of the sample. If the sampling is flawed, the laboratory results and subsequent fertilizer recommendations will be inherently incorrect.

1. Timing the Collection

The ideal window for sampling is immediately after harvest or 4 to 6 weeks before the next sowing season. In the Indian context, the months of **April and May** are most suitable, as the soil is fallow and results can be processed in time for the Kharif season.



2. The Protocol for Seasonal Crops

- **Demarcation:** Divide the farm into homogenous units. One sample should represent no more than **2 hectares (5 acres)**. If the soil color, slope, or previous cropping history varies, take separate samples.
- **The V Shape Method:** Navigate the field in a zig zag pattern. Clear any surface litter and dig a **'V' shaped hole** to a depth of 15–20 cm. Remove the soil from the hole, then scrape a 2 cm thick slice from the side of the V cut from top to bottom.
- **Depths:** 20 cm for seasonal crops, 30 cm for deep rooted crops like cotton or sugarcane, and up to 100 cm for horticultural trials.

3. The Quartering Technique

Collect soil from 10–15 spots across the field in a clean plastic bucket. Mix thoroughly. Spread the soil on a clean surface in a circle and divide it into four quarters. Discard two opposite quarters and remix the remaining two. Repeat this process until only about **500 grams** of representative soil remains.

4. Post Collection Care

- **Tools:** Use stainless steel augers or wooden scrapers. Avoid rusted iron tools, as they can contaminate the sample with iron, leading to false readings.
- **Drying:** Never dry the sample under direct sunlight, as high UV and heat kill the beneficial microbes. Air dry the sample in the shade on clean paper for 4–8 hours.
- **Packaging:** Use cloth or thick paper bags. Avoid plastic bags, which trap moisture and encourage fungal growth.

5. Documentation

Each bag must contain a label with the farmer's name, survey/gut number, village, sample depth, soil type, previous crop, intended future crop, and the date of collection.

Specialized Sampling for Horticulture

Fruit trees have deeper and more expansive root systems, requiring a different diagnostic approach. For new plantations, soil should be tested at three depths: **0–30 cm, 31–60 cm, and 61–90 cm** to check for sub surface alkalinity or lime (calcium carbonate) layers that could hinder tree growth.

For established orchards, take samples from the **'Canopy Area'** the area shaded by the tree at noon. Dig 12 inches (30 cm) deep at a distance of 2–4 feet from the trunk, as this is the primary zone for nutrient uptake.

What to Avoid: Common Sampling Pitfalls

To ensure the integrity of the sample, do not collect soil from:

- Areas near fertilizer bags or manure pits.
- Within 1 meter of field boundaries or bunds.
- The immediate base of a tree (except for specific horticultural tests).

- Areas near wells, borewells, or water channels.
- Cattle sheds or areas where animals are tied.
- Waterlogged patches or depressions in the field.

Decoding the Soil Health Card

Once the report arrives from the laboratory, focus on these key indicators:

1. **pH (Potential of Hydrogen):** The index of acidity or alkalinity. The ideal range is **6.5 to 7.5**. If the pH is above 8.5, the soil is saline/alkaline and may require **Gypsum**. If it is below 5.5, it is acidic and requires **Liming**.
2. **Organic Carbon (OC):** If OC is above 0.75%, the soil is healthy. To improve this, apply 10–15 tons of Well Decomposed Farm Yard Manure (FYM) per hectare every three years.
3. **Macronutrients (NPK):** * **Nitrogen (N):** Essential for vegetative growth (Target: 250 kg/ha).
   - **Phosphorus (P):** Crucial for root development and flowering (Target: 11 kg/ha).
   - **Potash (K):** Necessary for disease resistance and fruit quality (Target: 150 kg/ha).

Conclusion: A Call to Action

Protecting our soil is not merely an agricultural necessity; it is a moral obligation. By moving away from "guesswork based" farming and embracing scientific soil testing, we transition toward precision agriculture. Let us serve our 'Black Mother' with the respect and scientific rigor she deserves. In her health lies the prosperity of our farmers and the future of a resilient, self reliant India.

"Save the Soil, Save the Future."

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MANAGEMENT OF HEAT STRESS IN DAIRY ANIMALS

ABSTRACT

Heat stress is a condition in which an animal is unable to maintain its normal body temperature because the heat produced within the body and absorbed from the environment exceeds its ability to release it, particularly under hot and humid conditions. This condition adversely affects dairy animals by reducing growth, reproductive efficiency and milk production, particularly in tropical regions. It remains one of the major challenges for the dairy sector, as increasing temperature and humidity during summer negatively impact animal productivity, leading to substantial economic losses. This article provides an overview of the effects of heat stress on dairy animals and highlights key management strategies to reduce the heat stress.

Keywords: Heat stress, Dairy animals, Milk production, Temperature and humidity

INTRODUCTION

In developing countries like India, livestock plays a crucial role in the agricultural sector and contributes significantly to sustainable growth. As per the 20th Livestock census-2019, the total number of cattle and buffalo population in the country is 193.46 and 109.85 million, respectively. According to Basic Animal Husbandry Statistics-2025, India ranks 1st in the world in milk production, with a total milk production of 247.87 million tonnes. The per capita availability of milk in India is 485 gm per day in 2024-25. High temperature along with high humidity and little or no air movement can lead to severe heat stress in animals, adversely affecting their health and productivity. Exposure to high temperature and humidity can reduce milk yield, impair health and cause discomfort in dairy animals. Therefore, proper management of dairy cattle and buffaloes during summer is essential to reduce heat stress and maintain their health, welfare and productivity.

ANIMALS SUSCEPTIBLE TO HEAT STRESS AND INFLUENCING FACTORS

Crossbred and exotic cattle breeds are more susceptible to heat stress, while indigenous (local) breeds are relatively more thermo-tolerant. Buffaloes are particularly vulnerable due to their dark skin, sparse hair coat and a lower number of sweat glands compared to cattle. Skin colour and the length, density and condition of the hair coat greatly influence the absorption of solar radiation. Animals with light-coloured, dense and glossy coat reflect more solar radiation and are therefore less affected by heat stress, whereas those with dark, sparse and coarse hair coats absorb more heat and are more vulnerable.

CAUSES OF HEAT STRESS IN DAIRY ANIMALS

Among the various factors responsible for heat stress, the **combined effect of high temperature and humidity is the most critical**, as it severely limits the animal's ability to lose heat.

The primary cause of heat stress is the **high environmental temperature.** Dairy animals maintain body temperature within a narrow range, but when environmental temperatures rise above the upper critical limit (around 25–27°C for high-producing animals), their ability to lose heat becomes inadequate. As a result, heat accumulates in the body, leading to stress. In tropical regions, where temperatures often exceed 40–45°C, animals are frequently exposed to such conditions. High relative humidity worsens heat stress by reducing evaporative cooling, as moisture-saturated air limits heat loss through sweating and panting.

Direct exposure to solar radiation and poor ventilation significantly increases the heat load on animals. In addition to environmental factors, animals generate internal heat through the fermentation of feed in the rumen or caecum, physical activity and metabolic processes for maintenance, growth and production (pregnancy and milk yield). The amount of heat produced further depends on the animal's size and the quality and quantity of feed consumed by the animals.

EFFECT OF HEAT STRESS IN DAIRY ANIMALS

Continuous exposure of cattle to heat stress leads to an increase in rectal temperature, reduced feed intake, increased water consumption, decreased milk yield, alterations in milk composition (reduced milk fat and Solids Not Fat (SNF) content), reduced growth and even loss of body weight.

Apart from directly affecting animals, heat stress also influences the quality and quantity of feed and fodder available to animals. High temperature and humidity create favourable conditions for the growth and multiplication of parasites and thereby influencing diseases in animals.

METHODS TO REDUCE HEAT STRESS IN DAIRY ANIMALS

Good animal husbandry practices should focus on protecting animals from external heat sources while also reducing internal heat production by providing suitable and balanced feed and fodder.

Housing Management

Housing plays an important role in protecting animals from direct sunlight. Painting the roof top with white colour helps in reflecting the sunlight and keeps the shed cooler. In sheds with asbestos or metal roofs, the roof can be covered with insulating materials such as paddy straw or coconut palm leaves as an alternative method to reduce the heat load on animals. In addition, sprinkling water over the roof using a sprinkler system can further help in lowering the temperature inside the shed.

Dairy animals may be housed during the hottest part of the day in simple thatched, half walled sheds. On extremely hot days, especially in arid and semi-arid regions with hot surface winds, the open sides of the shed can be covered with thatch, bamboo, jute, hessian, or gunny bag curtains. Sprinkling water over these coverings 2–3 times a day further enhances the cooling effect and helps in reducing heat stress. Planting trees, shrubs or creepers and developing grass cover around the sheds can also reduce the unfavourable effects of sunlight on dairy animals. A shady tree is a cheap and good way of providing protection to dairy animals from direct sunlight.

Sheds should be well ventilated to allow free movement of air and the use of fans or water sprinkling can further help in cooling animals. Constructing sheds in an east–west direction helps reduce direct sun exposure during the day. Animals should be provided with enough clean and cool drinking water. Overcrowding of the animals should be avoided.

In addition, regular cleaning, timely removal of dung and maintaining dry floors help reduce parasite breeding sites. Animals should be routinely inspected for ticks and other external parasites and appropriate treatment with acaricides or deworming agents should be carried out as per the advice of the Veterinary Doctor.

Feeding and Nutritional Management

Dairy animals should be allowed for grazing only during the cool hours, such as early morning and late evening, to avoid heat stress. Night time grazing or feeding can also be practiced to improve feed intake and reduce heat load. Provision of good quality green fodder and easily digestible feed helps in reducing the heat produced inside the body during digestion.

Supplementation of mineral mixture and vitamins, supports animals in coping better with heat stress. Anti-stress vitamins such as vitamin C, A, E, and niacin, along with proper feeding practices, helps in maintaining milk production. In addition, ensuring good nutrition improves the animal's immunity, enabling it to better resist parasitic infestations during heat stress.

Special Care for Buffaloes During Summer

Instead of taking the buffaloes to ponds for wallowing, a more efficient alternative is to cool buffaloes within the shed by splashing water on them 3–4 times a day for short durations during the peak heat period (11 a.m. to 3 p.m.). On larger dairy farms, simple shower systems can be installed along the roof and operated during the afternoon hours. In summer, buffaloes usually show oestrus (heat) during cooler night hours and the signs are shorter and less pronounced. Careful heat detection and breeding during night time can help achieve good conception even in summer.

CONCLUSION

Simple and practical measures such as improving housing conditions, providing shade and cooling, ensuring adequate supply of clean and cool drinking water, adopting suitable feeding strategies can greatly help animals cope with higher temperatures. Greater importance should be given to selecting the breeds that can tolerate higher temperatures. By adopting these practices, the farmers can maintain animal comfort, sustain milk production and improve overall farm profitability even under hot climatic conditions.

The information presented is compiled from standard textbooks and recent scientific studies on animal husbandry.

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ARTICLE ID: 10

Rising Agricultural NPAs and Unequal Credit Governance in India: A Growing Agrarian Concern

Abstract

India's credit system is witnessing a shift in financial distress from corporate borrowers to the agricultural sector, raising concerns about equity in credit governance. Despite improvements in overall asset quality, gross non-performing assets (NPAs) in agriculture increased from ₹1.31 lakh crore in 2023-24 to ₹1.43 lakh crore in 2024-25, with the sector's share in total NPAs rising from 28.7% to 34.1%. At the same time, agricultural indebtedness continues to deepen, with states such as Punjab and Haryana reporting outstanding farm loans of ₹97,471 crore and ₹60,816 crore respectively. Under the Kisan Credit Card scheme, while loan accounts declined from 3.07 crore in FY2021 to 2.98 crore in FY2024, NPAs rose sharply by over 42%, indicating worsening repayment capacity. In contrast, loan write-off patterns reveal a structural imbalance: between FY2020 and FY2024, banks wrote off ₹4.38 lakh crore in industrial loans compared to only ₹0.86 lakh crore in agriculture, with corporate borrowers accounting for nearly 85.5% of total write-offs since 2014. The article argues that rising agricultural NPAs are rooted in unstable farm incomes, inadequate price realisation, only about 12% of farmers receive MSP and declining public investment. It calls for a shift from a narrow banking approach to a broader policy framework focused on income stability, risk mitigation, and institutional debt relief, including the need for a national-level mechanism to address agrarian distress.

Introduction

India's credit system reveals a persistent imbalance in how financial distress is managed across sectors. While non-performing assets (NPAs) in industry and services have declined in recent years, stress in agriculture has intensified, exposing structural vulnerabilities in a sector that supports over half the country's population. This divergence raises critical concerns about the equity and priorities of financial governance.

The expansion of institutional credit has improved access to finance for farmers, but it has also increased their exposure to risk in the absence of stable incomes, remunerative prices, and effective safeguards. Rising agricultural NPAs and deepening indebtedness indicate that financial stress is increasingly concentrated among small and marginal farmers rather than large corporate borrowers. At the same time, loan write-off patterns highlight a stark asymmetry. Corporate borrowers account for the majority of write-offs, while farmers despite their greater vulnerability face stricter recovery processes and limited relief. This contrast points to a systemic imbalance in the treatment of financial distress.

This article examines the growing burden of agricultural debt, the rising share of NPAs in the sector, and the institutional responses to agrarian distress. It argues for a shift from a narrow banking approach to a broader policy framework centred on income stability, public investment, and equitable credit practices.

Changing patterns of NPA's in Indian Agriculture

Punjab is one of the most indebted agricultural states in India, with a large proportion of farm households dependent on borrowed credit. As of September 2025, farmers in Punjab have about ₹97,471 crore in outstanding institutional agricultural loans distributed across 25.23 lakh loan accounts. Haryana, another major agricultural state in northern India, also shows a significant level of farmer indebtedness. Over 25.67 lakh farmers in Haryana collectively owed about ₹60,816 crore in agricultural loans by September 2025.

While NPAs have declined in almost all sectors over the years, but the agriculture sector shows a different trend. The gross NPAs in agriculture increased from ₹1.31 lakh crore in 2023-24 to ₹1.43 lakh crore in 2024-25[1]. As a result, the share of agriculture in total bank NPAs rose from 28.7% to 34.1% during the same period. This indicates that financial distress in agriculture is increasing as compared other sectors of Indian economy. The key point during these years is that only 12% of the farmers received the MSP for selling their produce, rest all sold their produce below MSP.

Corporate Write-offs vs Agricultural Distress: A Structural Imbalance

Loan write-off data also highlights interesting patterns in India's credit system. Rs 1.09 lakh crore of loans were written off for large industries and services in FY 2023, while ₹0.70 lakh crore were written off in FY 2022[2]. Between FY 2020 and FY 2024, scheduled commercial banks wrote off Rs 4.38 lakh crore of industrial loans compared to Rs 0.86 lakh crore of agricultural loans. Over a longer period from 2014 to September 2025, corporate and industrial loans accounted for about 85.5% of total loan write-offs, while agriculture accounted for about 14.5% despite the fact that agriculture is the backbone of our country and most of the population of India is directly and indirectly involved in agriculture. The people involved in agriculture should be the priority for the governments owing to their lower incomes and small amounts of loans.

Although corporate loan write-offs are much larger in absolute terms due to the bigger size of corporate loans, agricultural borrowers are more numerous and financially vulnerable. Farmers generally depend on seasonal crop income to repay loans. When crops fail or prices collapse, their ability to repay becomes severely affected, leading to rising indebtedness and NPAs. The agriculture sector involves above 50% of the population, thus waiving off loans of the distressed farmers is to be prioritised for the well-being of the country.

Credit Expansion and Growing Default Risks

Evidence of financial stress in agriculture sector is also visible in specific credit schemes. Under the Kisan Credit Card (KCC) scheme, the number of farmer loan accounts declined from 3.07 crore in FY 2021 to 2.98 crore in FY 2024[3]. However, the outstanding amount in NPA accounts increased sharply from ₹68,547 crore in FY 2021 to ₹97,543 crore by December 2025, representing a 42.3% increase within four years.

Agricultural credit in India is expected to grow significantly, with total lending to the sector projected to exceed ₹31.5 lakh crore in FY2026, representing about a 9% increase from the previous year[4]. Banks and financial institutions disbursed around ₹28.98 lakh crore in FY2025 through commercial banks, cooperative banks, and regional rural banks. Nearly 60% of this credit is used for short-term crop loans, while the remaining portion supports long-term agricultural investments such as irrigation, machinery, and allied activities. The rise in agricultural credit reflects increasing formalisation of rural lending and efforts to expand institutional finance in the farm sector, although authorities are also working to reduce regional imbalances in credit distribution across states.

At the same time, the agriculture sector is increasingly availing institutional credit. Agricultural borrowings from banks increased from ₹17.26 lakh crore in March 2023 to ₹20.71 lakh crore in March 2024, and further

[1] Trend and Progress of Banking in India (2024-25)
[2] https://indianexpress.com/article/business/banking-and-finance/over-half-of-fy23-bank-loan-write-offs-linked-to-large-industries-services-sector-9054593
[3] Farm lending: Kisan Credit Card bad loans rise by 42% in four years | Express Investigations News - The Indian Express
[4] https://www.financialexpress.com/policy/economy/agri-credit-may-rise-9/3843649

to ₹24.03 lakh crore in March 2025[1]. This shows the growing need for credit to finance crop production, farm inputs, and investments. The annual growth of credit in agriculture during this period was about 15.2%, which is significantly higher than the 8.8% credit growth in the industrial sector. While access to credit is important for agricultural development, it also increases the risk of loan defaults when farmers face crop losses or price shocks.

The issue of agricultural NPAs is also visible at the state level. For example, in Maharashtra, banks reported farm loan NPAs of about ₹35,477 crore as of June 2025[5]. The total agricultural credit in the state was ₹2.78 lakh crore across 1.33 crore farmer accounts, and around 12.75% of these loans had turned into NPAs. Public sector banks accounted for the largest share of these bad loans, with over ₹20,000 crore, followed by cooperative banks with about ₹9,527 crore. Another factor influencing agricultural indebtedness is the decline in public investment in agriculture. The share of public expenditure on agriculture in total government spending declined from about 11% in 2010-11 to around 9.5% in 2019-20[6]. During the same period, agriculture's share in the country's Gross Value Added (GVA) declined only slightly from 18.2% to 17.8%. This means that government spending on agriculture has declined faster than the sector's economic importance. Thus, the 90% of the agricultural investments are made by farmers themselves.

Public investment has historically played an important role in improving irrigation, agricultural research, technology, and rural infrastructure. However, since the 1980s, public investment in agriculture has been gradually declining, and farmers increasingly depend on private investment and borrowed credit to sustain production. As farmers rely more on loans for seeds, fertilizers, irrigation, and machinery, their financial risk increases. When crop failures or market fluctuations occur, repayment becomes difficult and loans may turn into NPAs.

Rising Farm Indebtedness and Regional Disparities

Punjab is one of the most indebted agricultural states in India, with a large proportion of farm households dependent on borrowed credit. As of September 2025, farmers in Punjab have about ₹97,471 crore in outstanding institutional agricultural loans distributed across 25.23 lakh loan accounts.[7] Haryana, another major agricultural state in northern India, also shows a significant level of farmer indebtedness. Over 25.67 lakh farmers in Haryana collectively owed about ₹60,816 crore in agricultural loans by September 2025[8].

Institutional Responses to Agrarian Debt

In Kerala, the government established the Kerala Farmers' Debt Relief Commission to address the growing problem of farm indebtedness. The commission has received about 6.28 lakh applications for debt relief, out of which 5.30 lakh cases have been processed[9]. It has recommended debt relief worth about ₹565 crore, with eligible farmers receiving relief of up to ₹2 lakh on their loans. Surveys indicate that nearly 72% of farmers in Kerala are indebted, with an average debt of about ₹5.46 lakh per farmer.

The existence of such institutions highlights the seriousness of agrarian distress. Debt relief mechanisms help protect farmers from legal recovery proceedings and reduce the burden of unpaid loans. At the same time, they also indicate the need for broader reforms in agricultural policy. Reducing NPAs in agriculture therefore requires more than just better banking practices. It also requires stable farm incomes, effective crop insurance, improved market access, climate-resilient agriculture, and better risk-management mechanisms. In addition to state-level initiatives such as the Kerala Farmers' Debt Relief Commission, there is also a growing need for

[5] https://timesofindia.indiatimes.com/city/nagpur/maha-banks-have-over-rs35000cr-farm-loan-non-performing-assets/articleshow/125002458.cms

[6] *Public Spending on Agriculture in India (2010-11 to 2019-20)*

[7] https://timesofindia.indiatimes.com/city/chandigarh/institutional-farm-loans-punjab-haryana-farmers-owe-over-rs-2-lakh-crore/articleshow/126016106.cms

[8] https://timesofindia.indiatimes.com/city/chandigarh/25-71-farmers-in-haryana-burdened-with-rs-60-8k-crore-in-debt-cm-saini/articleshow/126064393.cms

[9] https://www.onmanorama.com/news/kerala/2022/10/10/rise-in-farmers-debt-reveals-kifa-sample-survey.html

establishing a "National Debt Relief Commission" to support heavily indebted farmers across the country.
Although agriculture currently has a large share of NPAs, this was not always the case over last years. In 2015, agriculture accounted for about 10.5% of total NPAs, while industry accounted for 51.1% and services for 30.3%[10]. Over time, the pattern has changed. The banking sector has largely resolved corporate loan stress, but distress is now more widely spread among farmers and small borrowers.

Conclusion

The evidence presented in this article highlights a clear shift in the geography of financial distress within India's banking system - from large corporate borrowers to small and marginal farmers. While policy and institutional mechanisms have been effectively mobilised to resolve corporate NPAs, similar urgency and flexibility have not been extended to the agricultural sector. As a result, rising farm indebtedness and increasing NPAs are not merely outcomes of credit expansion, but symptoms of deeper structural weaknesses, including unstable farm incomes, inadequate price realisation, and declining public investment.

The contrast between corporate loan write-offs and the treatment of agricultural borrowers underscores a systemic imbalance in credit governance. Farmers, despite being more numerous and economically vulnerable, continue to face rigid recovery processes with limited access to structured relief. This asymmetry raises important questions about fairness, policy priorities, and the broader objectives of financial inclusion. Addressing agricultural NPAs, therefore, requires a shift from a narrow banking perspective to a more comprehensive policy approach. Strengthening income support mechanisms, ensuring effective implementation of remunerative pricing, expanding crop insurance, and revitalising public investment in agriculture are critical to reducing farmers' dependence on debt. At the institutional level, there is a strong case for establishing a national framework for debt relief to complement state-level initiatives and provide timely support to distressed farmers. Ultimately, resolving the agrarian credit crisis is not only a matter of financial stability but also of social and economic justice. A more balanced and inclusive credit system is essential to sustain rural livelihoods, restore confidence in institutional finance, and ensure that the burden of economic adjustment is not disproportionately borne by those least equipped to bear it.

[10] Financial Stability Report 2025 By RBI

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Carbon Sequestration in Vegetable Cropping Systems for Sustainable Soil Health

Abstract

Soil health degradation is a critical challenge in intensive vegetable cropping systems due to frequent tillage, continuous cultivation, and low organic matter return, leading to a decline in soil organic carbon (SOC). Carbon sequestration provides an effective strategy to restore soil health by capturing atmospheric carbon dioxide (CO_2) and storing it in soil as stable organic carbon. Vegetable cropping systems, despite their short duration, have considerable potential for carbon accumulation due to rapid biomass production and high cropping intensity. Carbon enters the soil through crop residues, root biomass, and root exudates and is subsequently transformed by soil microorganisms into stable carbon pools. The extent of sequestration is strongly influenced by management practices, including organic amendments, residue incorporation, crop rotation, cover cropping, and reduced tillage. Crop-specific strategies and microbial processes further enhance carbon stabilization. Increased SOC improves soil physical, chemical, and biological properties, thereby enhancing soil fertility and resilience. Therefore, adopting carbon-oriented management practices in vegetable cropping systems is essential for sustainable soil health regeneration and long-term agricultural productivity.

Keywords: Carbon sequestration, Soil organic carbon, Soil health, Sustainable agriculture, Vegetable cropping systems.

1. Introduction:

Soil health is a fundamental determinant of agricultural productivity and sustainability, regulating key processes such as nutrient cycling, water retention, and biological activity (Lal, 2015; Ray et al., 2025).

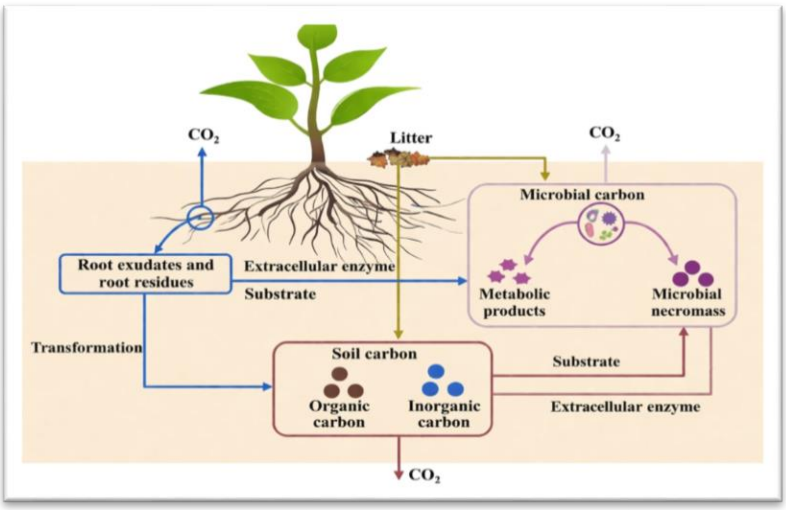

***Figure 1**. Conceptual diagram of soil carbon sequestration showing the transfer of atmospheric CO_2 into plant biomass and its transformation into stable soil organic carbon through microbial processes.*

In vegetable cropping systems, intensive management practices, including frequent tillage, continuous cropping, and high external input use have contributed to a progressive decline in soil quality (Lal, 2015). One of the primary indicators of this degradation is the reduction in soil organic carbon (SOC) (Batjes, 1996; Lal, 2004). Soil organic carbon plays a crucial role in maintaining soil structure, improving aggregation and porosity, and acting as a reservoir of essential nutrients (Six et al., 2002; Bationo et al., 2007). It also supports soil microbial activity responsible for organic matter decomposition and nutrient transformation (Six et al., 2002). A decline in SOC leads to poor soil structure, reduced fertility, and diminished biological activity, ultimately affecting crop productivity (Lal, 2015).

Carbon sequestration refers to the process of capturing atmospheric carbon dioxide (CO_2) through plant photosynthesis and storing it in plant biomass and soil organic matter (Lal, 2004; Paustian et al., 2016). In vegetable cropping systems, carbon is introduced into the soil through plant residues, root biomass, and root exudates. These carbon inputs are processed by soil microorganisms and transformed into stable soil carbon fractions, contributing to long-term soil fertility (Six et al., 2002).

The transfer of plant-derived carbon into soil organic carbon involves interactions among plant inputs, microbes, and soil properties. A portion of carbon is stabilized in soil aggregates and mineral-associated forms (Six et al., 2002). This enhances its persistence and improves soil structure, nutrient availability, and overall soil function.

The potential of vegetable cropping systems for carbon sequestration depends largely on management practices. Intensive tillage and residue removal accelerate carbon loss, whereas practices such as organic amendments, residue incorporation, crop rotation, cover cropping, and reduced tillage enhance carbon input and stabilization in soil (Smith, 2004; Meena et al., 2019). These practices improve soil physical, chemical, and biological properties and support soil health regeneration (Lal, 2015; Ray et al., 2025).

Vegetable cropping systems, therefore, offer significant opportunities for restoring degraded soils when managed sustainably. Enhancing soil organic carbon through carbon sequestration is essential for improving soil health, increasing productivity, and ensuring long-term agricultural sustainability (Lal, 2004; Paustian et al., 2016).

2. Mechanism of Carbon Sequestration in Vegetable Cropping Systems

Carbon sequestration in vegetable cropping systems involves the transformation and stabilization of plant-derived carbon within the soil (Lal, 2004; Paustian et al., 2016). The process begins with the assimilation of

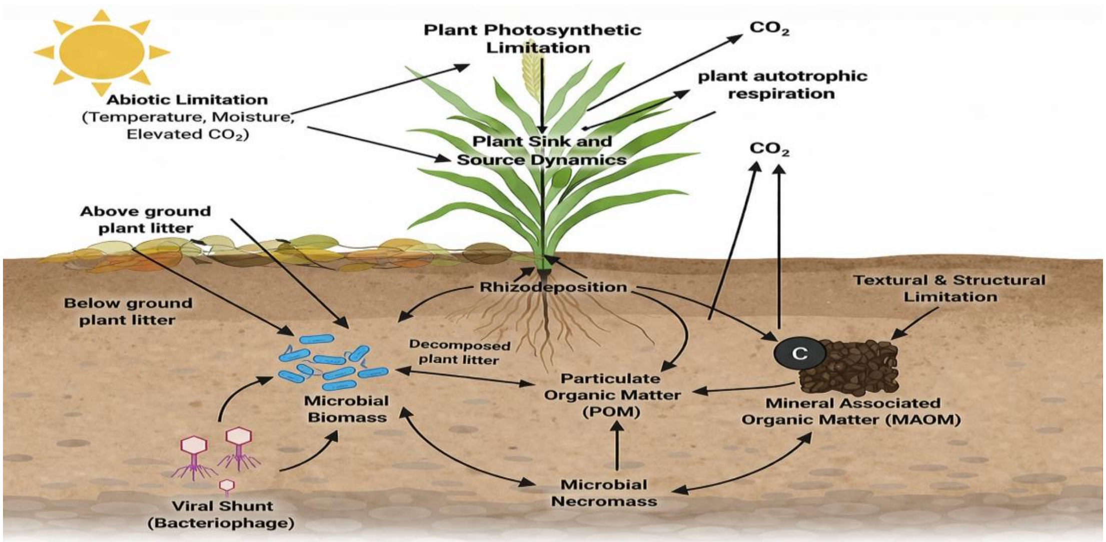

Figure 2. *Mechanism of soil carbon sequestration illustrating the transformation of plant-derived carbon into particulate organic matter (POM) and mineral-associated organic matter (MAOM) through microbial processes.*

atmospheric carbon dioxide (CO_2) by vegetable crops through photosynthesis, leading to the formation of plant biomass. A significant proportion of this carbon is transferred belowground through root biomass, root exudates, and crop residues. These inputs serve as primary sources of organic carbon in soil and act as substrates for soil microorganisms. Microbial decomposition of these materials forms different soil carbon fractions (Six et al., 2002; Bationo et al., 2007).

As illustrated in Figure 2, organic carbon is partitioned into two major fractions: particulate organic matter (POM) and mineral-associated organic matter (MAOM). POM represents a relatively labile carbon pool that is easily decomposed and contributes to short-term nutrient cycling. In contrast, MAOM is a more stable form of carbon associated with soil minerals and contributes to long-term carbon storage (Six et al., 2002).

Soil microorganisms play a central role in this transformation process. They use organic substrates to produce microbial biomass and metabolic by-products (Six et al., 2002; Paustian et al., 2016). Upon microbial death, these residues form microbial necromass, which is an important component of stable soil organic carbon. The association of organic compounds with soil minerals and aggregates further protects carbon from rapid decomposition (Six et al., 2002).

The stabilization of carbon in soil is influenced by several factors, including soil texture, aggregation, moisture, and temperature. Fine-textured soils with higher clay content generally exhibit greater carbon stabilization due to stronger mineral interactions (Six et al., 2002; Bationo et al., 2007). In contrast, frequent soil disturbance in vegetable cropping systems accelerates carbon loss by increasing the oxidation of organic matter (Lal, 2015).

3. Role of Microbial Processes in Carbon Sequestration

Soil microorganisms are the primary drivers of carbon cycling and play a crucial role in the formation and stabilization of soil organic carbon (SOC) in vegetable cropping systems. Plant-derived carbon enters the soil through crop residues, root biomass, and root exudates, which serve as energy sources for microbial communities (Six et al., 2002; Paustian et al., 2016). Microorganisms decompose organic matter and convert it into biomass. During this process, a portion of carbon is released back into the atmosphere as carbon dioxide (CO_2) through respiration, while the remaining carbon is incorporated into soil organic matter.

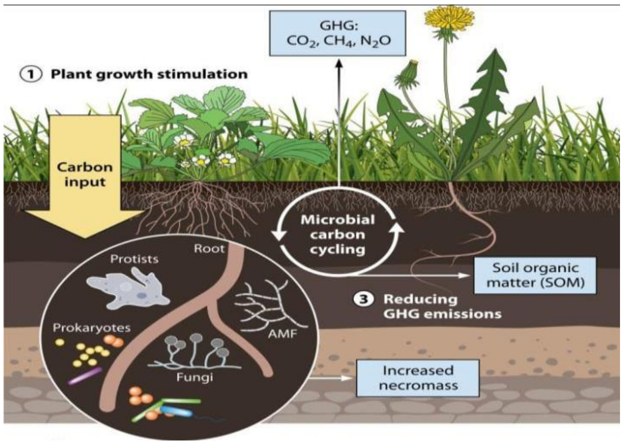

Figure 3. *Role of soil microorganisms in carbon sequestration showing decomposition of organic matter, formation of microbial biomass, and stabilization of carbon as microbial necromass.*

Microbial biomass represents a dynamic pool of carbon that contributes to soil fertility (Bationo et al., 2007). Upon death, microbial residues form necromass, a major component of stable soil organic carbon. These residues interact with soil minerals and are protected within soil aggregates, thereby reducing their susceptibility to decomposition (Six et al., 2002).

The efficiency of microbial processes is influenced by environmental factors such as soil moisture, temperature, and the availability of organic substrates (Paustian et al., 2016). Favorable conditions enhance microbial activity and carbon stabilization, whereas unfavorable conditions may limit decomposition and carbon transformation. In vegetable cropping systems, management practices significantly affect microbial activity. The application of organic amendments, residue incorporation, and cover cropping enhances microbial growth and promotes carbon sequestration (Meena et al., 2019; Smith, 2004). In contrast, excessive tillage disrupts soil structure, reduces microbial populations, and accelerates carbon loss (Lal, 2015).

Thus, microbial processes act as a critical link between plant-derived carbon inputs and the formation of stable soil organic carbon, playing a key role in soil health regeneration and sustainable agricultural production (Paustian et al., 2016; Ray et al., 2025).

4. Impact of Carbon Sequestration on Soil Health

Carbon sequestration plays a vital role in improving soil health by increasing soil organic carbon (SOC), which governs the physical, chemical, and biological properties of soil. In vegetable cropping systems, where soils are often subjected to intensive cultivation, enhancement of SOC is essential for restoring soil productivity and stability (Lal, 2015; Paustian et al., 2016; Ray et al., 2025).

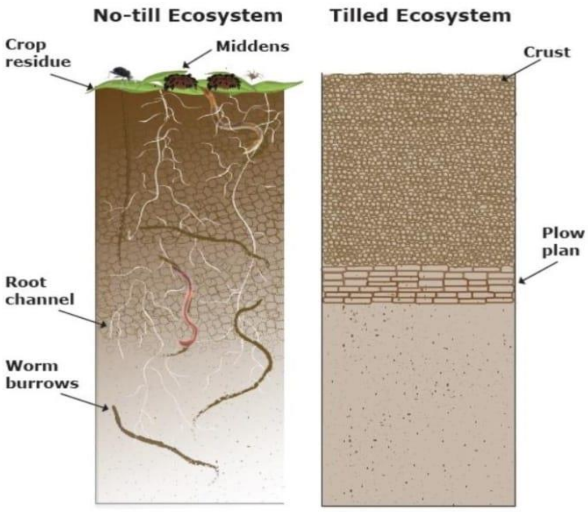

Figure 4. *Comparison of soil structure, root development, and biological activity under conventional tillage, reduced tillage, and natural soil systems.*

4.1 Physical Impact

Increased SOC improves soil aggregation and structure, leading to enhanced porosity and aeration. This facilitates better water infiltration, root penetration, and overall soil stability. Improved soil structure reduces the risks of compaction and erosion, which are common in intensively cultivated vegetable cropping systems (Six et al., 2002; Bationo et al., 2007).

4.2 Chemical Impact

Soil organic carbon acts as a reservoir of nutrients and enhances the cation exchange capacity (CEC). This improves nutrient retention and availability, leading to better nutrient use efficiency and sustained crop growth (Bationo et al., 2007).

4.3 Biological Impact

Higher SOC levels support diverse microbial communities and soil fauna such as earthworms. These organisms play a crucial role in organic matter decomposition, nutrient cycling, and the formation of stable soil aggregates, thereby improving overall soil functionality (Paustian et al., 2016).

4.4 System-Based Comparison

Soils under natural or minimally disturbed systems exhibit superior aggregation, deeper root growth, and higher biological activity. Reduced tillage systems show moderate improvements, whereas conventionally tilled soils often display poor structure, limited root development, and reduced biological activity (Lal, 2015).

5. Factors Influencing Carbon Sequestration

Carbon sequestration in vegetable cropping systems is influenced by climatic, soil, biological, and management factors. These factors regulate the balance between carbon input, transformation, and stabilization in soil (Paustian et al., 2016; Meena et al., 2019).

5.1 Climatic Factors

Climate plays a critical role in determining carbon sequestration potential. Temperature and rainfall directly influence plant growth, biomass production, and microbial activity (Smith, 2004; Paustian et al., 2016).

- Higher temperatures accelerate organic matter decomposition, leading to carbon loss
- Adequate moisture enhances plant growth and carbon input
- Extreme conditions such as drought or excessive rainfall reduce sequestration efficiency

5.2 Soil Properties

Soil characteristics significantly affect carbon stabilization and storage capacity (Six et al., 2002; Batjes, 1996).

- Soil texture: Clay-rich soils have higher carbon retention due to strong mineral interactions
- Soil structure: Well-aggregated soils protect organic carbon from decomposition

- Bulk density: Lower bulk density supports root growth and carbon input

5.3 Crop Type and Cropping System

Different crops vary in their ability to contribute carbon to soil (Bhavya et al., 2018; Saha et al., 2025).

- High biomass crops increase carbon input
- Deep-rooted crops enhance belowground carbon storage
- Leguminous crops improve soil fertility and SOC levels
- Cropping systems such as crop rotation and intercropping enhance carbon sequestration compared to monocropping systems.

5.4 Management Practices

Management practices are among the most influential factors affecting carbon sequestration (Lal, 2004; Meena et al., 2019; Avasiloaiei et al., 2023).

- Residue incorporation increases organic matter input
- Organic amendments enhance microbial activity and carbon stabilization
- Reduced tillage minimizes soil disturbance and carbon loss
- Cover cropping improves biomass production and soil protection

5.5 Microbial Activity

Soil microorganisms regulate carbon transformation and stabilization (Six et al., 2002; Paustian et al., 2016).

- Active microbial communities enhance decomposition and carbon cycling
- Microbial biomass contributes to stable carbon pools
- Environmental conditions influence microbial efficiency

5.6 Land Use and Cropping Intensity

Land use patterns strongly influence long-term carbon dynamics (Smith, 2004; Lal, 2015).

- Intensive cultivation often leads to SOC depletion
- Diversified cropping systems improve carbon storage
- Perennial systems generally store more carbon than annual vegetable cropping systems

6. Approaches for Carbon Sequestration in Vegetable Cropping Systems

Carbon sequestration in vegetable cropping systems can be enhanced through biological, soil-based, management, and technological approaches. These approaches improve soil organic carbon (SOC) through increased biomass input, enhanced microbial activity, and improved carbon stabilization (Paustian et al., 2016; Madhu Rani et al., 2026).

6.1 Biological (Biotic) Sequestration

Biological sequestration involves the fixation of atmospheric carbon dioxide (CO_2) by plants through photosynthesis and its storage in plant biomass and soil organic matter (Lal, 2004). Leafy vegetables such as *Spinacia oleracea* (spinach), *Lactuca sativa* (lettuce), and *Amaranthus spp.* produce high biomass within a short duration. Incorporation of their residues into soil significantly enhances organic carbon input.

6.2 Terrestrial (Soil-Based) Sequestration

Terrestrial sequestration refers to carbon storage in soil as SOC through continuous addition of organic matter.

Root and tuber crops such as *Daucus carota* (carrot), *Raphanus sativus* (radish), Beta vulgaris (beetroot), and *Solanum tuberosum* (potato) contribute significantly through root biomass and rhizodeposition (Meena et al., 2019; Batjes, 1996)

6.3 Agroforestry-Based Sequestration

Agroforestry systems integrate trees with vegetable crops. This increases long-term carbon storage in biomass and soil. These systems improve soil structure, reduce erosion, and enhance carbon stabilization (Saha et al., 2025).

6.4 Conservation Agriculture Practices

Conservation agriculture focuses on minimizing soil disturbance and maintaining soil cover (Lal, 2015; Meena et al., 2019).

- Reduced or no tillage
- Cover cropping
- Crop rotation

Leguminous vegetables such as *Pisum sativum* (pea), *Phaseolus vulgaris* (French bean), and *Vigna unguiculata* (cowpea) improve soil fertility through nitrogen fixation and enhance SOC levels.

6.5 Organic Input-Based Sequestration

Application of organic amendments such as farmyard manure, compost, and green manure significantly increases soil organic matter.

Fruit vegetables such as *Solanum lycopersicum* (tomato), *Solanum melongena* (brinjal), *Capsicum annuum* (chilli), and *Abelmoschus esculentus* (okra) respond well to integrated nutrient management practices involving organic inputs (Avasiloaiei et al., 2023; Khater et al., 2026).

6.6 Mulching and Residue Management

Mulching and residue retention improve soil moisture and reduce carbon loss (Bationo et al., 2007).

Cucurbit crops such as *Cucumis sativus* (cucumber), *Cucurbita spp.* (pumpkin), *Lagenaria siceraria* (bottle gourd), and *Momordica charantia* (bitter gourd) produce large biomass, which enhances SOC when retained in soil.

6.7 Biochar Application

Biochar is a stable, carbon-rich material that resists decomposition and contributes to long-term carbon storage. It also improves soil structure, nutrient retention, and water-holding capacity (Lehmann & Joseph, 2009).

6.8 Technological and Policy-Based Approaches

Technological approaches such as carbon capture and storage (CCS) and policy-driven mechanisms such as carbon credit systems support large-scale carbon sequestration (Paustian et al., 2016). Government incentives and sustainable agricultural policies encourage adoption of carbon-friendly practices.

7. Constraints and Limitations of Carbon Sequestration in Vegetable Cropping Systems

Despite its potential, carbon sequestration in vegetable cropping systems is limited by biological, environmental, and socio-economic factors (Lal, 2015; Smith, 2004; Meena et al., 2019).

7.1 Short Crop Duration and Low Biomass

Vegetable crops generally have short growth cycles, which limits total biomass production and carbon input compared to perennial crops. As a result, their carbon sequestration potential is relatively lower (Bhavya et al., 2018; Madhu Rani et al., 2026).

7.2 Intensive Cultivation Practices

Frequent tillage, continuous cropping, and high input use accelerate the decomposition of organic matter and increase carbon loss through oxidation, reducing net carbon storage (Lal, 2004; Meena et al., 2019).

7.3 Soil Constraints

- Sandy soils have low carbon retention capacity (Batjes, 1996)
- Poor soil structure and compaction limit root growth (Lal, 2015)
- Low clay content reduces carbon stabilization (Six et al., 2002)

7.4 Climatic Limitations

- Drought reduces biomass production (Smith, 2004)
- High temperature accelerates organic matter decomposition (Paustian et al., 2016)
- Irregular rainfall affects plant growth and microbial activity (Paustian et al., 2016)
- Excess moisture may lead to anaerobic conditions (Meena et al., 2019)

7.5 Nutrient Limitations

Deficiency of essential nutrients limits plant growth and microbial activity, thereby reducing carbon input and stabilization in soil (Bationo et al., 2007; Meena et al., 2019).

7.6 Economic and Practical Constraints

- High cost of organic inputs such as compost and biochar (Avasiloaiei et al., 2023; Khater et al., 2026)
- Limited access to machinery for conservation practices (Lal, 2015)
- Lack of awareness among farmers (Ray et al., 2025)

7.7 Measurement and Verification Challenges

Accurate quantification of soil carbon is difficult due to spatial variability, slow accumulation rates, and the need for long-term monitoring (Paustian et al., 2016; Smith, 2004).

7.8 Risk of Carbon Loss

Carbon sequestration in vegetable cropping systems is influenced by several constraints, including biological, environmental, and management factors, which must be addressed to achieve sustainable and long-term carbon storage (Lal, 2004; Meena et al., 2019).

8. Conclusion

Carbon sequestration in vegetable cropping systems plays a crucial role in improving soil health, enhancing soil organic carbon (SOC), and mitigating climate change. The process involves transforming plant-derived carbon into stable soil carbon pools through microbial activity and soil interactions. Sustainable management practices such as organic amendments, residue incorporation, crop rotation, reduced tillage, and biochar application significantly enhance carbon sequestration. Crop-specific strategies, particularly the inclusion of legumes and high-biomass crops, further improve soil carbon levels. Although vegetable cropping systems have limitations due to their short duration and intensive management, the adoption of carbon-oriented practices can transform these systems into effective carbon sinks. Thus, integrating scientific management practices with appropriate crop selection is essential for achieving long-term soil health and agricultural sustainability.

9. Future Scope

Future research should focus on long-term evaluation of carbon sequestration in vegetable cropping systems under different agro-climatic conditions. The development of reliable methods for measuring and monitoring soil organic carbon is essential. Emphasis should be given to crop-specific and management-based strategies, including the use of organic amendments, biochar, and conservation agriculture practices to enhance carbon storage. The integration of advanced tools such as modeling and precision agriculture can further improve carbon assessment and decision-making. In addition, strengthening policy support, carbon credit mechanisms, and farmer awareness is necessary to promote large-scale adoption of carbon sequestration practices for sustainable soil health management.

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AI-Based Early and Late Detection of Postharvest Diseases in Apple

Abstract

Postharvest disease of apple (*Malus domestica* Borkh.) causes significant quality deterioration and economical losses ranging from 20-50% under storage condition. Major fungal pathogen includes *Penicillium expansum, Botrytis cinerea & Alternaria alternata*, which often establish latent infection during pre-harvest stages. Artificial Intelligence(AI) enables rapid, non-destructive detection using imaging & spectral techniques, improving early late diagnosis accuracy (90%). Recent advancement in Artificial Intelligence(AI), particularly deep learning(DL) & Machine Learning (ML), have enabled rapid, non-destructive detection of postharvest diseases using image processing, hyperspectral imaging, object detection models. Convolutional neural networks (CNNs), YOLO and spectral imaging systems have high detection accuracies (90%). This Article integrates pathogen biology, morphology, epidemiology, severity losses and AI-based detection and Forecasting strategies for improved postharvest management.

Keywords: *Apple, Artificial Intelligence, Deep learning, Forecasting, Hyperspectral Imaging, Postharvest diseases.*

1. INTRODUCTION

Apple (*Malus domestica* Borkh.*)* is one of the most economical temperate fruit crops cultivated globally, In India major apple producing states are Jammu and Kashmir contribute 65-75% of the total production with an estimated productivity of 10-12 t/ha. Himachal Pradesh follows with a share of approximately 20-25 % and a Productivity of 6-8 t/ha, while Uttarakhand contributes around 2-5 % with a lower productivity range from 2-4 t/ha. Post-harvest diseases significantly reduce fruit quality and market value, affects the supply chain and reduce farmer income, resulting in major economic losses. Post-harvest pathogens are predominantly necrotrophic fungi that invade host tissues through wounds & degrade them using enzymes ,major toxins such as Patulin, Citrinin, Ochratoxin A, Botrydial. Traditional detection methods, including visual inspection and laboratory culturing are time consuming and partially effective for detecting latent infection.

PATHOGEN DIVERSITY : Post-harvest pathogens of apple are dominated by Fungi capable of infecting fruits through wounds or latent infections. More than 90 species have been reported to cause post-harvest apple decay.

Major pathogen			
Common name	**Causual organism**	**Toxin produced**	**Severity**
Blue Mold	*Penicillium expansum*	Patulin	43.8 %
Grey Mold	*Botrytis cinerea*	Botrydial Botcinic acid	14%
Alternaria Rot	*Alternaria alternata*	Alternariol	10%
Bitter Rot	*Colletotrichum gleosporioides*	Colletotrichum	20%
Black Mold	*Aspergillus niger,* *A.flavus*	Ochratoxin A, Aflatoxin	3.2%
Rhizopus Rot	*Rhizopus stolonifer*	Rhizoxin	5%
Cladosporium Rot	*Cladosporium spp.*	Cladosporin	1 %
Apple ring Rot	*Botryosphaeria dothidea*	Mellein	14.1%

2. AI Detection Models:

AI based detection models in apple(*Malus domestica* Borkh) can be classified into five types:

1. **RGB (Red, Green, Blue) Computer Vision**
    - Detects by using visible symptoms i.e lesions discoloration
    - Models: CNN, Res Net, Efficient Net
    - Application: Late-stage Detection
2. **Hyperspectral Imaging(HIS)**
    - Detects internal/latent infection
    - Uses remote sensing, spectroscopy imaging (400-1000nm)
    - Models: SVM(91%), BP-ANN(94%), PLS-DA(89%)-Accuracy
3. **Thermal Imaging/Infrared Thermography**
    - Detects hidden moisture and respiration changes
    - Useful for early decay detection
    - Captures pictures of heat radiation
4. **Object detection Models**
    - YOLOv5s, Faster R-CNN
    - Detects Lesion Location + Severity
    - Real- Time application in sorting lines
5. **Sensor + IOT + Time series Models**
    - Environmental sensors: Temp. , R.H
    - Models: LSTM
    - Used for forecasting disease risk
6. **AI-Based detection system in Market:-**

System Type	Technology	Application	AI Role
Sorting machine	Computer vision	Fruit grading	Defect detection
Hyperspectral scanners	Spectral imaging	Internal rot detection	Early detection
Mobile apps	CNN models	Field diagnosis	Instant
Smart storage	IoT + AI	Disease detection	Forecasting

Modern Horticulture industries use the following:

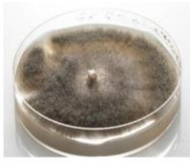
- Hyperspectral imaging systems
- Computer vision grading Machines
- AI-Based disease Detection apps -: Plantix,, AgroAI, Leaf Doctor, Agrico

3. Laboratory Identification

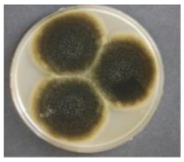
Pathogens are identified in laboratory conditions based on colony morphology and Microscopic structures such as conidia and conidiophores. AI enhances laboratory diagnosis through image classification of culture plates using CNN models and spectral analysis. Hyperspectral imaging detects internal infection that are not visible externally

Cultures

Picture 1:*Penicillium expansum*



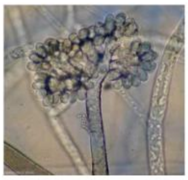
Picture 2:*Botrytis cineria*



Picture 3:*Alternaria alternata*

Microscopic observation

Picture 4:*Penicillium expansum*



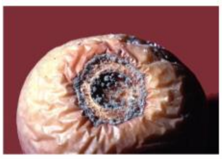
Picture 5:*Botrytis cinerea*

Picture 6: *Alternaria alternata*

4. Symptoms (Field & Storage)

Post-harvest diseases show distinct visual symptoms depending on the pathogen and storage conditions.

- Blue Mold causes soft rot with blue-green sporulation (*Penicillium expansum*)
- Grey Mold shows grey fuzzy growth *(Botrytis cinerea)*
- Black rot produces concentric dark lesions on fruit *(Alternaria alternata)*



Picture 7:*Penicillium expansum*

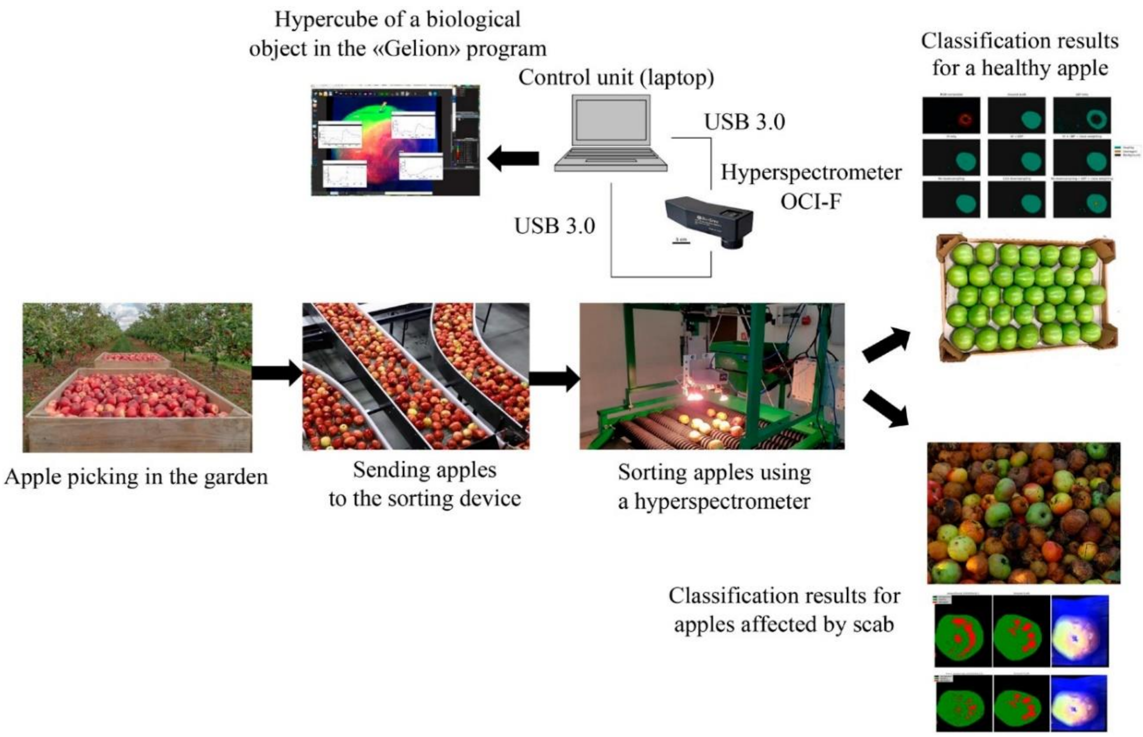
Picture 8: *Botrytis cinerea*

Picture 9: *Alternaria alternata*

5. Early and Late Detection Using AI

Disease	Pathogen	Lab Traits	Symptoms	Environmental condition	A.I Model	Detection Stage
Blue Mold	*Penicillium expansum*	Velvety, Blue colony	Blue rot	Low temp., High R.H	CNN	Early, Late
Grey Mold	*Botrytis cinerea*	Fluffy, Grey colony	Grey growth	High R.H	CNN	Late
Black rot	*Alternaria alternata*	Septate spores, Black colony	Lesions	Warm, Humid	CNN	Late
Bitter rot	*Colletotrichum spp.*	Acervuli	Sunken spots	High Temp.	YOLO	Early, Late
Soft rot	*Rhizopus stolonifera*	Sporangia	Watery rot	Warm, humid	Thermal + CNN	Late
Fusarium rot	*Fusarium spp.*	Curved spores, pink colony	Internal rot	Moderate	HIS + CNN	Early
Black Mold	*Aspergillus niger*	Black spores	Black growth	High R.H	ML	Early

AI-Based Forecasting Model



Early detection involves identifying latent infections using advanced techniques such as hyperspectral imaging and thermal sensing. Late detection focuses on visible symptoms analyzed using deep learning models, such as CNN (Convolutional neural Network) based classification models. AI systems integrate both approaches to provide comprehensive

disease monitoring of plants to maintain agricultural productivity.

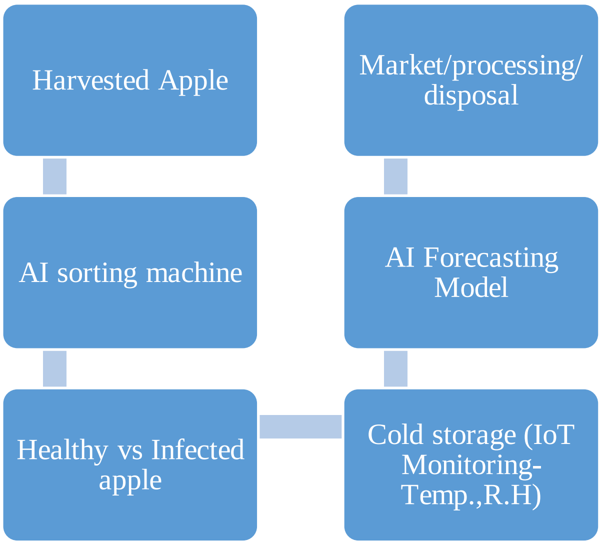
Early Detection (Latent Infection)

- Hyperspectral Imaging
- Thermal Imaging
- Spectral ML Model

Late Detection (Visible Symptoms)

- RBG Imaging
- CNN/YOLO
- Lesion detection

6. AI-Based Post harvest disease Management System



Explanation: AI-Based sorting systems uses computer vision to detect defects & diseases during grading.IoT enables storage systems monitor environmental conditions and integrate AI forecasting models to prevent disease spread

Conclusion

Conventional diagnostic approaches, such as visual assessment and laboratory culturing, remain useful but are limited in their ability to detect early or hidden infections in a timely manner. AI-based techniques, including image-based analysis, hyperspectral sensing & data-driven models, offers a better approach for faster and accurate detection. AI-Based systems are increasingly being utilized in post-harvest management of fruits, particularly in the apple supply chain.

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GUT HEALTH: FROM GUTTER TO GOLDMINE IN DISEASE PREVENTION AND HEALTHY AGING

Abstract

The human gut microbiota is a diverse and dynamic population of microorganisms which directly involved in immune function, metabolism and inter-organ communication, beyond digestion, and influences the development of chronic disease and aging. Dysbiosis, stimulated due to poor diet and lifestyle, disrupts the microbiota and fosters inflammation and disease progression. Gut heath is as a fundamental driver of healthy ageing and longevity. Imbalanced gut causes inflammation which results in cardiovascular and neurological disorders. Targeted dietary and lifestyle interventions offer promising strategies to restore microbial balance and support overall health.

Introduction

The human gastrointestinal tract is composed of trillions of microorganisms including bacteria, viruses, fungi, and archaea, collectively known as gut microbiota (Fig. 1). This diverse microbial community is crucial for the regulation of physiological balance within the body. The gut has traditionally been regarded as primarily a digestive organ for breaking down food and absorbing nutrients. But over the past two decades scientific knowledge has changed radically, with studies now recognizing gut as a core regulator of overall health. Gut microbiota contributes to food digestion, vitamin synthesis, regulation of metabolism, and immune system defences against other organisms. But more importantly it communicates with many different organ systems—from the immune system and brain—through complex biochemical pathways of feedback. Despite this major importance, modern dietary habits characterized by low fiber intake, large-scale processed food consumption and inactivity have all interfered with this delicate ecosystem. Gut health is often not sustained, and thus the epidemic of chronic diseases becomes more extreme. A more constructive perspective, where our perception of gut is no longer "suppressed" because it is no longer a passive system of gut function, but rather of being a beneficial, and vital, biological resource. The “gold mine” status of the gut recognises its significant contribution to maintaining health and disease prevention with lifestyle interventions.

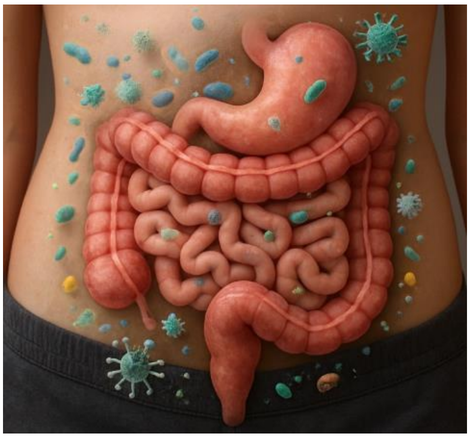

Figure 1- Human gut microbiota

Gut microbiome and immune regulation

The microbial community within the gut is an essential organ that contributes to the development and regulation of the immune system. A large percentage of immune cells (nearly 40%) lives in the gut-associated lymphoid tissue, where regular contact with microbial communities trains the immune response. This interaction provides equilibrium of immune tolerance and defence so the body can attack pathogenic agents with maximal efficacy without overreacting with an aggressive inflammatory response. A viable gut microbiome provides strength to the intestinal barrier by supporting tight junction quality, which prevents passage of pathogenic agents into the blood circulation through the gut and thus prevents unwanted substances from entering the bloodstream by the intestinal wall. Disturbance of the balance between the microbial population leads to the enlargement of intestinal permeability, and that permeability permits microbial substances like lipopolysaccharides to diffuse into our circulation and elicit systemic inflammation. Immune dysregulation associated with this is found in many inflammatory and autoimmune diseases. Furthermore, changes in gut microbiota composition due to aging results in impaired immune function — this creates susceptibility to infections and chronic conditions. This underscores the critical need for gut health as a bedrock of immune resilience across all life stages -- which is why the study demonstrates the need for gut health and longevity strategies and the impact of inflammation on immune resilience.

Gut health and chronic illness.: Gut dysbiosis, a pathological condition where a person's internal microbial community deteriorates due to disruption of the normal microbiota, with some good types of microbes decreasing and others bad microbes increasing (in abundance), is closely related to chronic diseases (Fig. 2). Changes in microbial composition affect essential metabolic pathways such as energy release, fat preservation, and insulin sensitivity. Such alterations lead to metabolic diseases with metabolic disturbances such as obesity and type 2 diabetes. And here microbial metabolites are crucial for cardiovascular state. Some substances like trimethylamine N-oxide have been associated with atherosclerosis, therefore demonstrating how gut microbiota impact heart disease. The gut–brain axis demonstrates a more central role of the microbiome, and the interplay between gut disease and neuroinflammation, mood disruption, Alzheimer's and cognitive impairment. Through these interlocking pathways, it's made clear that the gut is not passive to disease but drives its development and course. So keeping the microbes' balance is so crucial for preventing various chronic diseases like irritable bowel syndrome and many more.

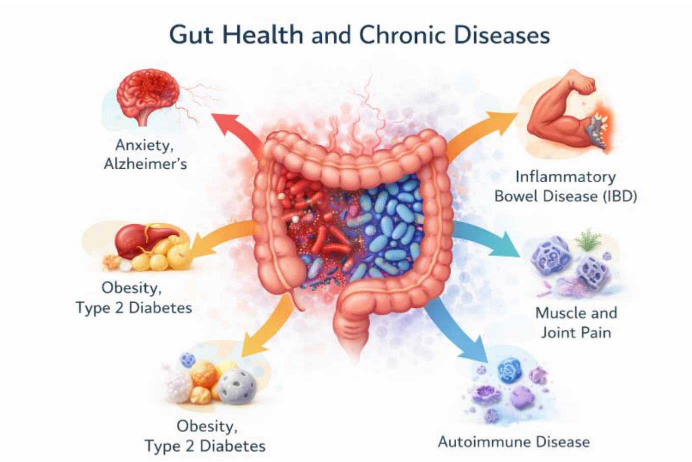

Figure 2- Chronic diseases related to gut dysbiosis

Gut Microbiota and Healthy Aging

Aging is a biological process of slowing or decline of physiological functions and increased susceptibility to disease. Alongside it is an alteration of gut microbiota that includes the reduction of diversity and the overgrowth of proinflammatory species. These changes can be brought about by various sources, including dieting, physical inactivity, immune degradation and medication use. A diverse, equilibrated gut microbiome is generally linked to better health and health longevity, while reduced diversity is associated with health frailty and increased risk of disease. The loss of the beneficial microbes -- especially microbes that produce the short-chain fatty acid -- compromises the integrity of the intestinal barrier causing systemic inflammation. This indicates a strong role for the gut microbiome in regulating aging. One of the essential mechanisms connecting gut health with aging is continuous under mild inflammation, also termed inflammaging. The dysbiosis leads to disturbance of intestinal barrier function, and microbial constituents can escape to circulation and precipitate chronic immune stimulation. This chronic inflammatory state accelerates tissue damage and functional decline over time. Cellular senescence, or a period in which a cell permanently stops dividing without dying, also serves to accelerate aging. Senescent cells are metabolically active but are non-divisional and secrete pro-inflammatory factors that further enhance tissue dysfunction. New evidence emerging suggests that the gut microbiota may influence cellular senescence rates by modulating oxidative stress and inflammatory pathways. So keeping the gut a healthy place may thus slow aging processes and improve general quality of life through a healthier environment in one's gut.

Inflammaging: The Gut and Inflammation Axis.

Inflammaging is a chronic low-grade state of inflammation mainly due to gut dysbiosis. Elevated gut permeability permits microbial toxins to enter the bloodstream, establishing sustained immune activation. This prolonged inflammation can lead to the pathologies of cardiovascular disease, metabolic maladies, neurodegeneration, and immune deficiencies. The gut therefore acts as both a cause and modulator of inflammation, so maintaining it is important for healthy aging.

Gut–Muscle Axis and Gut–Skin Axis in Aging

The gut microbiome can also affect musculoskeletal and skin health by interconnected physiological pathways. Microbial metabolites shape the gut–muscle axis as they modulate muscle protein synthesis, play a key role in mitochondrial performance, and play an important role in energy metabolism. Dysbiosis, in part due to a lack of beneficial metabolites, promotes sarcopenia, which is defined as a loss of lean muscle tissue and muscular strength. Likewise, the gut–skin axis shows how microbial imbalance promotes systemic inflammation and oxidative stress, thus influencing collagen production and accelerating skin aging. These linkages remind us that gut health influences not only internal physiological processes but also the external expressions of aging.

Gut–Brain axis and Aging Cognition T

The gut–brain axis is the bidirectional communication system that connects the gastrointestinal tract to the brain. Gut microbes also modulate brain function through neural, hormonal, and immune pathways, as they create neurotransmitters such as serotonin and gamma-aminobutyric acid. In contrast, age-associated modifications of gut microbiota are associated with neuroinflammation and altered neurotransmission and neurodegeneration in older people. Dysbiosis has been increasingly related to neurodegenerative diseases like Alzheimer’s and Parkinson’s disease. Dietary patterns which favor microbial diversity, especially fiber-rich diets, could save cognitive function and brain health with aging.

Microbiota-host interactions: the Gut as a “Gold Mine”.

The relationship between the gut and the host is core to maintain wellness. More than just a digestive organ, the gut microbiome provides several other critical roles (e.g., forming short-chain fatty acids by fermenting dietary fibre) outside of digestion. These metabolites work as a fuel for the colon cells and help the walls of the gut, to reinforce the intestinal barrier, to help modulate the immune response, and to reduce inflammation. Beyond short-chain fatty acids, gut microbes make vitamins and impact metabolic and signaling pathways that promote overall health. They’re also involved in the production of neurotransmitters, which connects gut function to good mental health. All these different functions are supported by the idea of the gut to be a biologically active system that facilitates physiological processes leading to a real “gold mine” of health.

Dietary Modification

Dietary Modification is one of the most important factors of the gut microbiome composition and function. Dietary fiber-rich diets also stimulate the growth of beneficial microbes (which secrete short-chain fatty acids) responsible for maintaining gut health and minimizing inflammation. Polyphenol-rich plant-based foods increase microbial diversity. Fermented foods bring in beneficial microbes that aid in the recovery of balance between microbes. Dietary patterns rich in processed foods, concentrated sugar and other less healthy fats disrupt microbial diversity, promoting inflammation. These findings underscore the role of long-time dietary practices in gut health and disease prevention.

Mechanisms Linking Gut Dysbiosis to Diseases

Gut dysbiosis contributes to disease through pathways that relate to gut dysbiosis contributing to chronicity and disease, including gut permeability, chronic inflammation, and metabolic signaling pathogenesis mechanisms. As bacterial toxins move into circulation, they elicit immune responses and altered microbial metabolites modulate energy metabolism and insulin sensitivity. Damaged gut-brain transmission impacts nervous function and stress responses. These processes generate a feedback loop in which gut disorder promotes disease, and pathology leads to worse gut disruption. Having learnt about these pathways, the well-being of the gut should be central to the development of systemic diseases.

Strategies to Maintain Gut Health

Diet, lifestyle, and external environments play an important role in gut health (Fig 3). Traditional practices like fasting, eating fermented food, plant-based diets, and the consumption of fermented and high-fiber diets are all traditional ways to support microbial balance. Modern approaches can also address this by introducing probiotics, which add beneficial microorganisms to the gut microbiota; prebiotics which act as substrates for growth; and personalized nutrition.

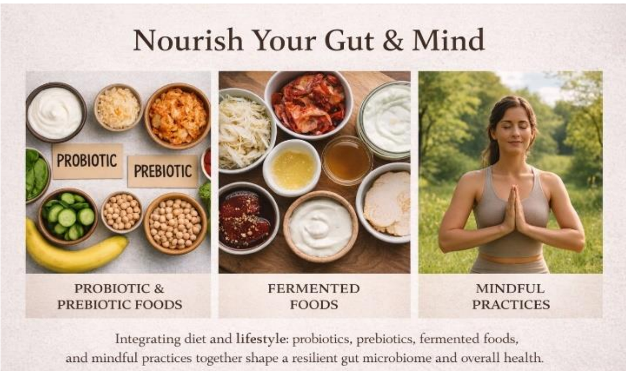

Figure 3 - Strategies to maintain healthy gut.

Diet rich in fiber is still one of the best strategies as a substrate for microbial fermentation and supports beneficial bacteria. Regular exercise, stress management, and adequate sleep are also important to the maintenance of microbial equilibrium. The use of antibiotics should also be closely monitored, particularly with proper dietary intervention for regaining microbial diversity. Combining old-fashioned wisdom with new-world science provides a more sustainable way to take care of the gut.

Conclusion

The gut is a fundamental pillar of health: a key part of a person's immune system, metabolism, inflammation, and aging. Being a significant intermediary between environmental exposures and physiological processes, the gut microbiota specifically is highly responsive to lifestyle choices. Balanced diets, regular exercise, stress reduction or stress management, and good quality sleep have the potential to markedly improve microbial balance and reduce illness risk in humans. Viewing the gut as a "gold mine" encourages the focus of our attention to become prevention and continual health maintenance—thus acting as a wise way to promote healthy aging, increase quality of life, and longevity.

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ENTREPRENEURSHIP AND MANAGEMENT INSIGHTS IN SOILLESS AGRICULTURE: CHALLENGES AND OPPORTUNITIES

Introduction

Soilless agriculture is a modern method of growing crops without natural soil, using nutrient-enriched water solutions or inert media such as cocopeat, perlite, or rockwool. Techniques like hydroponics, aeroponics, and aquaponics allow precise control over nutrients, pH, and environmental conditions, resulting in faster growth, higher yields, and efficient resource use.

Globally, the soilless farming market is expanding rapidly, valued at USD 12.1 billion in 2023 and projected to grow at a CAGR of 13.7% by 2030, with the hydroponics sector alone expected to reach USD 22 billion by 2028. Countries such as the Netherlands, Japan, Germany, and the United States lead large-scale adoption, with leafy greens and herbs accounting for over 50% of vertical farm output.

In India, soilless agriculture is gaining momentum, driven by urbanization, rising demand for pesticide-free produce, and water-efficient farming, with the market growing at a CAGR of 21.4%. As India's population is projected to reach 1.6 billion by 2050 and arable land decreases, soilless agriculture offers a sustainable, climate-resilient, and profitable pathway, fostering entrepreneurial opportunities in agritech and urban farming while addressing critical food security challenges.

Why Soilless Agriculture Attracts Entrepreneurs

Soilless cultivation offers entrepreneurs a high degree of efficiency, scalability, and profitability unmatched by conventional farming.

High-value output: Yields are 3–5 times higher than traditional farming, with shorter crop cycles allowing quicker turnover and faster cash flow.

Resource efficiency: These systems use up to 90% less water and 80% less space, crucial for land constrained cities.

Premium pricing: Consumers increasingly value produce that is pesticide-free, traceable, and locally grown.

Market differentiation: "Clean-label" branding enhances credibility and supports premium pricing strategies.

The entrepreneurial ecosystem is further strengthened by private investors, incubators, and climate-tech venture capital funds focusing on sustainable food systems.

Management Insights for Soilless Agribusiness

1. Operational Management

Efficient soilless farming depends on real-time monitoring of nutrient concentration, pH, humidity, and light intensity. IoT and AI-based systems automate these functions, ensuring consistency and quality. Studies report 10–15% higher yields in smart-controlled greenhouses compared to manual setups Automation also minimizes labour costs, improves precision fertigation, and reduces wastage.

2. Financial Management

The initial investment for a commercial hydroponic farm ranges between ₹ 40 lakh and ₹ 1.7 crore per acre, depending on infrastructure and automation level. Operating costs are largely energy and nutrient dependent, but returns are attractive—return on capital employed (ROCE) of 35–40% is achievable when production and marketing are optimized. Break-even is typically reached within 3.5–4 years, with long-term scalability through modular expansion.

3. Marketing and Brand Strategy

Entrepreneurs in soilless agriculture use digital branding and direct-to-consumer (D2C) models to reach urban markets. Marketing focuses on freshness, transparency, and sustainability with clear messages like *"Safe, Fresh, Sustainable."* Subscription boxes and farm-to-door deliveries provide steady income, and studies show that over 60% of urban consumers in India are willing to pay more for pesticide-free, soilless produce.

4. Supply Chain and Quality Management

Soilless produce particularly leafy greens and herbs is highly perishable, maintaining cold-chain logistics at 0–4 °C is essential. Efficient harvesting, packaging, and last-mile delivery systems ensure minimal post-harvest loss and maintain product quality. Collaborations with hotels, supermarkets, and restaurants strengthen market presence and reduce distribution risk.

Government Initiatives Supporting Soilless Agriculture

1. Mission for Integrated Development of Horticulture (MIDH)

The MIDH, a Centrally Sponsored Scheme, has been expanded to include hydroponics, aquaponics, vertical farming, and precision agriculture. Under MIDH, farmers can receive assistance of ₹350 per square meter for hydroponics and aeroponics, with a maximum area of 1,000 square meters eligible for support.

2. National Horticulture Mission (NHM)

The NHM, launched in 2005-06, aims to develop horticulture to its maximum potential in various states. It primarily focuses on fruits, vegetables, and other horticultural crops, and supports modern farming techniques, including soilless agriculture, to enhance production and income for farmers

3. Agriculture Infrastructure Fund (AIF)

The AIF provides financial support for the creation of post harvest infrastructure and community farming assets. Under this fund, farmers can avail of loans at subsidized interest rates to set up hydroponic and other modern farming systems

4. National Bank for Agriculture and Rural Development (NABARD)

NABARD supports soilless agriculture by providing subsidies for setting up hydroponic and vertical farming systems, offering concessional loans for modern farming infrastructure, conducting training programs to educate farmers and entrepreneurs, and partnering with agricultural incubators to help agritech startups grow.

5. Startup India

The Startup India initiative supports soilless agriculture by providing agritech startups with access to incubation centers, mentorship, funding opportunities, and simplified regulations, helping them grow and innovate in the sector.

SWOT analysis of soilless agriculture

Soilless agriculture, including hydroponics and aeroponics, offers significant strengths such as efficient water and nutrient use, higher yields, faster crop cycles, and the ability to grow in urban areas or poor soils with minimal pesticides. Its weaknesses include high initial setup costs, technical expertise requirements, and energy dependence. However, the sector presents strong opportunities with growing consumer demand for fresh, pesticide-free produce, potential for high-value crop exports, and integration with smart technologies like IoT and automation. Threats include market price fluctuations, system failures, limited awareness among farmers, and competition from traditional farming methods.

Conclusion

Entrepreneurship and management in soilless agriculture present a promising yet challenging landscape. While high initial costs, technical complexity, and market awareness remain key challenges, the sector offers significant opportunities through growing demand for fresh, pesticide-free produce, urban farming potential, and technological innovation. Effective management, strategic planning, and access to funding and incubation support are crucial for success. By leveraging these insights, entrepreneurs can build sustainable, profitable ventures that contribute to modern, resource-efficient, and climate-resilient agriculture.

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FOLIAR FERTILISATION OF NUTRIENTS IN SALT-AFFECTED AREAS

ABSTRACT

Salinity and alkalinity are among the major constraints limiting agricultural productivity, primarily by restricting nutrient uptake through plant roots and adversely affecting crop growth and quality. Excessive salinity imposes both osmotic and ionic stress on plants, resulting in reduced water availability, nutrient imbalances, and ion toxicity. These stresses disrupt key physiological processes, including water uptake, nutrient absorption, photosynthesis, and growth. Furthermore, salinity-induced oxidative stress leads to the overproduction of reactive oxygen species (ROS), which damage proteins, lipids, and nucleic acids, ultimately impairing plant growth and productivity. The availability of metallic micronutrients in soil is strongly influenced by soil pH and redox potential, posing significant challenges in alkaline soils. In general, alkaline and calcareous soils exhibit micronutrient deficiencies due to high adsorption and fixation capacities, whereas micronutrient availability is higher in acidic to neutral soils. These limitations highlight the need for innovative and resource-efficient strategies to improve nutrient use efficiency and crop productivity. Foliar fertilization has emerged as an effective approach to overcome these challenges, particularly in salt-affected soils. This method involves the direct application of liquid fertilizers to plant leaves, enabling nutrient absorption through the cuticle and stomata, thereby bypassing the root system that may be impaired under saline conditions. Foliar fertilization provides a rapid and efficient means of correcting nutrient deficiencies under adverse soil conditions. This review focuses on recent advances in understanding the beneficial role of foliar nutrition in enhancing nutrient uptake, mitigating stress, and improving crop yield under complex agricultural scenarios. It critically examines the mechanisms of absorption and translocation of foliar-applied nutrients, highlighting their efficiency and effectiveness. Additionally, it explores the combined use of foliar fertilization with biostimulants and its potential to improve crop yield and quality under environmental stresses. By optimizing the timing and concentration of foliar applications, nutrient use efficiency can be significantly improved. The review also discusses existing knowledge gaps to enhance the effectiveness of foliar nutrition from economic and ecological perspectives, emphasizing its potential to reduce yield gaps and support sustainable agriculture under challenging soil and environmental conditions.

INTRODUCTION

Ensuring agricultural sustainability is essential to achieving the United Nations' "Zero Hunger" goal. This challenge is further intensified by the rapidly increasing global population. In India, approximately 6.72 Mha of land is affected by salinity, leading to both salinity and alkalinity stresses in plants and negatively impacting the soil–plant system. With the global population expected to exceed 10 billion by 2050, food production must increase by nearly 50% to meet the demands of an additional 2 billion people.

However, this increase would require greater use of fertilizers and pesticides, potentially reduce nutrient efficiency and raise environmental concerns. Therefore, integrated and resource-efficient strategies are essential to address these challenges.

Soil salinity refers to the accumulation of soluble salts, particularly sodium chloride (NaCl), in the soil. Excess salinity adversely affects plant growth by inducing osmotic and ionic stress. Osmotic stress reduces soil water potential, making water uptake difficult and resulting in a condition similar to physiological drought. Ionic stress, primarily caused by sodium (Na^+) and chloride (Cl^-) ions, leads to nutrient imbalances, reduced enzymatic activity, and cellular damage. Plants growing under saline conditions frequently exhibit deficiencies of essential nutrients such as potassium (K), calcium (Ca), and magnesium (Mg), as excessive salt concentrations interfere with nutrient uptake and transport. Moreover, salinity-induced oxidative stress enhances the production of reactive oxygen species (ROS), which damage cellular components and impair plant growth and productivity.

Micronutrients, although required in small quantities, are crucial for plant growth and metabolic processes. Their availability is strongly influenced by soil pH and redox potential. Most micronutrients are readily available in acidic to neutral soils, whereas their availability declines in alkaline soils due to precipitation and fixation reactions, except for molybdenum (Mo). Additionally, soil biota, rhizosphere chemistry, and plant–microbe interactions play important roles in micronutrient solubilization and uptake.

To overcome these limitations, integrated and efficient nutrient management approaches are required. Foliar fertilization, which involves spraying dissolved nutrients directly onto plant leaves, has gained attention as a rapid, targeted, and environmentally sustainable strategy (White et al., 2015; Malhotra et al., 2020). It is particularly effective in enhancing crop productivity under both optimal and stress conditions (Bahrami-Rad and Hajiboland, 2017; Ruiz-Navarro et al., 2019). Foliar feeding ensures quick nutrient availability during critical growth stages (Pooniya and Shivay, 2013; El-Hady et al., 2020) and can also be used for biofortification to address micronutrient deficiencies in human diets (Hidoto et al., 2017; Wang et al., 2017). Furthermore, foliar nutrition improves nutrient use efficiency by bypassing soil-related constraints, thereby reducing nutrient losses due to leaching and volatilization (Lizbeth Lopez-Arredondo and Herrera-Estrella, 2012). It contributes to enhanced crop yield, improved produce quality, and reduced environmental impact. Although considerable research has been conducted on foliar fertilization under optimal conditions, a comprehensive understanding of its role under environmental and climatic stresses is still lacking. This review aims to address this gap by examining the mechanisms of foliar nutrient absorption and translocation through the cuticle, stomata, and trichomes. It also evaluates the potential of foliar fertilization to improve crop yield and quality under stress conditions, while highlighting its economic and ecological benefits (Fernández and Brown, 2013; Fernández et al., 2013; Fernández et al., 2021; Berry et al., 2019; Fernández and Bahamonde, 2020; Niu et al., 2021).

FOLIAR FERTILIZATION: A TARGETED NUTRIENT DELIVERY SYSTEM

Foliar feeding, the application of nutrients to the aerial parts of plants, dates back to 1844 when iron sulfate was first used to treat chlorosis. Today, it is widely adopted in modern agriculture, particularly in horticultural crops, due to its rapid and efficient response. Foliar fertilization involves spraying liquid fertilizers onto plant leaves, allowing nutrients to be absorbed directly through the cuticle and stomata. This method is particularly advantageous under saline conditions, where root-based nutrient uptake is impaired. The effectiveness of foliar fertilization in such environments is based on two key factors:

1. **Bypassing root constraints:** Salinity limits nutrient uptake due to osmotic stress and ion toxicity; foliar application provides an alternative pathway.
2. **Rapid nutrient availability:** Nutrients applied to leaves are quickly absorbed and utilized, making foliar fertilization highly

effective in correcting deficiencies during critical growth stages.

However, foliar fertilization is not a substitute for soil fertilization, which remains essential for supplying primary macronutrients (N, P, K). Instead, it serves as a complementary approach, particularly for supplying secondary nutrients (Ca, Mg, S) and micronutrients (Zn, Mn, Fe, Cu, B, Mo), and for supplementing nutrients during periods of high demand or stress.

Foliar feeding also plays an important role in delaying senescence during reproductive stages by maintaining photosynthetic activity and facilitating nutrient translocation to seeds, fruits, tubers, or vegetative organs. Additionally, early-stage foliar applications can enhance plant vigor and improve tolerance to environmental stresses.

The effectiveness of foliar fertilization depends on proper formulation and application. Suitable foliar fertilizers should possess:

- Low salt index to minimize leaf injury
- High solubility for efficient application
- High purity to avoid spray incompatibility and phytotoxic effects

FERTILIZER MATERIALS FOR FOLIAR APPLICATION

Nitrogen: Urea is considered the most suitable nitrogen source for foliar application due to its high solubility and low salt index. It also enhances the absorption of other nutrients by increasing leaf permeability (Gray et al.). However, urea must contain low biuret levels (≤0.2%) to prevent foliar burn (Halliday et al.; Gray et al.). Modern formulations with reduced biuret content are safer for plant application (Follet et al.). Alternative nitrogen sources include ammonium polyphosphates, ammonium thiosulfate (12-0-0-26S), fluid ammonium sulfate (8-0-0-9S), and ammoniated ortho-phosphates, which are effective at low concentrations with minimal risk of leaf injury.

Phosphorus: The combined use of polyphosphates and orthophosphates enhances phosphorus absorption and reduces leaf burn, as it provides multiple forms of phosphorus simultaneously (Barel et al.).

Potassium: Potassium polyphosphates are suitable due to their low salt index and high solubility. Other effective sources include potassium sulfate, potassium nitrate, potassium hydroxide, and potassium thiosulfate, depending on availability and application requirements.

Secondary and Micronutrients: Foliar application of secondary nutrients (Ca, Mg, S) and micronutrients (Zn, Mn, Fe, Cu, B, Mo) is effective for correcting deficiencies. However, their absorption and translocation may be limited, making the selection of appropriate nutrient sources critical. Synthetic chelates are generally less effective for foliar application because their large molecular size restricts penetration through leaf tissues (Wallece et al., 1962; Wittiwer et al., 1964).

For example, chelated zinc was not more effective than inorganic sources in grapes and was inferior to $ZnSO_4$ in vegetables. Similarly, chelated iron did not outperform inorganic iron sprays, and copper chelates were less effective than Bordeaux mixture in almonds. Chelated magnesium was also found to be less effective than $MgSO_4$ in apples. Although chelated iron performed similarly to ferrous sulfate in grain sorghum, its higher cost limited its practical use.

In contrast, organic chelating agents such as amino acids, citric acid, malic acid, phenolic compounds, glucoheptonate, and glucosyl glycine have been shown to enhance foliar nutrient absorption (Wittiwer et al., 1964).

Table below shows Common Nutrient Element Deficiency Disorders in Crops Corrected by Foliar Applications of the Deficient Nutrient (Wittiwer et.al, 1964)

Nutrient Deficiency	Corrective Nutrient	Foliar Spray Recommended (lbs/acre)
Nitrogen corn wheat cotton Potato sugarcane	Urea	5-20 (lbs/100 gal) 20-800 (lbs/100 gal) 20-50 (lbs/100 gal) 20 (lbs/100 gal) 10 - 20 (lbs/100 gal)
Phosphorous Sugar Cane	Orthophosphoric acid Ammonium phosphates Potassium phosphates	5 - 25 5 - 25 5 - 25
Potassium Citrus	Potassium sulfate Potassium Nitrate	5-10 (lbs/100 gal) 25-100 (lbs/100 gal)
Calcium Blossom-end rot of tomatoes Blackheart of celery	Calcium chloride Calcium nitrate or Calcium chloride	10 - 20 CaCl2 5 - 10 CaCl2
Magnesium Celery, tomatoes, apples and oranges	Magnesium sulfate or Magnesium nitrate	10-20 MgSO4
Copper vegetable and fruit crops	Bordeaux mixture Basic copper sulfate	1 - 3
Zinc row crops, corn,tomatoes, beans	Zinc sulfate or Zinc oxide	1 - 2
Manganese beans, soybeans, celery, tomatoes, citrus, etc	Manganese sulfate	5 - 10
Iron pineapple and grain sorghum	Iron sulfate	10 - 15
Molybdenum yellow spot in citrus, Whiptail in cauliflower	Sodium molybdate or Ammonium molybdate	2 - 4 (oz.)

MECHANISMS OF ABSORPTION AND TRANSLOCATION OF FOLIAR-APPLIED MINERALS

The efficiency of foliar fertilization largely depends on the mechanisms governing the absorption and translocation of applied nutrients within plant tissues. These processes determine how effectively nutrients penetrate leaf surfaces and are subsequently transported to sites of utilization.

Absorption Mechanisms

Foliar-applied minerals are absorbed through multiple pathways on the leaf surface. One of the primary routes is cuticular penetration, where nutrients diffuse through the waxy cuticle covering the leaf surface (Fernandez et.al.2009). The cuticle, although hydrophobic, allows the passage of dissolved nutrients under suitable conditions. Another important pathway is stomatal uptake, where nutrients enter through the stomatal openings present on leaf surfaces (Fernandez et.al. 2009). This pathway is particularly significant under favorable environmental conditions that promote stomatal opening. In addition, nutrients can be absorbed directly by **epidermal cells**, which form the outermost layer of leaves and other aerial plant parts (Schönherr et.al.2006). These **multiple** entry routes collectively enhance the efficiency of foliar nutrient uptake.

Translocation Mechanisms

Once absorbed, nutrients are transported within the plant through two primary pathways: the **apoplastic pathway** and the **symplastic pathway**. In the apoplastic pathway, nutrients move through cell walls and intercellular spaces without crossing cell membranes (Fernandez et.al.2009). In contrast, the symplastic pathway involves movement through the cytoplasm of interconnected cells via plasmodesmata (Eichert. et.al.2008).

The combined action of these pathways ensures effective distribution of nutrients from the site of absorption to metabolically active tissues. Foliar application enables rapid correction of nutrient deficiencies, as nutrients become immediately available to plant tissues, resulting in a quick physiological response (Fernandez et.al.2009). Furthermore, this method reduces the plant's dependency on soil for nutrient uptake, making it particularly advantageous under conditions where soil nutrient availability is limited or unfavorable (Fernandez et.al.2009). Additionally, foliar fertilization allows precise nutrient delivery, minimizing nutrient losses through leaching and reducing environmental contamination (Fernandez et.al.2009). Therefore, foliar fertilization is considered a valuable tool in modern agriculture, especially under environmental stresses where soil-based nutrient uptake is constrained (Ishfak et.al.2022).

FOLIAR NUTRITION AND CROP RESILIENCE

Foliar nutrition has gained significant attention as a strategy to enhance crop resilience and productivity under environmental stresses. A meta-analysis evaluating the effectiveness of foliar-applied mineral nutrients demonstrated that foliar fertilization can increase crop yield by 15–19% and improve quality traits by 9–29% (Ostertag et.al.2016).

Recent studies further highlight the potential of foliar nutrition in mitigating stress effects. For example, foliar application of calcium and potassium has been shown to alleviate heat stress in crops such as wheat (Jacquens et.al.2022). Similarly, a comprehensive review by Bhupenchandra et.al. reported that foliar application of biostimulants enhances root development, nutrient uptake, and drought tolerance.

The mechanism of foliar nutrition involves the absorption of nutrients through the cuticle and stomata, followed by their translocation to different plant parts. This targeted nutrient delivery system is particularly effective in correcting specific deficiencies and improving overall plant health. Moreover, foliar fertilization provides a rapid response to nutrient deficiencies and environmental stresses, thereby enhancing crop yield and quality. It also reduces dependence on soil-applied fertilizers, which are often less efficient due to soil-related constraints such as pH imbalance and microbial interactions.

RECENT ADVANCEMENTS IN FOLIAR FERTILIZATION IN SALT-AFFECTED SOILS

1. Improved Nutrient Availability and Uptake

In saline soils, the availability and uptake of essential nutrients such as potassium, calcium, and magnesium are significantly reduced due to high concentrations of sodium and chloride ions. Sodium competes with potassium for uptake, while chloride interferes with calcium and magnesium availability. Foliar fertilization bypasses these soil constraints, ensuring efficient nutrient delivery directly to plant tissues.

Potassium plays a vital role in osmotic regulation and enzyme activation, and its foliar application helps maintain ionic balance and improve water uptake under saline conditions. Calcium, on the other hand, is essential for maintaining cell wall integrity and membrane stability, thereby reducing salinity-induced cellular damage. For instance, the foliar fertilizer FFNV5 was developed to correct micronutrient deficiencies in alkaline soils. Its application improved tomato quality, resulting in total acidity levels approximately 27% higher than the control and 75% higher than soil fertilization alone (Tellez et.al,2007).

Similarly, Kandil et.al. (2022) reported that foliar application of zinc at 2000 mg/L significantly increased rice grain yield and improved nutrient-use efficiency. Supporting these findings, Yogi et al. (2023) demonstrated that foliar zinc fertilization enhanced yield, biofortification, and nutrient-use efficiency in upland rice. In another study, Harish et al. (2022) [5.1] highlighted the benefits of combining zero-tillage with foliar phosphorus application in a maize–wheat system, emphasizing the importance of crop-specific nutrient management strategies for improving productivity.

2. Mitigation of Oxidative Stress

Salinity induces oxidative stress in plants by increasing the production of reactive oxygen species (ROS), including superoxide radicals, hydrogen peroxide, and hydroxyl radicals. These ROS damage cellular components such as lipids, proteins, and DNA. Foliar application of micronutrients such as zinc (Zn) (0.3–0.5% w/v) (Mitler et.al. 2022) and iron (Fe) (500–1000 mg/L) enhances the plant’s antioxidant defense system. These nutrients activate key antioxidant enzymes, including superoxide dismutase (SOD) and catalase (CAT), which neutralize ROS and protect plants from oxidative damage under saline conditions.

3. Enhanced Photosynthesis and Growth

Salinity negatively affects photosynthesis by reducing chlorophyll content and stomatal conductance. Foliar application of nitrogen (N), magnesium (Mg), and iron (Fe) improves photosynthetic efficiency by enhancing chlorophyll synthesis and carbon fixation. Magnesium, being the central component of chlorophyll, plays a crucial role in maintaining photosynthetic activity. Its foliar application helps alleviate chlorosis commonly observed in salt-stressed plants, thereby improving growth and productivity.

A study on wheat demonstrated that combined soil and foliar application of $ZnSO_4$ (5 kg ha^{-1} soil + 1.0% foliar) resulted in higher grain protein content and improved cost–benefit ratio (Kathak et.al., 2015).

4. Increased Yield and Biomass

Numerous studies have confirmed the positive impact of foliar fertilization on crop yield and biomass under saline and alkaline conditions. Foliar application of potassium and calcium has been shown to enhance vegetative and reproductive growth in crops such as wheat, rice, and tomato.

For example, foliar spraying of potassium nitrate (10–20 mM) on wheat at early growth stages (14 days after germination) improved grain yield, water-use efficiency, and salt tolerance (Abeed et al., 2020). Similarly, foliar application of phosphorus, nitrogen, and zinc in alkaline soils produced significantly higher grain yield compared to granular fertilizers (Holloway et.al., 2001). Fluid fertilizers improved shoot dry weight, grain yield, and phosphorus uptake due to enhanced nutrient availability. Foliar application of calcium chloride ($CaCl_2$) during flowering reduced blossom-end rot in tomato, improving fruit quality under saline conditions. Moreover, combined foliar application of micronutrients (14% Mn + 12% Fe + 16% Zn) applied at 20 and 45 days after transplanting significantly increased grain yield, straw yield, and yield components in rice under saline conditions (Zayed et.al. 2011).

GUIDELINES FOR FOLIAR APPLICATION

1. Proper Concentration and Timing

Appropriate concentration and timing are critical to avoid leaf injury and maximize nutrient absorption. Sprays should not be applied during high temperatures or direct sunlight. Base solutions should include nitrogen, with ratios such as 1:2 or 1:3 ($N:P_2O_5$) during early growth stages and 2:1:1 ($N:P_2O_5: K_2O$) during grain-filling stages. Micronutrients should be applied based on tissue analysis and always in combination with nitrogen.

2. Compatibility with Other Inputs

Foliar fertilizers can be combined with biostimulants such as seaweed extracts and silicon to enhance stress tolerance (Khan et al., 2009). However, compatibility must be ensured. For example, urea is incompatible with lime, sulfur, Karathane, Glyodin, Phygon, Phosdrin, and Sevin. Magnesium sulfate should not be mixed with arsenicals or copper sprays, and manganese solutions are incompatible with phosphate, iron sulfate, or Nabam.

3. Frequent Applications

In saline environments, frequent foliar applications (2–4 sprays) with low concentrations (3–8% nitrogen) are recommended to maintain nutrient supply. However, excessive application should be avoided to prevent nutrient imbalances.

4. Optimal Growth Stage

Timing of application is crucial and should coincide with critical growth stages that determine yield potential. Regular monitoring and plant tissue analysis, such as DRIS (Diagnosis and Recommendation Integrated System), help identify nutrient limitations and optimize application strategies (Gray et.al., Halliday et.al.).

5. Optimal Crop Condition

Well-nourished crops respond more effectively to foliar feeding due to better absorption and translocation. While stressed crops show reduced response, timely foliar application before stress onset can improve resilience and recovery.

6. Meteorological Conditions

Foliar application should be carried out during early morning or evening hours under favorable conditions, including wind speeds below 5 mph and relative humidity above 70%. Rainfall within 24–48 hours may reduce effectiveness by washing off nutrients. Table Below provides the absorption rates or entry times for different nutrients into the leaf tissue. (Gray et.al, Grewig et.al, McNall et.al).

Nutrient	Time for 50% Absorption
Nitrogen (as urea)	½-2 hours
Phosphorous	5-10 days
Potassium	10-24 hours
Calcium	1-2 days
Magnesium	2-5 hours
Sulphur	8 days
Zinc	1-2 days
Manganese	1-2 days
Iron	10-20 days
Molybdenum	10-20 days

DISCUSSION

The present review underscores the growing importance of foliar fertilization as an efficient nutrient management strategy under conditions of salinity and alkalinity stress. These stresses interfere with plant water relations, nutrient acquisition, and metabolic activities, ultimately leading to significant reductions in crop productivity. Under such circumstances, soil-applied fertilizers often show limited effectiveness due to nutrient fixation, reduced solubility, and ionic competition in the rhizosphere.

Foliar application offers a practical alternative by circumventing soil-related limitations and supplying nutrients directly to plant tissues. The uptake of nutrients occurs through multiple pathways, including penetration across the cuticle, entry via stomata, and absorption through epidermal cells, followed by their distribution through apoplastic and symplastic routes. These processes collectively facilitate rapid nutrient assimilation and explain the immediate physiological responses observed after foliar application, particularly under stress conditions (Fernandez et.al.2009; Eichert. et.al.2008; Schönherr et.al.2006).

Evidence from experimental studies and meta-analyses further supports the effectiveness of foliar nutrition in enhancing crop performance. Reported increases in yield and quality attributes (Ostertag et.al.2016) highlight its potential across a range of environmental conditions. Moreover, the application of essential nutrients such as potassium, calcium, zinc, and iron through foliar sprays has been shown to alleviate salinity-induced damage by improving ionic balance, stabilizing cellular structures, and enhancing antioxidant enzyme activity (Mitler et.al. 2022; Abeed et al., 2020).

The integration of foliar fertilization with complementary approaches such as biostimulant application and conservation agricultural practices further strengthens its effectiveness. Studies including Bhupenchandra et.al. and Harish et al. (2022) demonstrate that such combined strategies improve nutrient uptake, water-use efficiency, and plant tolerance to environmental stress.

Despite these advantages, the success of foliar fertilization is influenced by several factors, including climatic conditions, plant growth stage, and nutrient formulation. Inappropriate application—particularly excessive concentrations or unfavorable timing—can result in leaf injury or reduced efficiency. Additionally, the limited mobility of certain nutrients within plant tissues may restrict their redistribution after foliar uptake. Overall, foliar fertilization should be viewed as a supplementary approach rather than a replacement for soil fertilization, with significant potential to enhance nutrient use efficiency and crop productivity under challenging environmental conditions.

CONCLUSION

Salinity and alkalinity continue to pose serious challenges to sustainable crop production by restricting nutrient availability, disturbing physiological processes, and lowering both yield and crop quality. Under such stress conditions, the efficiency of conventional soil fertilization is often compromised. In this context, foliar fertilization represents an effective and practical solution. By enabling direct nutrient absorption through leaf surfaces and facilitating rapid movement within plant tissues, it ensures timely correction of nutrient deficiencies. Foliar nutrition contributes to improved nutrient uptake, enhanced photosynthetic performance, reduced oxidative damage, and overall better crop productivity under saline and alkaline environments.

Furthermore, the combined use of foliar-applied nutrients with micronutrients, secondary nutrients, and biostimulants enhances plant resilience and improves crop quality. Its role in minimizing nutrient losses and reducing environmental impacts also supports its relevance in sustainable agriculture.

However, the effectiveness of foliar fertilization depends on careful management, including appropriate selection of nutrient sources, concentration, timing, and environmental conditions. When applied strategically, foliar nutrition can play a key role in narrowing yield gaps and improving agricultural sustainability in stress-affected regions.

FUTURE SCOPE

Although foliar fertilization has shown considerable promise, several areas require further investigation to enhance its effectiveness and facilitate wider adoption.

1. **Refinement of Application Practices:** Future research should focus on identifying optimal nutrient concentrations, application timing, and frequency tailored to specific crops and growth stages to maximize efficiency while minimizing the risk of phytotoxicity.
2. **Mechanistic Understanding:** There is a need for deeper insights into the physiological and molecular processes involved in foliar nutrient absorption, transport, and utilization, particularly under stress conditions.
3. **Innovative Fertilizer Formulations:** The development of advanced formulations, including nano-based fertilizers and improved carriers, could enhance nutrient penetration, retention, and utilization efficiency.
4. **Integration with Modern Technologies:** Incorporating precision agriculture tools such as remote sensing, drones, and data-driven nutrient management systems can enable more accurate and site-specific foliar applications.
5. **Synergistic Approaches:** Further exploration of the combined use of foliar fertilizers with biostimulants, beneficial microbes, and stress-alleviating compounds may improve plant resilience under multiple stress conditions.
6. **Sustainability and Economic Evaluation:** Long-term assessments of the economic feasibility and environmental impact of foliar fertilization are essential to promote its adoption among farmers.
7. **Climate Resilience:** With increasing climate variability, future studies should examine the role of foliar nutrition in enhancing crop tolerance to combined stresses such as salinity, drought, and high temperatures.

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FROM GREEN REVOLUTION TO EVERGREEN REVOLUTION: THE SHIFT TOWARD SUSTAINABLE FARMING

ABSTRACT

The transition from the Green Revolution to the Evergreen Revolution highlights the need for sustainable agricultural development. While the Green Revolution improved food production, it also caused environmental degradation and resource depletion. The Evergreen Revolution emphasizes increasing productivity through eco-friendly practices such as organic farming, integrated management, and efficient resource use. This approach aims to achieve long-term food security while preserving soil health, biodiversity, and natural resources for future generations.

INTRODUCTION-

The world is going to face food security in the coming years due to the rapid increase in population. Agriculture, being the backbone of our country, ensures food security, but in recent years, countries have been striving to increase their food production to cope with the population. The arrival of the green revolution during the 20th century, though remarkably increased the agricultural production by introducing high-yielding varieties (HYV), chemical fertilizers, pesticides and transformed agriculture, but it also has some serious consequences on soil health, fertility, productivity, decline in groundwater, and ecology. Dependency on chemical input has increased to such an extent that insects and pests are now resistant to a large number of chemicals due to overdose or overuse. This concerns the long-term sustainability of the farming system.

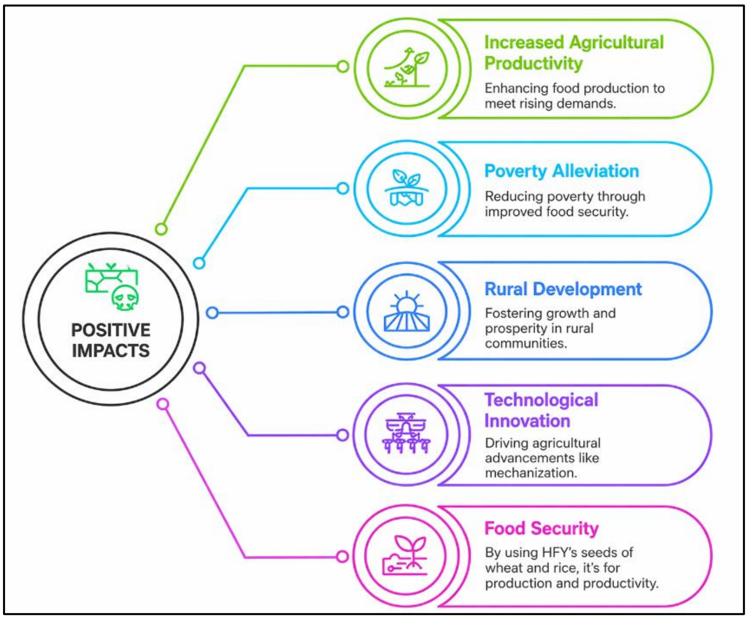

Fig. 1 Positive impacts of the green revolution

Paul Hawken (1993) advised- "Leave the world better than you found it, take no more than you need, try not to harm life or the environment, make amends if you do" and "The first rule of sustainability is to align with natural forces or at least not try to defy them".

The word "Sustain", from the Latin sustinere (sus from below and tenere from to hold), to keep in existence, implies long – term support.

According to FAO, "The management and conservation of the natural resource base, and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such development conserves land, water, plant and animal genetic resources, is environmentally non–degrading, technically appropriate, economically viable and socially acceptable."

To overcome these concerns, the concept of the evergreen revolution emerged to increase production and productivity while maintaining ecological balance and soil health, without harming nature. The shift of agriculture can only be assured by conserving resource bases, by integrating the biological cycle. In a population-rich, but land-hungry countries like India, China, and Bangladesh, there is no option except to increase production under conditions of diminishing per capita availability of arable land and irrigation water and expanding biotic and abiotic stresses. (M.S. Swaminathan, 1996)

GREEN REVOLUTION AND ITS IMPACTS

The Green Revolution began in the late 1960s to increase crop yield production, and its main aim is to maintain food security, economic growth, and productivity. Higher food production helps many countries escape from famine, ensuring food security, essentially in India and Asia. Alongside these gains, serious health problems, social, and environmental problems have emerged.

Norman Ernest Borlaug (1914-2009) was an American agricultural scientist and plant pathologist who played a vital role in transforming global agriculture through the development of high-yielding and disease -resistant wheat varieties. His methods were later introduced to India and Pakistan in the 1960s, nearly doubling wheat production and significantly enhancing food security in these countries. By his contributions, he received numerous honours, including the Nobel Peace Prize in 1970, the Presidential Medal of Freedom, and the Congressional Gold Medal. He is known as the father of the Green Revolution worldwide, and in India, Dr M.S. Swaminathan. He played a pivotal role in enhancing agricultural production during the 1960s and 1970s by developing HYVs of wheat and rice, which significantly boosted the food security in the country.

In 1943, India suffered from the world's worst food crisis due to the Bengal Famine, which led to the death of ~ 4 million people in eastern India due to hunger. Even after independence in 1947, until 1967, the government of India largely focused on expanding the farming areas. But the population is growing at a much faster rate than food production. So, immediate action is needed to secure the food security of India, and that action came in the form of the Green Revolution. The Green Revolution started in Punjab, Haryana, and western Uttar Pradesh, which is called as the "Granary of India".

FEATURES OF THE GREEN REVOLUTION

1. Use of high-yielding seeds, especially in wheat and rice.
2. Irrigation expansion via canals and tube wells.
3. Higher chemical inputs like fertilizers, pesticides, etc.
4. Mechanization with the help of tractors, threshers, etc.

IMPACTS DUE TO THE GREEN REVOLUTION

There are positive and negative impacts that came along with the green revolution, which are as follows-

EVERGREEN REVOLUTION & ITS NEED FOR SUSTAINABLE AGRICULTURE

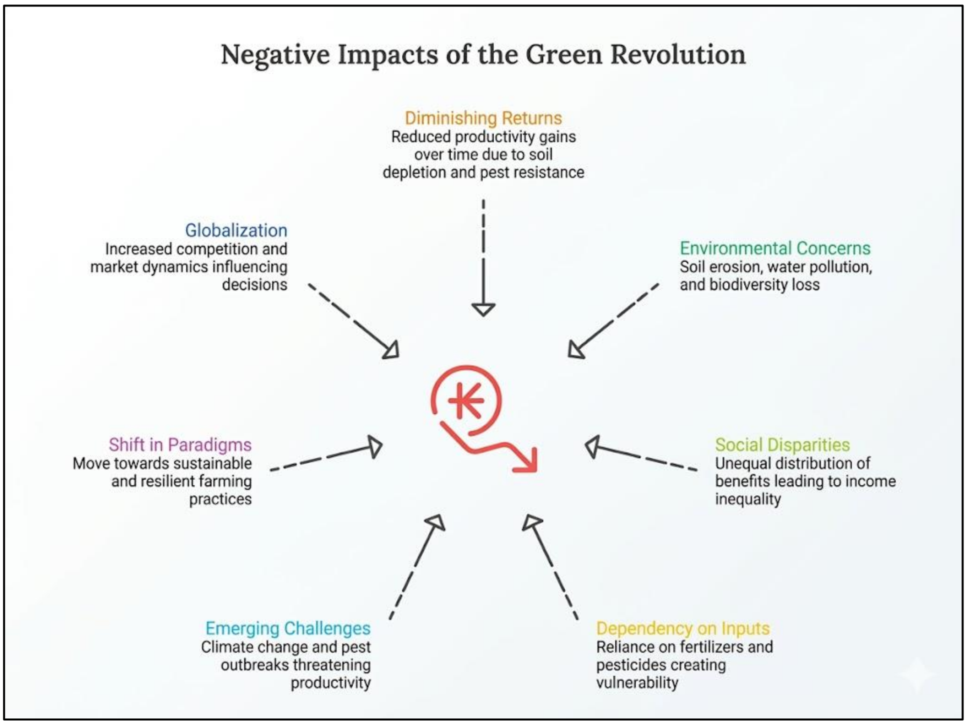

Fig. 2 Negative impacts of the green revolution

The term "Evergreen Revolution" was coined by Dr M.S. Swaminathan to describe a strategy for enhancing output, i.e., crop yield and productivity, without endangering short- and long–term food production goals. The main objective of the Green Revolution is to produce more output using fewer inputs, such as less water consumption, pesticides, fertilizers, and less land area, to achieve sustainable agriculture. The productivity of farms can be increased by using or introducing ICT tools in the fields and other new technologies.

NEED FOR SUSTAINABLE AGRICULTURE

The Evergreen Revolution is primarily focused on sustainable agriculture by utilizing local available resources and those inputs that will not harm the soil, water, environment and humans.

• Failure of the Green Revolution due to its various long-term negative impacts triggered the need for the evergreen revolution.

• More nutrient-rich pulses and other millets were replaced by wheat and rice crops only.

• Due to higher utilization and application of inputs such as fertilizer, the soil loses its fertility.

• Indian agriculture shifted to become regional and cereals-centric.

• Due to overwatering, fields became saturated and more salinized.

• Intensive agriculture without using conservation agriculture practices, maintaining soil fertility and soil structure.

• Using more underground water for irrigation purposes causes the lowering of the underground water level, especially in Punjab, Haryana and western U.P.

KEY APPROACHES OF EVERGREEN REVOLUTION

To ensure the green revolution remains relevant and sustainable in the long term, the concept of the evergreen revolution came, and the key approaches are as follows-

1. Enhance agroecological approaches: Promote the agroecological principle that prioritize soil health, biodiversity and ecosystem resilience. It integrates the traditional knowledge with modern agriculture practices that are environmentally sustainable, socially equitable and economically viable.

2. Promote sustainable consumption and production: Promote sustainable consumption and production patterns across the food value chain and a diversified

diet, reduce food waste and minimize post – harvest losses to ensure food security and nutrition for all.

3. Empower small landholder farmers: Farmers having a land area of 1-2 ha come under small landholder farmers. Empowerment of small land by access to credit, markets, extension services and technology. Enhance inclusive policies that prioritize the needs and rights of small holders, women farmers and marginalized communities.

4. Invest in rural infrastructure and services: Strengthen rural infrastructure and services, including transportation networks, market facilities, irrigation systems and access to clean water and energy. Enhance rural communities with access to information, education, and training opportunities to build their capacity and resilience.

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PARTNERS IN PARASITISM: A BIOLOGICAL TALE

Abstract

In nature's intricate web, mutualism exemplifies how organisms thrive through interdependent alliances, with the parasitoid-polydnavirus (PDV) relationship standing out as a remarkable case of coevolution. Parasitoid wasps, primarily from Hymenoptera, form obligate mutualistic bonds with PDVs (family Polydnaviridae), including bracoviruses (BVs) and ichnoviruses (IVs). These viruses, integrated into wasp genomes and vertically transmitted, replicate exclusively in wasp calyx cells and are injected into secondary hosts during oviposition, suppressing host immunity without replicating there. Evolved convergently over 100 million years from distinct viral ancestors, PDVs enable parasitoid success by disrupting host cellular (e.g., hemocyte inactivation, encapsulation) and humoral (e.g., melanization inhibition) defenses. Beyond dyadic benefits, this symbiosis drives multitrophic interactions: PDVs alter parasitized herbivore phenotypes, modifying oral secretions that influence plant defenses and herbivore-induced volatiles (HIPVs), indirectly attracting hyperparasitoids. This alliance underscores PDVs' dual role as benign wasp symbionts and pathogenic host manipulators, revealing evolutionary pressures like gene duplication under selection. The parasitoid-PDV mutualism highlights nature's bizarre ingenuity in survival strategies.

Keywords: Polydnavirus; Parasitoid- Polydnavirus mutualism; Symbiosis, Obligate mutualism; Multitrophic interations

Introduction

In nature, every organism must survive and reproduce to ensure its existence and the existence of one organism depends upon existence of others. This planet Earth is great example of how the smallest organism depends upon the bigger one and vice versa. Its beautiful yet complicated how every organism need the other one in most bizarre and amazing way. Mutualism is a type of interaction in which both partners benefit from each other (Bascompte, 2019). One example of this interaction is Parasitoid- Polydnavirus mutualism, an intricate relation which beholds evolutionary history ultimately resulting in the success of parasitoid in several ways. This article will tell you the story of parasitoid and its alliance with polydnaviruses (PDVs) in an intriguing way.

Nature of association

Parasitoids are unique beings of insect realm, mostly belong to order Hymenoptera but some are also members of order Diptera and Coleoptera (Godfray 1994; Fernandez Goya et al. 2022). The parasitoids can be endoparasitic and exoparasitic. Endoparasites lay egg inside host, upon hatching the parasitoid larvae consume the host and emerge as adult parasitoid. Parasitoids can be idiobionts (host may permanently paralysed or killed at the time of oviposition) or koinobionts (host is able to carry on with its life while the parasitoid larva(e) develops). Most koinobionts are endoparasites and show more host specialization than idiobionts.

Several groups of endoparasitic hymenopterans have evolved a mutualistic association with PDVs. The PDVs belong to family Polydnaviridae which have circular double stranded DNA (Webb et al., 2006) and possess obligate mutualism with endoparasitic hymenopterans. Two genera of PDVs have been described within the family Polydnaviridae, Ichnoviruses (IVs) and Bracoviruses (BVs), which are associated with parasitoid wasp species of the families Ichneumonidae and Braconidae, respectively. The replication cycles of PDVs are similar to those of typical viruses and include attachment, penetration and entry into host cells, uncoating of the virus nucleocapsid or capsids, replication of the viral nucleic acid in the nucleus, expression of the virus gene, synthesis of virus-specific proteins, and packaging of infectious progeny virions. However, because polydnavirus life cycles and replication are split across and dependent upon two different insect hosts, the aforementioned activities do not take place in this order, in contrast to conventional viruses. PDVs coexist well with their major hosts, parasitoid wasps, where they develop and proliferate but exhibit few detrimental effects. Only a particular population of specialized calyx cells within the female parasitoid oviduct are capable of their morphogenesis and active replication (Gundersen-Rindal et al, 2013). The detrimental effects of these viruses are exerted primarily on the secondary host, where they are injected during parasitoid wasp oviposition along with egg(s), venom, ovarian and other parasitoid proteins and invade host tissues (Schmidt, Theopold, and Strand 2001). During oviposition of parasitoid eggs, PDV particles are injected into the host and infect many host cell types but do not replicate. Virulence gene expression leads to modifications in host physiology. PDVs are vertically transmitted as proviruses through the germ line of wasps but also function as gene delivery vectors that wasps rely upon to genetically manipulate the hosts they parasitize (Strand and Burke, 2014).

History and evolution

Brachoviruses are evolved from nudivirus ancestor and Ichnoviruses are evolved from a progenitor virus that has not yet been characterised (Gundersen-Rindal et al., 2013). The mutualism between Polydnavirus and Parasitoid wasps reveals to be convergent evolution which have established obligate mutualistic associations with parasitoid wasps more than 100 million years ago (Bezier et al. 2009). The Polydnaviridae (PDV), including the Bracovirus (BV) and Ichnovirus genera, originated from the integration of unrelated viruses in the genomes of two parasitoid wasp lineages, in a remarkable example of convergent evolution (Herniou et al., 2014). The virus is anticipated to show a decrease in genomic complexity and evolve under wasp phyletic limitations because it is a wasp mutualist symbiont. high positive selection on the cystatin bracovirus gene for the acquisition of additional functionalities by gene duplication or acquisition is one example of the high selection pressures that the PDVs, a secondary host pathogenic symbiont, is probably enduring (Serbielle et al., 2008).

Significance of Parasioid- Polydnavirus mutualism

1. **Immunosuppression of secondary host**

Insect innate immunity is assorted into two classes, cellular and humoral functions, although there is considerable overlap between the two. The PDVs are able to tackle both immune response of secondary host. They inhibit cellular immune response such as Apoptosis and hemocyte inactivation, Cytoskeleton degradation and encapsulation disruption as well as humoral immune response like Inhibition of melanization and Inhibition of defense molecules for which they have developed various mechanisms (X.-q. Ye et al., 2-18).

2. **Multitrophic interactions**

Virus induced plant- mediated response to herbivore

The PDVs has significant contribution in plant-herbivore interaction, thus contributing to multitrophic interactions. When herbivore host is parasitized by parasitoid, the PDVs get injected to host which bring various physiological and phenotypical changes in the host this ultimately affect how plant response to herbivore attack. Alteration of herbivore phenotype led to change in composition of herbivore oral secretion; also, viral produced peptides are secreted. This induces changes in plant chemical defense and change in herbivore induced plant volatiles (HIPV) (Cusumano and Volkoff, 2021). It has been revealed that the caterpillars which are artificially infected with PDVs can mimic the response of plant induced by parasitized herbivore. Although PDVs stays untouched by plant, they still affect the plant response via changes they make in infected host (Tan et al., 2018).

Revelation of parasitoid to hyperparasitoids

A situation like this always bears pros and cons. So far, we have understood how PDVs play important role in success of parastioids. But not always, they pave path for hyperparasitoids to reach their hosts, parasitoids. The change in oral secretion of parasitized herbivore is crucial for secretion of plant volatiles; these plant volatiles are used as compass by hyperparasitoids. Symbiotic organisms may be key drivers of multitrophic ecological interactions (Zhu et al., 2018).

Conclusion

The parasitoid-polydnavirus mutualism exemplifies nature's masterful engineering, where ancient viral integration empowers wasps to conquer hosts through immunosuppression and multitrophic manipulation. This obligate alliance not only ensures parasitoid reproductive success but also reshapes ecological cascades—from herbivore-plant interactions to hyperparasitoid foraging. As convergent evolution continues to refine this bizarre symbiosis, it offers profound insights into symbiosis-driven adaptation, urging further exploration of its genomic and ecological frontiers.

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TYPES OF EGGS, LARVA AND PUPA IN INSECTS

DIFFERENT TYPES OF EGGS OBSERVED IN INSECTS:

A) SINGLY LAID

1) Sculptured egg: Chorion with reticulate markings and ridges. Eg: castor butterfly

2) Elongate egg: Eggs are cigar shaped. Eg: Sorghum shoot fly

3) Rounded egg: Eggs are either spherical or globular. Eg: Citrus butterfly.

4) Nit:

Egg of head louse is called nit. It is cemented to the base of the hair. There is an egg stigma at the posterior end, which assists in attachment.

5) Egg with float:

Egg is boat shaped with a conspicuous float on either side. The lateral sides are expanded. The expansions serve as floats. Eg: Anopheles mosquito.

b) LAID IN GROUPS

1) Pedicellate eggs:

Eggs are laid in silken stalks of about 1.25 mm length in on groups plants. **Eg: Green lace wing**

2) Barrel shaped eggs:

Eggs are barrel shaped. They look like miniature batteries. They are deposited in compactly arranged masses. **Eg: Stink bug.**

3) Ootheca:

Eggs are deposited by cockroach in a brown bean like chitinous capsule. Each ootheca consists of a double layered wrapper protecting two parallel rows of eggs. Oothecae are carried for several days protruding from the abdomen of female prior to oviposition in a secluded spot. Chitinous egg case is produced out of the secretions of collaterial glands. **Eg: Cockroach**

4) Egg pod:

Grasshoppers secrete a frothy material that encases an egg mass which is deposited in the ground. The egg mass lacks a definite covering. On the top of the egg the frothy substance hardens to form a plug which prevents the drying of eggs.

Eg: Grasshopper

5) Egg case:

Mantids deposit their eggs on twigs in a foamy secretion called spumaline which eventually hardens to produce an egg case or ootheca. **Eg: Mantids**

6) Egg mass:

Moths lay eggs in groups in a mass of its body hairs. Anal tuft of hairs found at the end of the abdomen is mainly used for this purpose. Eg: Rice stem borer. Female silk worm moth under captivity lays eggs on egg card. Each egg mass is called a dfl (disease free laying). **Eg. Moths**

7) Egg raft: In **culex mosquitoes**, the eggs are laid in a compact mass consisting of 200 – 300 eggs are called egg raft in water. **Eg. culex mosquitoes**

DIFFERENT TYPES OF LARVA OBSERVED IN INSECTS:

There are three main types of insectlarvae namely oligopod, polypod and apodous.

1) **OLIGOPOD:** Thoracic legs are well developed. Abdominal legs are absent. There are subtypes:

a) **Campodeiform:** Body is elongate, depressed and well sclerotised. Head is prognathous. Thoracic legs are long. A pair of abdominal cerci or caudal processes is usually present. Larvae are generally predators and are very active.

Eg: grub of ant lion or grub of lady bird beetle.

b) Scarabaeiform:

Body is 'C' shaped, stout and subcylindrical. Head is well developed. Thoracic legsa re short. Caudal processes are absent. Larva is sluggish, burrowing into wood or soil.

Eg: grub of rhinocerous beetle

2) **POLYPOD OR ERUCIFORM**:

The body consists of an elongate trunk with large sclerotised head capsule. Three pairs of thoracic legs and upto five pairs of unjointed abdominal legs or prologs are present.

a) Hairy caterpillar:

The body hairs may be dense, sparse or arranged in tufts. Hairs may cause irritation, when touched.

Eg: Red hairy caterpillar.

b) Slug caterpillar:

larva is thick, short, stout and fleshy. Larval head is small and retractile. Thoracic legs are minute. Abdominal legs are absent. Larva has poisonous scoli distributed all over the body. Such larva is also called platyform larva.

Eg. Slug caterpillar

c) Semilooper: Either three or four pairs of prologs are present. Prologs are either wanting or rudimentaly in either third or third and fourth abdominal segments.

Eg: Castor semilooper.

c) **Looper:** They are also called measuring worm or earth measurer or inch worm. In this type only two pairs of prologs are present in sixth and tenth abdominal segments.

Eg: Tomato looper

3) APODOUS

They are larvae without appendages for locomotion. Based on the degree of development and sclerotization of head capsule, there are three subtypes.

a) Eucephalous

larva with well-developed head capsule with functional mandibles, maxillae stemmata and antennae.

Eg: Wriggler (larva of mosquito) and grub of red palm weevil.

b) Hemicephalous:

Head capsule is reduced and can be with drawn into thorax. Eg: Larva of horse fly and robber fly.

c) Acephalous

Head capsule is absent. They are also called vermiform larvae.

Eg: maggot (larva of housefly)

DIFFERENT TYPES OF PUPA OBSERVED IN INSECTS:

There are three main types of pupae.

1. **OBTECT:** Various appendages of the pupa viz., antennae, legs and wings pads are glued to the body by a secretion produced during the last larval moult. Exposed surface of the appendages are more heavily sclerotised than those adjacent to body.

   Eg: moth pupa.

a) **Chrysalis:** It is the naked obtect pupa of butterfly. It is angular and attractively coloured.The pupa is attached to the substratum by hooks present at the terminal end of the abdomen called cremaster. The middle part of the chrysalis is attached to the substratum by two strong silken threads called gridle.

Eg. Butterfly

b) **Tumbler:** Pupa of mosquito is called tumbler. It is comma shaped with rudimentary appendages. Breathing trumpets are present in the cephalic end and anal paddles are present at the end of the abdomen. Abdomen is capable of jerky movements which are produced by the anal paddles. The pupa is very active **Eg. Mosquito**

2) **EXARATE:** Various appendages viz., antennae, legs and wing pads are not glued to the body. All oligopod larvae will turn into exarate pupae. The pupa is soft and pale.

Eg: Pupa of rhinocerous beetle.

3) **COARCTATE:** The pupal case is barrel shaped, smooth with no apparent appendages. The last larval skin is changed into a case containing the exarate pupa. The hardened dark brown pupal case is called puparium.

Eg: Fly pupa.

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LPG INSECURITY AND THE REVERSION TO BIOMASS COOKING IN SOUTH ASIA WITH SPECIAL REFERENCE TO INDIA

Abstract

The transition to clean cooking energy has been a major developmental priority in South Asia, particularly in India through large-scale initiatives such as the Pradhan Mantri Ujjwala Yojana (PMUY). However, recent disruptions in global energy markets, rising LPG prices, and supply constraints have challenged the sustainability of this transition. In both India and Pakistan, economically vulnerable households are increasingly reverting to traditional biomass fuels such as firewood and agricultural residues. This article examines the intersection of energy insecurity, affordability, and policy implementation, highlighting the gap between access and sustained usage of clean fuels. It further explores the environmental, health, and socio-economic implications of this shift and suggests pathways toward a resilient and sustainable cooking energy system.

Keywords: LPG shortage, Ujjwala scheme, biomass fuel, energy insecurity, rural households.

Introduction

Clean cooking energy is a fundamental component of sustainable development, directly influencing public health, environmental protection, and socio-economic progress. South Asian nations, especially India, have worked hard over the last ten years to switch households from conventional biomass fuels to greener substitutes like Liquefied Petroleum Gas (LPG). The Pradhan Mantri Ujjwala Yojana (PMUY), which was introduced in 2016 to give women from economically disadvantaged groups discounted LPG connections, is a historic project in this area. With millions of households gaining connections and enjoying better living conditions, the program has been well acknowledged for increasing access to LPG (MoPNG, 2023). Similar initiatives have also been seen in nearby nations like Pakistan, where governments have tried to lower reliance on solid fuels by increasing LPG usage. However, access to LPG does not guarantee consistent usage. LPG prices have risen and become less affordable in recent years due to supply chain interruptions, geopolitical conflicts, and the volatility of the world energy market (IEA, 2022). For low-income homes, these difficulties have been especially acute, which has caused a progressive return to traditional cooking techniques. This new tendency draws attention to an important problem: price, dependability, and shock resistance are just as important to the sustainability of clean cooking transitions as access.

Energy Crisis and LPG Supply Disruptions in South Asia

Due to its reliance on imported energy resources, South Asia is extremely susceptible to changes in the world market. Due to its heavy reliance on imports, LPG is strongly impacted by fluctuations in global prices and logistical issues. These problems are frequently made worse by trade uncertainty and geopolitical conflicts, which result in shortages of supplies and price increases (World Bank, 2023).

LPG prices in India have fluctuated significantly over time despite government interventions. Even a little rise in refill costs can result in lower consumption for households that are economically disadvantaged. Similar issues have occasionally led to LPG shortages in Pakistan, especially in rural and isolated locations. The impact of these disruptions is not uniform. Urban populations may adjust through alternative fuels or increased expenditure, but rural households often lack such flexibility. As a result, they resort to traditional biomass fuels, which are locally available and free of direct cost.

Ujjwala Scheme: Progress and Ground Realities

An important development in India's energy strategy is the Pradhan Mantri Ujjwala Yojana. It has enhanced social empowerment and energy access by focusing on women and underrepresented groups. However, a number of studies show that low refill rates limit the scheme's benefits. Many recipients continue to rely on firewood for daily cooking and use LPG sparingly, saving it for certain uses. The "fuel stacking" phenomena is a reflection of rural households' economic circumstances. One of the biggest obstacles is still the price of LPG refills. The upfront cost of cylinder refilling can be prohibitive, even with incentives. Sustained consumption is further limited by problems including inconsistent supply, great distances to distribution centers, and ignorance.

Reversion to Biomass: Socio-Economic Drivers

The switch back to cooking with biomass is a socioeconomic adaptation as much as a technological setback. Affordability and accessibility are more important to households than long-term environmental and health concerns. In rural locations, firewood, agricultural leftovers, and dung cakes are easily accessible, giving them a dependable backup. These conventional fuels offer a sense of energy assurance during emergencies that LPG cannot always ensure. Another factor is acquaintance with the culture. Many homes are used to using traditional cooking techniques, and switching to LPG requires behavioral adjustments that might not be completely maintained without ongoing assistance.

Health Implications of Traditional Cooking Practices

There are serious health risks associated with the rising usage of biomass fuels. High amounts of smoke and pollutants, such as carbon monoxide and particulate matter, are produced by conventional stoves. Long-term exposure to these contaminants can cause heart problems, respiratory disorders, and other health concerns (WHO, 2021). Because they spend more time in culinary situations, women and children are more at risk. The health benefits of clean cooking campaigns could be undone by switching back to biomass fuels.

Environmental Consequences and Sustainability Concerns

The extensive usage of firewood may lead to land deterioration and deforestation from an environmental standpoint. Long-term ecological harm could result from the unsustainable harvesting of biomass resources. It is crucial to remember that biomass is not intrinsically unsustainable. It has the potential to be a renewable energy source if properly handled. When its use is motivated more by necessity than by sustainable planning, a problem occurs. Due to financial and infrastructural limitations, a theoretically sustainable resource is used in an unsustainable way, creating a contradiction.

Energy Poverty and the Access–Affordability Gap

The current state of affairs highlights a significant disparity between energy affordability and access. Although initiatives like the Pradhan Mantri Ujjwala Yojana have been successful in increasing access, the problem of persistent affordability has not been entirely resolved. When households cannot afford to regularly employ the renewable energy sources that are available, energy poverty continues. This emphasizes the need for a more comprehensive approach to energy policy, one that takes economic resilience into account in addition to infrastructure.

Pathways Toward a Resilient Cooking Energy System

Addressing the challenges of LPG non-availability and biomass dependence requires a multi-dimensional strategy:

- **Strengthening subsidy mechanisms** to ensure affordability of LPG refills
- **Decentralizing distribution systems** to improve accessibility in rural areas
- **Promoting alternative clean energy solutions** such as biogas and solar cookers
- **Encouraging improved biomass cookstoves** as transitional technologies
- **Enhancing awareness programs** on health and environmental impacts

Such measures can help bridge the gap between immediate needs and long-term sustainability goals.

Conclusion

In South Asia, the switch from conventional biomass fuels to clean cooking energy is a noteworthy trend. Recent patterns, however, suggest that this advancement is brittle and susceptible to outside shocks like price swings and energy crises. Initiatives such as the Pradhan Mantri Ujjwala Yojana have established a solid basis for access to clean energy in India.

However, in the lack of consistent cost and dependability, the resurgence of biomass-based cooking underscores the shortcomings of access-focused policy. The circumstances necessitate a paradigm change in energy policy that puts sustainability, inclusion, and resilience first. In order to safeguard human health and the integrity of the environment, it is imperative that clean cooking energy be made available and reasonably priced even in times of need.

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Speed Breeding:
Compressing Decades of Crop Improvement into Years

ABSTRACT

Climate change is threatening India's food security. Under moderate projections, rice, wheat, and maize yields could fall by 8 to 20 per cent by 2050. Yet conventional plant breeding takes 10 to 14 years to deliver a new variety from the laboratory to farmers' fields. Speed breeding collapses that timeline by controlling photoperiod, temperature, and humidity inside growing chambers, driving crops through multiple complete life cycles within a single year. Between 2023 and 2025, researchers at four publicly funded Indian institutions in Varanasi, Ludhiana, Hyderabad, and Srinagar developed validated protocols that cut breeding timelines for rice, pigeonpea, and finger millet by half to three-quarters, without touching the plant's genome. This article examines how speed breeding works, what India's scientists have already achieved, its present limitations, and the policy investments needed to scale it.

Keywords: *Accelerated generation advance, BioE3 policy, climate-resilient agriculture, controlled environment agriculture, finger millet, food security, genetic bottlenecking, ICRISAT, IRRI, Oryzasativa, photoperiod manipulation, pigeonpea, plant breeding, Punjab Agricultural University, Rapid Ragi, seed systems, SKUAST-Kashmir, speed breeding, SpeedFlower, SpeedyPaddy, yield stagnation*

Introduction

In 2022, Rashpinder Singh, a Punjab wheat farmer, entered the harvest expecting 1,800 kilograms per acre. He collected 800. An early heat wave scorched the grains before they could fill wheat, potato, and mustard lost to a single season. What happened to Singh was not a freak event. It was a preview of what lies ahead.

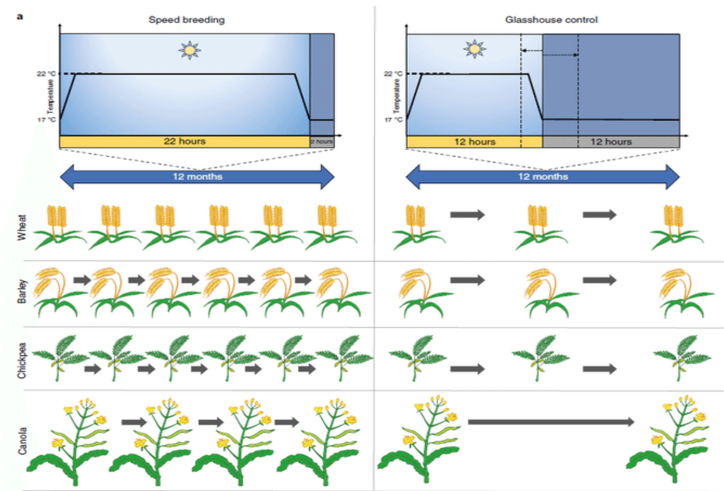

Figure 1: Speed breeding accelerates generation time of major crop plants. Reprinted from "Speed breeding is a powerful tool to accelerate crop research and breeding," by A. Watson et al., 2018, Nature Plants, 4(1), p. 24.

India is home to 1.4 billion people, and 80 per cent of its small and marginal farmers grow crops entirely on rainfall. ICAR has warned that rainfed rice could lose up to 20 per cent of its yield by 2050 without adaptive action (ICAR/MoEFCC, December 2023). Conventional breeding takes 10 to 14 years to bring a new variety from the first cross to farmers' fields (ICRISAT scientists, Down to Earth, February 2026). The climate will not wait a decade.

Speed breeding is the agricultural research community's direct response. Scientists manage conditions in a controlled growing chamber. This lets crops complete multiple life cycles in one year. As a result, they can develop and release climate-resilient varieties much faster. Crucially, no genetic modification is involved at any stage.

Why Conventional Breeding Cannot Win This Race

Plant breeding involves crossing two parents: one that yields well and another that tolerates drought. Then, offspring are grown over several generations, keeping only the best at each stage. Biology imposes a hard constraint: most crop species complete just one or two full life cycles outdoors each year. Pigeonpea (arhar dal) will not flower until daylight shortens to under 11 hours, locking breeders to autumn. Rice is tied to the monsoon; wheat to winter.

The result is a multi-decade process. Pigeonpea took 12 to 13 years from the first cross to the released cultivar (Gangashetty et al., 2024). In contrast, rice's crossing and inbreeding phase lasted 6 to 7 years before field trials started (Kabade et al., 2023). A 2025 review in Reproduction and Breeding found yield stagnation now affects 76 per cent of India's wheat area and 47 per cent of its rice area (Kayess et al., 2025). India needs a steady flow of climate-adapted varieties. The conventional system cannot provide them fast enough.

What is Speed Breeding?

Speed breeding convinces plants to move through their lives faster. Researchers in a controlled setting change three main factors: photoperiod (daily light hours), temperature, and relative humidity. They set each to the crop's optimum and extend light periods beyond what any outdoor location can offer. Plants flower, set seed, and mature far sooner than normal. Seeds are picked at the best time and sown right away, so there are no long gaps between outdoor seasons.

Critically, no genetic modification is involved. Foreign DNA is never introduced, the genome is not edited, and the plant's hereditary code remains entirely unchanged. The varieties made are legally and biologically the same as those from traditional field programmes. So, they don't face extra regulatory checks under Indian biosafety law. Professor Asif Bashir Shikari from SKUAST-Kashmir told Mongabay India in September 2025 that the technology poses no biosafety concerns or regulatory challenges in India.

India's Protocols: What Scientists Have Built

SpeedFlower: Rice (IRRI-SARC, Varanasi)

IRRI's South Asia Regional Centre created SpeedFlower. It uses 800 micromoles of red-to-blue light per square metre per second. This level is much higher than natural sunlight. Rice completes 5.1 to 6.3 generations annually (58–71 days each), compressing a 6-to-7-year process to 1.5–2 years. The protocol is validated in 198 varieties across all 12 sub-groups of Oryza sativa. This uses germplasm from the 3,000 Rice Genome Project (Kabade et al., 2023).

SpeedyPaddy: Rice (Punjab Agricultural University, Ludhiana)

PAU's SpeedyPaddy produces 4 to 5 rice generations each year. It uses cheap halogen tubes instead of expensive LEDs. This change cuts the time from lab lines to field trials from 6–7 years to just 2 years. That's a 71 per cent reduction (Sandhu et al., 2024). Cost-effective equipment makes this protocol accessible to institutions with limited budgets.

SB-Pigeonpea and Rapid Ragi: ICRISAT, Hyderabad

India faces an annual pigeonpea (arhar) shortfall of 1.5 million tonnes worth USD 800 million in imports (ICRISAT, June 2025). ICRISAT's protocol manages photoperiod across three growth stages to cut the core breeding phase from 7 years to 2–4 years. The main product is ICPV 25444, the first heat-tolerant pigeonpea. It can survive temperatures up to 45°C and matures in 125 days. In trials, it yielded 2 t/ha in Karnataka, Odisha, and Telangana. It is awaiting commercial release (Gangashetty et al., 2024). The Rapid Ragi protocol for finger millet (ragi) produces 4 to 5 generations each year. It only needs a 9-hour light period and basic temperature control—no special lighting is required. This makes it easy for many institutions to replicate (Sajja et al., 2025).

SKUAST-Kashmir: Rice in a Cold Climate

Kashmir's environment normally limits rice to one summer crop. Professor Shikari's team achieved four complete rice generations in a single calendar year, replicated independently in 2024 and 2025, targeting blast-resistant and cold-tolerant varieties (Mongabay India, September 2025).

Table 1: Speed Breeding Protocols at Indian Institutions (2023–2025)

Protocol	Crop	Generations /Year	Timeline Reduction	Institution
SpeedFlower	Rice	5.1–6.3	6–7 yrs → 1.5–2 yrs	IRRI-SARC, Varanasi
SpeedyPaddy	Rice	4–5	6–7 yrs → 2 yrs (71%)	PAU, Ludhiana
SB-Pigeonpea	Pigeon pea (Arhar)	3–4	7 yrs → 2–4 yrs	ICRISAT, Hyderabad
Rapid Ragi	Finger Millet (Ragi)	4–5	Significant reduction	ICRISAT, Hyderabad
SB-Rice (SKUAST)	Rice	4	Replicated 2024–25	SKUAST-K, Srinagar

Sources: Kabade et al. (2023); Sandhu et al. (2024); Gangashetty et al. (2024); Sajja et al. (2025); Shikari, Mongabay India (Sep 2025)

Honest Limits: What Speed Breeding Cannot Yet Do

Speed breeding's controlled chambers use a lot of energy. Lighting and climate control run all the time. Costs go up during extreme weather when reliable electricity is crucial (Rai, 2022). Most of India's 63 State Agricultural Universities don't have the same facilities. Funding gaps shown in peer-reviewed studies still limit public-sector adoption (Kabade et al., 2023). A second risk demands management: genetic bottlenecking. Rapid cycling on elite lines can reduce the diversity of the breeding pool. This erodes the genetic reservoir needed to tackle unexpected pests or climate stresses (Sinha et al., 2023; Gudi et al., 2022). Speed multiplies the consequences of a breeder's decisions it does not improve them. Critically, speed breeding shortens only the in-chamber phase. Each variety requires one to two years of field trials in different locations across India before it can be officially released (Shikari, Mongabay India, September 2025). At its best, the technology compresses 14 years to 4–6. Profound but not instant.

What Needs to Change: From Promise to Policy

India's BioE3 Policy (August 2024) prioritises climate-resilient agriculture. It encourages the use of biotechnology and AI to speed up crop development (Government of India, August 2024). Intent is there; infrastructure investment is not. Speed breeding facilities are key national assets, like irrigation networks. They should be funded through a coordinated effort from ICAR, the Department of Science and Technology, and the Department of Biotechnology. This approach is better than piecemeal grants that only support a few centres.

The crop portfolio also needs broadening. Current Indian effort concentrates on rice and pigeonpea. Sorghum, pearl millet (bajra), and lentils all rainfed, nutritionally critical, and climate-exposed attract far less attention. Under NICRA, speed breeding protocols for these underserved crops should be mandated and financed. A faster breeding cycle means little without a reformed seed system. Naresh Kumar from ICRISAT told IndiaSpend in December 2025 that India needs a bigger seed value chain. Also, farmers need ongoing awareness to reach all 650,000 villages. Accelerated breeding and improved seed delivery are linked challenges. They both need to progress together.

Conclusion

Speed breeding works with the rules of plant genetics intelligently and urgently. Indian scientists found that by managing light, temperature, and humidity in a growing chamber, they can cut breeding times for rice, pigeonpea, and finger millet by 50% to 75%. This method requires no genetic modification and faces no regulatory hurdles. Four validated protocols are operational; a heat-tolerant pigeonpea cultivar is under evaluation. We need to grow facilities at India's public universities. We should also expand support for neglected crops and improve the seed value chain. The clock is running speed breeding may be the most practical tool to ensure climate-adapted crops arrive in time to matter.

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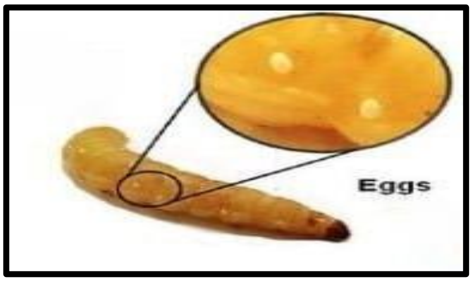
UZI FLY

The uzi fly (*Exorista bombycis* or *Exorista sorbillans*) is a major parasitic pest of the silkworm (*Bombyx mori*) causing significant economic losses to the sericulture industry. The fly is an endo-larval parasitoid, meaning its larvae develop inside the body of the silkworm

Life cycle of the uzi fly

Egg: A female uzi fly lays tiny eggs, often 1-2 at a time, on the silkworm larva. Eggs hatch in about 1.5 to 2 days, or 2-5 days.

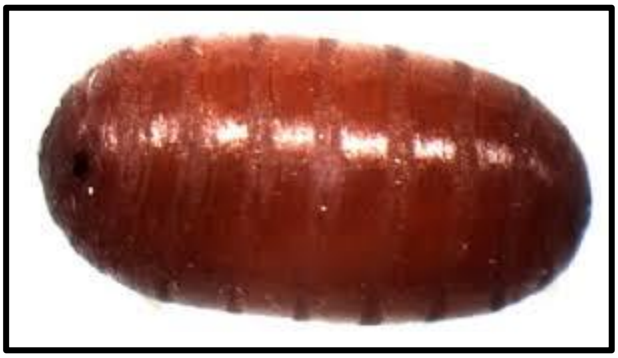


Larva (Maggot):

- ✓ After hatching, the maggot bores into the silkworm, creating a black scar at the entry point.
- ✓ The maggot feeds on the silkworm's tissues, undergoes three instars (stages between molts), and develops for about 6-8 days.
- ✓ The mature maggot leaves the silkworm by creating an opening and then spends 12-20 hours on its own to pupate.

Pupa:

- ✓ The maggot pupates in dark places like soil, cracks, or crevices.
- ✓ This stage lasts for about 10 to 12 days.



Adult:

- ✓ The adult uzi fly emerges from the pupa.
- ✓ The adult lifespan varies, with males living for about 10-18 days and females for about 18-22 days.
- ✓ Adults mate, and the female begins the cycle again by laying more eggs.

Nature of Damage and Symptoms

The female uzi fly lays one or two tiny, creamy white eggs, typically on the intersegmental regions of late instar silkworm larvae (4th or 5th instar).

Black Scar

- ✓ The primary symptom of infestation is a black scar or spot at the point where the maggot hatches and bores into the silkworm's body.

Larval Death

- ✓ The maggot feeds on the internal tissues of the silkworm for about 6-8 days.
- ✓ If the silkworm is infested during the early instars, it dies before it spin a cocoon.

Pierced Cocoons

- ✓ If the infestation occurs in the late fifth instar, the silkworm may spin a cocoon, but the mature maggot will cut a circular hole to emerge, rendering the cocoon unreelable and valueless for commercial silk production.

Behavioral Changes

- ✓ Infested larvae may become sluggish, and their skin might appear shiny before death.

Control and Prevention Measures

Integrated Pest Management (IPM) strategies are recommended, as silkworms are highly sensitive to chemical insecticides.

Cultural/Mechanical Methods

Exclusion

- ✓ The most effective preventive measure is to provide physical barriers.
- ✓ Windows and doors of rearing houses should be fitted with fine wire mesh or nylon nets, and an anteroom can be used at the entrance to prevent adult flies from entering.

Hygiene

- ✓ Maintain strict sanitary conditions in the rearing room.

Litter Disposal

- ✓ After rearing, the silkworm litter should be collected, packed in plastic bags, and kept outside for at least 15 days to destroy any uzi pupae within.

Infested Larvae

- ✓ Manually collect and destroy infested silkworms or pupae by burning or dipping them in a 0.5% soap solution.

Physical Methods

Uzi Traps

- ✓ Use uzi traps with a yellow-colored attractant solution (such as a 1% benzoic acid solution or organic baits) to capture adult flies. These should be placed inside and outside the rearing house from the third silkworm instar onwards.

Biological Methods

Natural Enemies

- ✓ Release the natural pupal parasitoid, *Nesolynx thymus*, in the rearing house.
- ✓ This beneficial insect lays its eggs on uzi fly pupae, killing them and thus reducing the overall uzi fly population.

Chemical Methods

- ✓ Due to the silkworm's sensitivity, chemical methods are limited. Benzoic acid is sometimes used as an ovicide to kill the eggs on the silkworm body when applied within 48 hours of egg laying.

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IN OVO FEEDING: A NOVEL APPROACH IN POULTRY NUTRITION

Introduction

The poultry industry continues to expand in response to rising demand for high-quality protein, necessitating advanced nutritional strategies to improve productivity and efficiency. *In ovo* feeding is one such innovation, involving the injection of nutrients and bioactive compounds into the egg during late incubation. This approach addresses the limitations of yolk-derived nutrition, particularly during the critical final stages of embryonic development. By supplying essential nutrients directly to the embryo, in ovo feeding enhances immune function, gastrointestinal development, and metabolic efficiency, leading to improved hatchability, early growth, and survivability. Widely applied in commercial poultry production, especially in broilers and turkeys, this technique represents a promising tool for optimizing early-life nutrition and overall production performance.

Methods of In Ovo Technology

In ovo technology includes techniques applied during egg incubation to improve embryonic development, hatchability, and post-hatch performance.

1. **In Ovo Injection:** A core method involving the injection of small volumes of nutrients, vaccines, or bioactive compounds into the egg (usually into the amniotic fluid). It is performed using automated systems for accuracy and uniformity.
2. **In Ovo Feeding:** Nutrient solutions (carbohydrates, amino acids, vitamins, minerals) are injected to support embryo growth. Early-stage injections target the albumen, while later-stage injections are directed into the yolk sac or amniotic fluid for efficient absorption.
3. **In Ovo Vaccination:** Vaccines are delivered into the egg to provide early immunity against diseases such as Marek's disease, improving chick health and reducing post-hatch stress.
4. **In Ovo Gene Editing:** A modern technique that modifies the embryo's genetic material to enhance desirable traits like disease resistance and growth performance.
5. **In Ovo Light Treatment:** Controlled light exposure during incubation helps regulate circadian rhythms, improve growth, and enhance physiological development.
6. **In Ovo Electrolyte Supplementation:**Injection of electrolytes (e.g., sodium, potassium, chloride) helps maintain fluid balance and supports embryo survival, especially under heat stress.
7. **In Ovo Heat Treatment:**Thermal manipulation during incubation improves heat tolerance and maintains optimal embryonic development within the thermoneutral range.

Nutrients for in ovo feeding

The primary aim of in ovo nutrition is to accelerate embryonic growth and improve post-hatch performance. Commonly used nutrients include:

- Carbohydrates (e.g., glucose, sucrose, maltose) to provide immediate energy

- Amino acids to promote gastrointestinal development and hatchability
- Fatty acids for energy and cell structure
- Vitamins and minerals for metabolic regulation
- Bioactive compounds for enhanced physiological functions

Routes of In Ovo Feeding: Nutrients can be administered through two main routes:

- **Intra-embryonic route:** Direct injection into embryonic tissues
- **Extra-embryonic route:** Injection into structures such as the yolk sac, albumen, amnion, allantois, chorion, or air cell, from where nutrients are absorbed

Applications and Advantages of in-Ovo Feeding:

In ovo feeding is an effective technique to enhance embryonic development and improve post-hatch performance in poultry.

1. **Improved Chick Quality:** Promotes better organ development, immunity, and overall chick vitality, leading to higher survival and growth rates.
2. **Efficient Nutrient Delivery:** Ensures direct and timely supply of essential nutrients during critical stages of embryonic development.
3. **Enhanced Immunity:** Early introduction of immunostimulants or probiotics strengthens disease resistance and reduces mortality.
4. **Reduced Post-Hatch Stress:** Improves energy reserves, helping chicks adapt quickly to external conditions and increasing early feed intake.
5. **Precision Nutrition:** Allows targeted nutrient delivery, improving gut development and feed efficiency.
6. **Environmental Sustainability:** Enhances nutrient utilization, reducing feed wastage and environmental impact.

Challenges: Despite its proven benefits, the commercial application of *in ovo* feeding faces several key challenges:

1. **Precision and Uniformity:** Accurate control of injection timing, site, and volume is essential. Maintaining consistency across large egg batches remains technically demanding and may affect embryo viability.
2. **Sterility and Biosecurity:** Strict aseptic conditions are required to prevent contamination. Ensuring consistent sanitation and biosecurity protocols at scale can be challenging.
3. **Embryo Sensitivity:** Embryos are highly susceptible to mechanical stress. Improper handling or injection techniques can lead to injury or mortality.
4. **Limited Injection Volume:** The small capacity of the egg restricts the volume and variety of nutrients or bioactive compounds that can be delivered.
5. **Cost and Infrastructure:** mplementation requires specialized automated equipment and skilled personnel, leading to high initial and operational costs.
6. **Regulatory Compliance:** Use of vaccines and novel additives is subject to regulatory approval, which may delay or limit adoption in different regions.
7. **Lack of Long-Term Evidence:** While short-term benefits are well documented, comprehensive data on long-term effects on performance, health, and product quality are still limited.

Conclusion: *In ovo* feeding shows significant potential to enhance embryonic nutrition and physiological development, resulting in improved chick quality at hatch. However, its long-term effects on growth performance and overall productivity remain inconsistent due to variability in study outcomes and the absence of standardized protocols. The development of uniform methodologies covering nutrient composition, injection timing, route, and dosage is essential to ensure reproducibility and optimize results. Despite current limitations, *in ovo* feeding remains a promising innovation in poultry nutrition, with reported benefits including improved early nutrient utilization, enhanced immunity, reduced post-hatch mortality, and better muscle development. With further research and protocol refinement, it has strong potential for successful integration into commercial poultry production systems.

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SOIL MICROBIOME DYNAMICS & THEIR ROLE IN SOIL FERTILITY & PLANT NUTRITION

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Abstract

Soil is a dynamic and living system that supports plant growth and agricultural productivity. It contains a wide range of microorganisms collectively known as the soil microbiome. These microorganisms include bacteria, fungi, actinomycetes, algae, protozoa, nematodes, and earthworms. They play an essential role in nutrient cycling, organic matter decomposition, soil aggregation, and plant growth promotion. Soil microbes are directly involved in nitrogen fixation, phosphorus solubilization, mineralization, and improvement of soil health. The rhizosphere and phyllosphere are important zones where plant-microbe interactions occur actively. Modern agriculture often depends heavily on chemical fertilizers, which may negatively affect microbial diversity and soil quality. Therefore, understanding soil microbiome dynamics is important for sustainable agriculture, higher nutrient use efficiency, and long-term soil fertility.

1. INTRODUCTION

Soil is a living system that supports plant growth, regulates nutrient cycling, and maintains ecosystem stability. One of the most important components of soil is the **soil microbiome**, which consists of a vast and diverse community of microorganisms such as bacteria, fungi, actinomycetes, algae, protozoa, and soil fauna. These organisms are essential for maintaining soil fertility, improving soil structure, decomposing organic matter, and making nutrients available to plants.

The soil microbiome plays a central role in key biogeochemical cycles, particularly the nitrogen, phosphorus, and carbon cycles. Microorganisms convert unavailable forms of nutrients into plant-available forms through processes such as nitrogen fixation, ammonification, nitrification, phosphorus solubilization, and organic matter decomposition. Without microbial activity, nutrients would remain locked in the soil and organic residues, limiting plant growth and agricultural productivity.

In recent years, increasing attention has been given to the soil microbiome due to its importance in sustainable agriculture. Excessive use of chemical fertilizers and pesticides has negatively affected soil biological health, leading to soil degradation and reduced productivity. In contrast, the use of biofertilizers, compost, and microbial inoculants has shown positive effects on soil fertility, crop yield, and environmental sustainability.

Therefore, understanding soil microbiome dynamics and their role in soil fertility and plant nutrition is essential for developing eco-friendly and sustainable agricultural practices that ensure long-term food security and environmental protection.

2 SOIL MICROBIOME COMPOSTION AND DIVERSITY

Compared with topsoil (0-15 cm), the lower layers of soil contains fewer microorganisms due to the depletion of oxygen and nutrients (Hoorman, 2020)

Micro organisms	Number/g of soil
Bacteria	$10^8 – 10^9$
Actinomycetes	$10^7 – 10^8$
Fungi	$10^5 – 10^6$
Algae	$10^4 – 10^5$
Protozoa	$10^3 – 10^4$
Nematodes	$10^2 – 10^3$

3. RHIZOSPHERE & PHYLLOSPHERE: The term rhizosphere first coined by "Lorents Hiltner". It is the region of soil contact with the roots of plant. It content many microorganism influenced by the roots & it is a relatively stable, nutrient-rich environment.

Phyllosphere - The term phyllosphere first coined by "Ruinen" The phyllosphere is a term used in microbiology to refer to the total above-ground portions of plant.

4. CLASSIFICATION OF SOIL ORGANISMS

Living organism present in the soil are grouped into categories as follows-

(A) **Soil flora** (Micro flora): Bacteria, Fungi, Actinomycetes and Algae.

Macro flora: Plant roots, Macro algae

(B) **Soil fauna** (Micro fauna): Protozoa, Nematodes, Earthworm,

Macro fauna: Moles, Ants and Rodents.

Relative proportion/percentage of various soil microorganism are: Bacteria-aerobic (70%) anaerobic (13%), actinomycetes (13%), fungi (3%), and (algae, protozoa, viruses) 0.2-0.8%.Soil organism play key role in the nutrient transformation.

(A) SOIL FLORA

(1) Micro flora

BACTERIA- Bacteria are prokaryotes, single celled organisms. They are known for rapid proliferation and reproduced by binary fission. Size varies from 0.5 to 1 micron in diameter and 1 to 10 micron (length). The genus *Bacillus* has largest species of the soil followed by *Pseudomonas.*

CLASSIFICATION OF BACTERIA

(A) Based on nutrition - Bacteria are classified into different groups depending on how they obtain **carbon, energy, and electrons** for growth.

1. **Autotrophic Bacteria-** These bacteria prepare their own food from inorganic substances.

(A) **Photoautotrophic Bacteria-** Use sunlight as an energy source. Example: *Cyanobacteria, Chlorobium*

(B) **Chemoautotrophic Bacteria-** Obtain energy by oxidizing inorganic compounds like ammonia, sulfur, iron, or hydrogen. Example: *Nitrosomonas*, *Nitrobacter*, *Thiobacillus*

(2) Heterotrophic Bacteria- These bacteria depend on organic substances for food. Example:*Rhizobium, Frankia, Anabaena, Azotobacter, derxia, Beijerinckia.*

(b) Based on temperature:-

(1) **Psychrophiles**-Psychrophilic bacteria are cold-loving microorganisms (extremophiles) that thrive in freezing to cold environments (below 10°C). e.g *Arthrobacter*

(2) **Mesophiles-** Mesophilic bacteria are microorganisms that thrive in moderate temperatures, typically growing best between 20°C and 45°C. e.g *Streptococcus ,Clostridium*

(3) **Thermophiles-** heat-loving microorganisms that thrive in extremely hot environments 45°C to over 100°C. e.g. *Bacillus*

FUNGUS- Fungi are heterotrophs, lack of chlorophyll and are primarily responsible for organic matter decomposition. Fungi are eukaryotic and hence more closely related to plants and animals than to bacteria. They also have membrane bound organelles such as mitochondria. Fungi have a cell wall composed of glucans and chitin.

A mutually beneficial (symbiotic) association between fungi and the roots of higher plants is called 'Mycorrhizae" (fungus root), is useful in adsorption of nutrients. Eg. VAM-fungi

ALGAE- The term algae are used to describe a large collection of photosynthetic, eukaryotic organisms. Algae are a very wide and varied group of simple, usually autotrophic organisms. Algae can make its own nutrient through a process known as photosynthesis. Reproduction in algae occurs in both asexual and sexual forms. Asexual reproduction occurs by spore formation. Soil algae are chlorophyll-containing organisms. They are autotrophic. The algae are classified on the basis of the colour (pigments) as: (1) Cyanophyta (blue green) (2) Chlorophyta (grass green), (3) Xanthophyta (yellow green).

Blue green algae, also known as "Cyanobacteria" they fix about 20 kg N per ha. They fix nitrogen in specialized cellular structures "heterocysts". Cyanobacteria are the major microbes which fix nitrogen in paddy fields. The agricultural importance of cyanobacteria in rice cultivation is because of their nitrogen-fixing ability and other positive effects on soil and plants.

ACTINOMYCETES

Actinomycetes are important soil components, & they are more common in dry soil, high pH, high temperature. They are next to bacteria in numbers and are fairly widely distributed in soils. The smell of fresh soil wetted upon first rains is due to the production of volatile aromatic compounds by actinomycetes like "geosmin".

(2) MACRO FLORA:- Roots of higher plants

Functions in soil- The dead plant contribute to the formation of the soil organic matter which , provides food, energy and nutrients to microorganisms and also higher plants process of cycling of plant nutrients .

(B) SOIL FAUNA-

(1) Micro fauna- Protozoa, Nematodes.

(A) Protozoa - Protozoa are single-celled, eukaryotic microorganism. When protozoa eat bacteria, they speed up the cycling of nitrogen, making nitrogen more available to plants. They are larger than bacteria, varying from a few microns to a few millimeters.

(B) Nematodes

Nematode, also called roundworm. The number of named species is about 20,000. Nematodes are bilaterally symmetrical, elongate, and usually tapered at both ends. Nematodes range in size from microscopic to 7 metres. This speeds up nutrient recycling.

(2) MACRO FAUNA- Earthworm, Moles, Ants and Rodents.

(A) Earthworms: Earthworms are commonly found in soil, eating a wide variety of organic matter. Earthworms are one of the most important soil animals; they have the capability to maintain the fertility of the soil and therefore play a key role in sustainability. They are also known as farmer's friend, ploughman of the field, intestines of the earth, ecological engineers, and biological indicators. Earthworms are functionally very important and diverse, and therefore potentially useful for the management of biodiversity and ecosystem services.

Species:

(a) Eisenia fetida

(b) Lumbricus rubellus

(c) Eudrilus Eugenie.

(B) Moles

Moles Any burrowing, often blind insectivore in the family Talpidae. Most species have short legs and tail, a pointed head, velvety greyish fur, no external ears, and a strong odour. They range from 3.5 to 8 in. (9 to 20 cm) long. Moles are active day and night, digging surface tunnels in search of earthworms, grubs, and other invertebrates.

5. ROLE OF ORGANISM IN SOIL FERTILITY MAINTAINING

Nitrogen cycle : The percentage of nitrogen in atmosphere 78% plant do not uptake directly, the conversion of atmospheric nitrogen into plant-usable forms through the biological nitrogen fixation. This process completed in four stage-

1. Nitrogen fixation

2. Ammonification

3. Nitrification

4. Denitrification

(1) Nitrogen Fixation: Nitrogen fixation is a process by which atmospheric **nitrogen** is **converted** into **ammonia** with the help of nitrogen fixing bacteria.

MECHANISMS OF NITROGEN FIXATION BY LEGUME *RHIZOBIUM* -The rhizobium are symbiotically associated with the root of legume. The rhizobium obtain nutrition from the cell of roots and enter the fix of nitrogen into ammonia. Legume roots secrete chemical signals, particularly flavonoids, which attract Rhizobium bacteria present in the soil & attached near the root hairs. The rhizobia are delivered into cortical cells, they change their morphology and physiology to become bacteroid, the actual seat of N_2 fixation. Bacteroides produce nitrogenase enzyme and responsible for fixation of nitrogen are embedded into leghaemoglobin, a hemeprotein. The role of leghaemoglobin is to regulate the supply of oxygen to bacteroid.

(2) Ammonification-The decomposition of dead plant (in form of organic N_2) or living organisms release of ammonia with the help of micro organisms.

(3) Nitrification- Nitrification is the process that converts ammonia to nitrite and then to nitrate and is another important step in the global nitrogen cycle. Most nitrification occurs aerobically and is carried out exclusively by prokaryotes. There are two distinct steps of nitrification that are carried out by distinct types of microorganisms. The first step is the oxidation of ammonia to nitrite, which is carried out by microbes known as ammonia-oxidizers. Aerobic ammonia oxidizers convert ammonia to nitrite via the intermediate hydroxylamine, a process that requires two different enzymes, ammonia monooxygenase and hydroxylamine oxidoreductase (Figure 4). The process generates a very small amount of energy relative to many other types of metabolism; as a result, nitrosofiers are notoriously very slow growers. Additionally, aerobic ammonia oxidizers are also autotrophs, fixing carbon dioxide to produce organic carbon, much like photosynthetic organisms, but using ammonia as the energy source instead of light.

Unlike nitrogen fixation that is carried out by many different kinds of microbes, ammonia oxidation is less broadly distributed among prokaryotes. Until recently, it was thought that all ammonia oxidation was carried out by only a few types of bacteria in the genera *Nitrosomonas*, *Nitrosospira*, and *Nitrosococcus*. However, in 2005 an archaeon was discovered that could also oxidize ammonia (Koenneke *et al*. 2005). Since their discovery, ammonia-oxidizing Archaea have often been found to outnumber the ammonia-oxidizing Bacteria in many habitats. In the past several years, ammonia-oxidizing Archaea have been found to be abundant in oceans, soils, and salt marshes, suggesting an important role in the nitrogen cycle for these newly-discovered organisms. Currently, only one ammonia-oxidizing archaeon has been grown in pure culture, *Nitrosopumilus maritimus*, so our understanding of their physiological diversity is limited. The second step in nitrification is the oxidation of nitrite (NO_2^-) to nitrate (NO_3^-) (Figure 2). This step is carried out by a completely separate group of prokaryotes, known as nitrite-oxidizing Bacteria. Some of the genera involved in nitrite oxidation include *Nitrospira*, *Nitrobacter*, *Nitrococcus*, and *Nitrospina*. Similar to ammonia oxidizers, the energy generated from the oxidation of nitrite to nitrate is very small, and thus growth yields are very low. In fact, ammonia- and nitrite-oxidizers must oxidize many molecules of ammonia or nitrite in order to fix a single molecule of CO_2. For complete nitrification, both ammonia oxidation and nitrite oxidation must occur.

(4) Denitrification-Denitrification is a natural biological process in the nitrogen cycle where converting nitrates (NO_3^-) into gaseous nitrogen (N_2) or nitrous oxide (N_2O) with the help of denitrifying bacteria under anaerobic (low oxygen) conditions. Common genera of these bacteria include *Pseudomonas, Bacillus , Paracoccus, and Clostridium*

Nitrate (NO_3^-) → Nitrite (NO_2^-) → Nitric oxide (NO) → Nitrous oxide (N_2O) → Nitrogen gas (N_2).

2. PHOSPHORUS SOLUBILIZATION-: Phosphorus solubilizing bacteria (PSB) are a group of beneficial microorganisms that convert insoluble phosphorus into soluble forms, that can be readily absorbed by plant roots.

1. Mechanisms of Solubilization - They secrete organic acids which lower the soil pH and dissolve insoluble phosphates. Enzyme production such as phosphatases & phytases react with Al Fe & breakdown to release phosphate from organic compounds. Phosphate-solubilizing bacteria is *Bacillus* and *Pseudomonas.*

2. **Decomposition-** Fungi and bacteria break down organic matter into humus, releasing essential nutrients.

MECHANISMS OF ARBUSCULAR MYCORRHIZA FUNGI - The spore of Am fungi germinate in soil nearest the root. Fungal hyphae contact the root surface and penetrate the outer root cells.

Formation of Symbiotic Structure: **Endomycorrhiza-** The plant produce organic molecules by photosynthesis & fungi get absorb compound in the farm of sugar, & fungus helps transfer of nutrients in plant roots.

Hartig Net (in Ectomycorrhiza):- form the outer layer of the root. A network of hyphae grows between cortical cells, it help to nutrient transfer. Hyphae absorb & deliver micro, macronutrients & water to plant.

- **Mycorrhizal Associations:-** It is a symbiotic relationships between fungus and plant roots. enhancing water and nutrient absorption (especially phosphorus).

- **Ectotrophic Mycorrhiza:-** When the fungus forms a mantle or sheath around the root surface (called Harting net) The fungi which form this type of association are species of ***Boletus*** and ***Amanita.***

- **Endo-mycorrhiza**:- When the fungus develops intracellularly in the root without forming Harting net. In this association, the penetration of roots cells formation of terminal spherical structure called **vesicles**, which contain **oil droplets** and p**hosphorus**. This type of mycorrhiza is called "**Vesicular Arbuscular Mycorrhizae" (VAM).**

BENEFICIAL EFFECT OF AM FUNGI- The beneficial effect of these fungi on nutrient uptake has been attributed to three factors-

1. Increased absorption of available nutrients from soil as the fungus changes root morphology, which results in the larger root surface available for nutrient absorption. Fungal filaments also act as the absorption surface.

2. P is insoluble in the soil, Increasing the solubilizing of P with the help of AM fungi which thus become available to plants.

3. Increasing the nutrient mobility due to faster intracellular nutrient absorption and mobilizing nutrients from the soil in the root.

7. **MICROBIAL INTERACTION**: One organism can be located on the surface of another organism as an ectobiont or located within another organism as endobiont. Microbial interaction may be positive such as mutualism, proto-cooperation, commensalism or may be negative such as parasitism, predation or competition.

TYPES OF MICROBIAL INTERACTION

1. **Positive interaction**:- **Mutualism, Symbiosis,**
2. **Negative interaction**:-**Antagonisms, Parasitism**, **Predation, Competition**

(I) **Mutualism-** A relationship in which both organisms benefit and are dependent on each other . *Example:* Rhizobium, mycorrhizae.

(II) **Amensalism (antagonism):-** A relationship where one organism inhibits another by producing harmful substances, while itself remains unaffected. eg. Antibiotic *Penicillium*, which kills various bacteria.

(III) **Competition:-** A negative relationship in which two organisms compete for the same space or nutrients, affecting the growth of both. *Example:* Diatoms and cyanobacteria.

(IV) **Parasitism:-** A relationship in which one organism (parasite) benefits by obtaining nutrients from another organism (host), causing harm to the host. *Example:* Cuscuta in lucerne, Striga in sorghum.

(V) **Predation-** A relationship where one organism (predator) attacks and consumes another organism (prey), usually resulting in the death of the prey. *Example:* Protozoa and nematodes feeding on bacteria and fungi.

8. FACTORS INFLUENCING SOIL MICROORGANISM COMPOSITION AND DIVERSITY

Soil microbial diversity and composition are shaped by both **abiotic** (non-living: pH, moisture, temp, nutrients) and **biotic** (living: plants, predators, organic matter, other microbes) factors, with abiotic factors often setting broad limits and biotic interactions fine-tuning specific communities, though their interplay varies by ecosystem type, with pH and carbon often critical drivers.

Abiotic factors

- ✓ **Soil Properties Texture:-** Sandy soils often have less microbial biomass compared to clayey or loamy soils due to differences in water and nutrient retention.
- ✓ **pH:-** Neutral to slightly acidic soils favor higher microbial diversity. Extreme pH levels can limit specific microbial populations.
- ✓ **Moisture Content:-** Water availability impacts microbial activity, as microbes require moisture for metabolism.
- ✓ **Temperature:-** Microbial growth rates are temperature-dependent, with certain microbes thriving in specific temperature ranges.
- ✓ **Nutrient Availability:-** Organic matter and nutrients like carbon, nitrogen, and phosphorus influence the abundance and diversity of microbes.

Environmental and management factors-

- ✓ **Land use and agriculture tillage:-** Intensive tillage disrupts microbial habitats, potentially reducing diversity.
- ✓ **Fertilizer:-** Excess chemical fertilizers can Favor fast-growing microbes while inhibiting slow-growing ones. Organic amendments, like compost, generally enhance diversity.
- ✓ **Pesticides: -** Over use can kill or suppress sensitive microbial populations.
- ✓ **Climate change:-** Alterations in temperature, rainfall patterns, and CO_2 levels affect microbial survival and activity.

Biotic factors-

- ✓ **Faunal activities:-** Earthworms and soil-dwelling insects alter microbial communities by breaking down organic matter, mixing soil layers, and creating micro habitats.
- ✓ Organic Matter (OM)**:-** Quality and quantity (litter, residues) are primary food sources, influencing decomposers.
- ✓ Plants & Roots**:-** Provide carbon (root exudates), influence soil structure, and create specific micro habitats (rhizosphere).
- ✓ Other Microorganisms**:-** Competition, predation, and symbiotic relationships (e.g., bacteria-fungi) structure communities.
- ✓ Microfauna & Macrofauna**:-** Earthworms, nematodes, etc., alter soil structure, nutrient cycling, and microbial habitats.

Conclusion: The soil microbiome is the foundation of soil fertility and plant nutrition. Soil microorganisms perform essential functions such as nutrient cycling, decomposition, soil aggregation, and plant growth promotion. Sustainable agricultural practices that conserve and enhance microbial diversity are necessary for long-term productivity and environmental protection. Future farming systems should focus on managing soil as a living ecosystem rather than only as a medium for fertilizers.

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CLIMATE-SMART CROPPING SYSTEMS: A PATH TO RESILIENT AGRICULTURE

Strategies for Sustainable and Adaptive Farming under Climate Change

Abstract

Climate change has become a significant threat to agricultural sustainability, impacting crop yields, soil quality, and water access. Climate-smart cropping systems (CSCS) provide a comprehensive method to improve agricultural resilience, productivity, and environmental sustainability. These systems rely on three main pillars: boosting productivity, adjusting to climate changes, and cutting down on greenhouse gas emissions. This paper examines the idea, elements, and advantages of climate-smart cropping systems, such as conservation agriculture, effective water management, crop variety, and precision farming technologies. It also emphasizes their contribution to enhancing resource-use efficiency and improving farmers' livelihoods, especially in developing countries such as India. The research finds that broadly implementing climate-smart practices is crucial for creating sustainable and resilient agricultural systems in the face of changing climate conditions.

Keywords: Climate change, Climate-smart agriculture, Crop diversification, Resilience, Sustainable agriculture

INTRODUCTION

Agriculture is very sensitive to climate change because it relies heavily on climate factors like temperature and precipitation. The rising occurrence of extreme weather events, such as droughts and floods, has had a major impact on crop yields and global food security. Research suggests that increasing temperatures and climate fluctuations may lead to lower crop production, especially in tropical and subtropical areas.

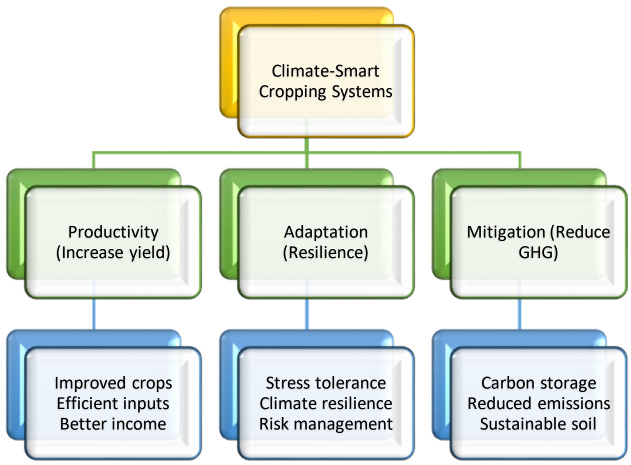
Climate-smart agriculture (CSA) has emerged as a strategic method to tackle these issues by improving productivity, resilience, and environmental sustainability. It emphasizes fulfilling food needs while reducing environmental effects and adjusting to climate change. In areas like Asia, where development is ongoing, climate change has already caused soil degradation, water shortages, and a rise in pest problems, making it essential to implement sustainable farming methods.

CONCEPT AND PRINCIPLES OF CLIMATE-SMART CROPPING SYSTEMS

Climate-smart cropping systems is mainly based on three major objectives:

1. Increasing agricultural productivity and income
2. Enhancing resilience and adaptive capacity

Reducing greenhouse gas emissions



These principles seek to promote sustainable agricultural growth and manage climate-related risks. CSA combines technological advancements, better crop management, and effective resource use to ensure long-term sustainability.

KEY COMPONENTS OF CLIMATE-SMART CROPPING SYSTEMS

Conservation Agriculture

Conservation agriculture mainly includes minimal soil disruption, keeping crop residues, and rotating crops. These methods enhance soil structure, minimize erosion, and increase water retention. It also helps in reducing climate change by enhancing soil organic carbon and lowering greenhouse gas emissions.

Soil Carbon Sequestration

Soil is essential in reducing climate change by capturing and storing carbon. Implementing sustainable practices like conservation tillage, cover cropping, and the use of organic amendments can notably enhance soil carbon storage, which in turn helps lower atmospheric carbon dioxide levels.

Efficient Water Management

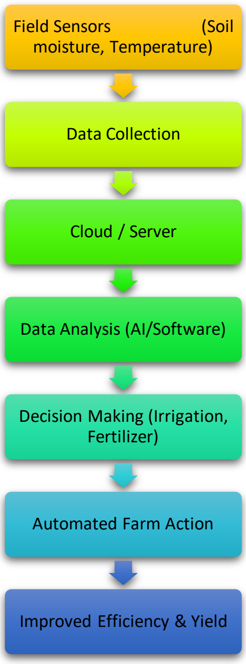
Water scarcity poses a significant challenge to agriculture in the context of climate change. Climate-smart methods like drip irrigation, sprinkler systems, and alternate wetting and drying (AWD) enhance water efficiency and increase crop yields. Research indicates that using AWD in rice farming improves water use efficiency without reducing crop output.

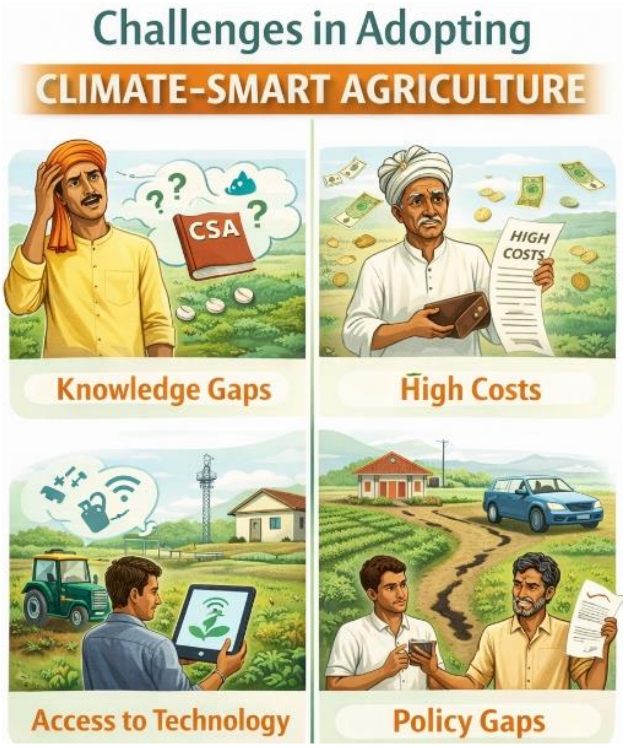
Crop Diversification and Intensification

Crop diversification lowers risk by distributing it among various crops, whereas intensification enhances output per unit of land. Systems like rice-wheat cropping systems can be enhanced by diversification, zero tillage, and residue management to improve sustainability.

ROLE OF PRECISION AGRICULTURE AND IoT

Modern Advanced technologies like precision agriculture and the Internet of Things (IoT) are essential components of climate-smart systems. IoT-based sensors allow for real-time tracking of soil moisture, temperature, and crop conditions, facilitating effective resource management. These technologies assist in lowering input costs, enhancing productivity, and reducing environmental effects. Wireless sensor networks help support ongoing monitoring and decision-making in agricultural systems, improving efficiency and sustainability.





BENEFITS OF CLIMATE-SMART CROPPING SYSTEMS

Climate-smart cropping systems provide several benefits:

- Increased crop productivity and yield stability
- Improved soil fertility and structure
- Enhanced water-use efficiency
- Reduced greenhouse gas emissions
- Improved farmer income and livelihood security

Studies have shown that farmers adopting climate-smart practices achieve higher resource-use efficiency and better economic returns compared to conventional farming systems.

CHALLENGES IN ADOPTION

Despite their advantages, several challenges hinder the implementation of climate-smart practices:

- Lack of awareness and technical knowledge
- High initial investment costs
- Limited access to advanced technologies
- Inadequate institutional and policy support

Socioeconomic factors such as access to credit and extension services significantly influence the adoption of CSA practices among farmers.

INDIAN PERSPECTIVE AND FUTURE PROSPECTS

In India, programs like the National Innovations on Climate Resilient Agriculture (NICRA) have shown how climate-smart methods, including rainwater harvesting, micro-irrigation, and enhanced cropping systems, can be effective. These interventions have boosted cropping intensity and enhanced productivity across multiple regions.

The future of climate-smart agriculture depends on incorporating advanced technologies, improving policy support, and increasing farmer awareness.

CONCLUSION

Climate-smart cropping systems offer a sustainable approach to tackle the challenges posed by climate change in agriculture. By incorporating conservation methods, effective resource management, and contemporary technologies, these systems improve resilience, productivity, and environmental sustainability. Their broad implementation is crucial for guaranteeing food security and promoting sustainable agricultural growth in the future.

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Fertilizer Use Efficiency in Intensive Cropping Systems: Balancing Productivity and Environmental Sustainability

Abstract

Agricultural systems are under increasing pressure to increase crop yields due to the world's growing food demand, which frequently leads to overuse of fertilizer. A crucial indicator for sustainable agriculture is Fertilizer Use Efficiency (FUE), which is the ratio of crop nutrient uptake to total nutrient applied. The science of FUE, site-specific nutrient management (SSNM) techniques, precision agriculture instruments, biological nitrogen fixation, and enhanced-efficiency fertilizers (EEFs) are all covered in this article. Based on available data, it makes the case that increasing FUE is both economically and agronomically viable, and that not doing so has serious negative effects on the environment, such as eutrophication, greenhouse gas emissions, and nitrate poisoning of groundwater. This article highlights the scalable strategies for sustainable intensification
Keywords: Precision agriculture, Fertilizer use Efficiency, Biological nitrogen fixation, Food demand, Groundwater.

Introduction

By 2050, there will be 9.7 billion people on the planet, which would put hitherto unheard-of strain on food production systems. As a result, the majority agricultural paradigm is intense cropping, which is defined by high-yielding cultivars, automation, and substantial pesticide inputs. Global nitrogen fertilizer use exceeded 110 million tonnes in 2022. but crop nitrogen use efficiency (NUE) for cereals frequently falls below 40%, meaning that more than half of applied nitrogen is lost to the environment through leaching, denitrification, and volatilization Similarly, phosphorus recovery efficiency at the field scale seldom exceeds 25–30%. The mechanisms of nutrient loss, agronomic and technological approaches to enhancing FUE, and the legislative framework required to scale adoption across intensive cropping landscapes are all reviewed in this paper.

2. Mechanisms of Nutrient Loss in Intensive Systems

2.1 Nitrogen Pathways

The soil-plant system undergoes a complicated transition when nitrogen gets delivered as urea or ammonium-based fertilizers. Specially in high-temperature, alkaline, or low-moisture environments, ammonia volatilization from surface-applied urea can account for 15–40% of applied N. In coarse-textured or extensively irrigated soils, nitrification the microbial conversion of NH_4^+ to NO_3^- makes nitrogen extremely vulnerable to leaching; in South Asian rice-wheat systems, leaching losses of up to 50 kg N ha^{-1} yr^{-1} have been documented. 10 to 30 percent of applied N as N2 and N2O can be attributed to denitrification in anaerobic environments (such as flooded rice fields).

2.2 Phosphorus Loses

Because of its great sorption affinity for soil particles, phosphorus losses are mostly caused by surface runoff and erosion rather than leaching, in contrast to nitrogen. Particulate-P losses can reach 1–5 kg P ha^{-1} yr^{-1} in sloping agricultural landscapes with high rainfall, which greatly contributes to downstream eutrophication. Another avenue of concern in tile-drained agroecosystems is dissolved reactive phosphorus in subsurface drainage.

2.3 Potassium and Micronutrient Dynamics

Particularly in South and Southeast Asia, potassium depletion is becoming more common in intensively farmed soils where crop removal rates exceed replenishment. On sandy, acidic soils, potassium leaching is important, and when K is plentiful, crop luxury consumption lowers agronomic efficiency. By restricting root architecture and enzyme activity essential to nitrogen metabolism, micronutrient imbalances, particularly those involving zinc, boron, and iron, further reduce NUE.

3. Strategies to Improve Fertilizer Use Efficiency

3.1 The 4R Nutrient Stewardship Framework

A popular operational guide for enhancing FUE is provided by the 4R concept, which stands for Right Source, Right dose, Right Time, and Right method. Applying the proper source involves selecting fertilizer materials that are appropriate for the pH, texture, and physiology of the soil. To prevent both excessive fertilization and insufficient fertilization, proper rate application necessitates soil testing and calibrated yield-goal targets.

3.2 Stie Specific Nutrient Management (SSNM)

A technique of managing plant nutrients that maximizes yield and nutrient usage efficiency by applying the appropriate source and quantity of fertilizers at the appropriate time and location, depending on the particular soil conditions, crop requirements, and field variability Leaf colour charts (LCC), and optical sensors to measure crop nitrogen status in real time, site-specific nutrient management (SSNM).

3.3 Precision Agriculture & Digital Tools

The convergence of remote sensing, geographic information systems (GIS), variable rate technology (VRT) Satellite-derived vegetation indices particularly the Normalized Difference Vegetation Index (NDVI) and the Red-Edge Chlorophyll Index (CIre). More recently, drone-based multispectral imaging has enabled canopy-level N diagnostics with sub-meter spatial resolution.

PRECISION AGRICULTURE TOOLS FOR FUE IMPROVEMENT

Leaf Color Charts (LCC): Low-cost, visual tool for real-time canopy N diagnosis.

Active Optical Sensors (NDVI, SPAD): Reflectance-based crop N status; calibrated for VRT applicators.

Drone/UAV Multispectral Imaging: Sub-meter resolution canopy N mapping for large-scale fields.

Variable Rate Technology (VRT): GPS-guided applicators that vary fertilizer rate by field zone.

Soil Electrical Conductivity (EC) Mapping: Delineates management zones for site-specific nutrient prescription.

AI-Powered Fertilizer Decision Tools: Machine learning models integrating soil, weather, and yield history.

3.4 Enhanced Efficiency Fertilizers (EEFs)

In order to minimize losses at the source, enhanced-efficiency fertilizers are a product-level technological intervention that synchronizes nitrogen delivery with crop need. Slow-release fertilizers (SRFs), controlled-release fertilizers (CRFs), and fertilizers with urease or nitrification inhibitors are the three main types. Polymer-coated urea (PCU), a leading CRF, encapsulates urea granules in semipermeable membranes that regulate N release over 60–180 days depending on soil temperature.

3.5 Biological Approaches & Integrated Nutrient Management (INM)

According to (Herridge et al. (2008), well-modulated soybean, chickpea, and clover fix 100–300 kg N ha^{-1} yr^{-1}, and BNF contributes around 100–140 T N yr^{-1} to agricultural ecosystems worldwide. According to (Peoples et al. 2009), adding legume intercrops or cover crops to intensive cereal rotations can reduce external N inputs by 30–80 kg N ha^{-1} in the subsequent season.

Integrated Nutrient Management (INM) combining mineral fertilizers with organic amendments (compost, farmyard manure, green manure) improves soil organic matter, cation exchange capacity, and microbial biomass, collectively enhancing both nutrient supply and retention.

4. Conclusion

The evidence reviewed here demonstrates unequivocally that large, economically and ecologically meaningful improvements in FUE are achievable across diverse cropping systems through the integrated application of site-specific nutrient management, precision agriculture tools, enhanced-efficiency fertilizers, biological approaches, and genetic improvement. No single technology or practice constitutes a silver bullet. FUE technologies, and value the public goods generated by cleaner air, water, and soil.

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Carbon Sequestration in Vegetable Cropping Systems for Sustainable Soil Health

Abstract

The global agricultural sector faces an unprecedented challenge: feeding a growing world population while simultaneously reversing decades of environmental degradation. Sustainable cropping systems have emerged as a scientifically grounded and practically viable response to this dual mandate. This article examines the principles, key components, and measurable benefits of sustainable cropping systems, exploring practices such as crop rotation, intercropping, cover cropping, and integrated pest management (IPM). Supported by empirical data (Figure 1) and a structured decision-making framework (Figure 2), the article argues that transitioning to sustainable cropping is not merely an ecological imperative but also an economic opportunity for farmers, policymakers, and agri-businesses worldwide.

Keywords: Groundwater, Biodiversity, Conventional Farming, Climate Change.

Introduction

Agriculture has been the backbone of human civilization for over 10,000 years. Yet modern intensive farming while dramatically increasing short-term yields has left a trail of environmental degradations oil erosion, groundwater depletion, biodiversity loss, and significant greenhouse gas emissions. According to the Food and Agriculture Organization (FAO), agriculture accounts for approximately 23% of global anthropogenic greenhouse gas emissions and is the leading driver of freshwater consumption globally. In response, the concept of sustainable cropping systems has gained substantial scientific and policy traction. Unlike conventional monoculture approaches, sustainable cropping systems integrate agronomic, ecological, and socioeconomic principles to maintain productivity while preserving natural resources for future generations. This article provides a comprehensive overview of sustainable cropping systems from their foundational principles to their practical implementation and demonstrates their superiority over conventional farming.

Key Components of Sustainable Cropping Systems

Sustainable Cropping Systems: The Future of Farming

Sustainable cropping systems are not a single practice but a holistic framework comprising several interdependent components:

1.1 Crop Rotation

Crop rotation involves sequentially growing different crop species on the same land across seasons or years. This practice disrupts pest and pathogen cycles, improves soil structure, and enhances nutrient availability. For instance, alternating nitrogen-fixing legumes (e.g., chickpea, lentil) with cereal crops (e.g., wheat, maize) naturally replenishes soil nitrogen, reducing dependence on synthetic fertilizers by up to 40%. (Kakraliya et al., 2018).

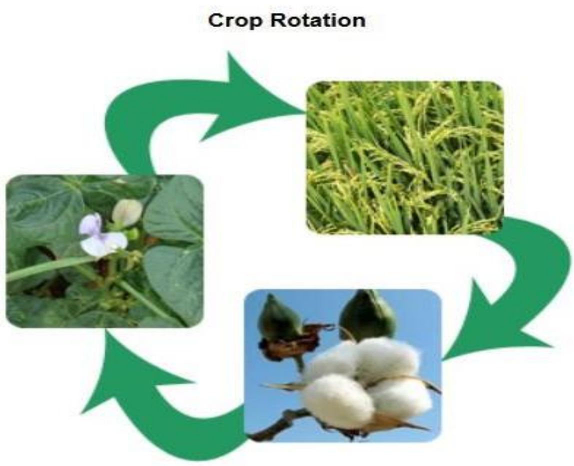

Fig 1 Crop Rotation

1.2 Intercropping and Mixed Cropping
Intercropping is the simultaneous cultivation of two or more crop species in proximity. This strategy maximizes resource use efficiency, improves light interception, suppresses weed growth, and creates habitat for beneficial insects. Classical examples include the Mesoamerican "Three Sisters" system maize, beans, and squash which has sustained farmers for millennia through complementary resource sharing.

1.3 Cover Cropping

Fig 2 Intercropping in Sunflower to Smoother Weeds

Cover crops are a vital component of sustainable cropping systems; Cover crops are crops grown between two main cropping seasons or alongside main crops to cover the soil surface. such as clover, rye, are grown between main crop seasons to protect and enrich the soil. They prevent erosion, suppress weeds, add organic matter, and improve soil water infiltration. Research consistently shows that cover cropping can increase soil organic carbon (SOC) by 0.3–0.5 tons per hectare per year, directly contributing to climate change mitigation.

1.4 Integrated Pest Management (IPM)
Sustainable cropping systems aim to balance productivity with environmental protection, and pest management is a critical component. IPM combines biological, cultural, physical, and chemical tools to minimize pest damage while reducing pesticide use and its associated environmental. IPM integrates multiple control strategies to keep pest populations below economic threshold levels while minimizing risks to humans, animals, and the environment. Biological controls such as the use of Trichogramma wasps against stem borers have proven as effective as synthetic insecticides in numerous field trials, while preserving beneficial insect populations critical for pollination.

1.5 Conservation Tillage and No-Till Farming
Zero tillage, also known as no-till farming, is a key practice in sustainable cropping systems that involves growing crops without disturbing the soil through ploughing or tillage.
Instead of conventional land preparation, seeds are directly sown into the soil with minimal disturbance, often using specialized seed drills. Conventional tillage disrupts soil structure, releases stored carbon, and accelerates erosion. No-till and reduced-till systems preserve soil integrity, enhance microbial diversity, and reduce fuel consumption. Studies in South Asia indicate that adopting no-till wheat after rice paddy can reduce production costs by ₹3,000–5,000 per hectare while maintaining comparable yields. (Somasundaram et al., 2020)

2. Performance Analysis: Sustainable vs. Conventional Farming

Parameter	Conventional Farming	Sustainable Farming
Productivity (Short-term)	High initial yields	Moderate but stable yields
Productivity (Long-term)	Declines over time	Sustained or improved
Soil Health	Degrades due to chemicals	Improves with organic matter

Input Cost	High (fertilizers, pesticides)	Lower (natural inputs)
Water Use Efficiency	Lower	Higher
Environmental Impact	High pollution	Eco-friendly
Biodiversity	Low	High
Pest Management	Chemical-based	IPM-based
Climate Resilience	Low	High
Profitability	Variable (input dependent)	Stable and long-term

Conclusion

The future of farming will be defined by those who recognise that soil health is not a means to an end but the foundation upon which all food security rests. Governments, research institutions, farmers, and consumers must collectively invest in, advocate for, and practice sustainable cropping not as an option, but as an obligation to present and future generations .

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FROM SOIL TO SUSTAINABILITY: RETHINKING CROPPING SYSTEMS

Abstract

Modern agriculture stands at a crossroads. While global food demand continues to rise, conventional cropping systems often reliant on monocultures, synthetic inputs and intensive tillage are contributing to soil degradation, biodiversity loss and greenhouse gas emissions (Darvishi et al., 2021; Tubiello et al., 2013). In response, a paradigm shift is underway: rethinking cropping systems to prioritize soil health and long term sustainability. This transformation emphasizes agroecological principles that work with natural processes rather than against them, aiming to balance productivity with environmental stewardship.

Keywords: Conventional cropping systems, monocultures, paradigm shift and stewardship.

Introduction

Sustainable cropping systems are essential for addressing the environmental and productivity challenges of modern agriculture. These systems prioritize soil health through practices such as crop rotation, cover cropping, intercropping and reduced tillage, which collectively enhance soil structure, nutrient cycling and biodiversity (Lazicki et al., 2016; Congreves et al., 2015). Cover crops, for example, improve soil organic matter, reduce erosion, and suppress weeds, while legume-based intercropping systems contribute to nitrogen fixation and lower greenhouse gas emissions (Scholberg et al., 2010; Jensen et al., 2012). Diversified cropping enhances resilience to climate extremes and reduces reliance on synthetic inputs, supporting long-term food security (Boody et al., 2005; Bybee-Finley et al., 2024). Conservation agriculture emphasizing minimal soil disturbance, permanent soil cover and crop diversity further promotes sustainability by improving water retention and carbon sequestration (Hobbs et al., 2007; FAO, 2015a). Despite their benefits, adoption barriers such as policy constraints and market limitations persist, requiring integrated efforts to scale these practices (Bowman & Zilberman, 2013).

Achieving sustainability by diversified cropping systems

Enhancing Soil Health through Diversified Practices

Soil health is the foundation of sustainable agriculture. It is determined by a combination of physical, chemical, and biological properties that support plant growth and ecosystem services (Lazicki et al., 2016). Diversified cropping systems such as crop rotation, intercropping, and cover cropping have been shown to improve these properties significantly. For instance, extended crop rotations that include forage perennials like alfalfa reduce soil bulk density and hardness, creating better conditions for root growth and water infiltration (Lazicki et al., 2016; Celik et al., 2010). These systems also enhance soil aggregation and organic matter, which are critical for carbon sequestration and nutrient cycling (Degens, 1997; Lafond et al., 1993).

Table 1:

Practices	Key Benefits	Estimated soil health improvement
Cover Cropping	Reduces erosion, increases organic matter	10–20%
Crop Rotation	Better nutrient cycling, reduced pests	7–15%
Reduced/No-till	Minimizes erosion, increases carbon	15–25%
Organic Amendments	Enhances nutrient content and water retention	18–30%
Agroforestry	Erosion control, carbon sequestration	12–24%

The Role of Cover Crops and Green Manures

Cover crops are increasingly recognized as a powerful tool for sustainable soil management. Planted during fallow periods, they protect the soil from erosion, suppress weeds and improve nutrient retention (Scholberg et al., 2010; Gerhards & Schappert, 2020). Leguminous cover crops, such as clover or vetch, contribute to nitrogen fixation, reducing the need for synthetic fertilizers (Fageria et. al., 2007). When incorporated into the soil as green manure, these crops enhance microbial activity, improve soil structure, and increase organic matter content (Talgre et al., 2012; Reddy et. al., 2016). By maintaining living roots in the soil year-round, cover cropping supports a vibrant soil microbiome, which plays a key role in nutrient availability and plant health (Blanco-Canqui et al., 2022).

Intercropping and Resource Use Efficiency

Intercropping, or the simultaneous cultivation of two or more crops in proximity, leverages species complementarity to improve resource use efficiency. This practice can enhance light, water, and nutrient capture by exploiting differences in root architecture and canopy structure (Mazzafera et al., 2021; Jensen et al., 2020). For example, growing a deep rooted crop alongside a shallow rooted one allows for more complete soil nutrient uptake. Intercropping has also been associated with improved pest and disease control, reduced weed pressure and higher relative yields compared to monocultures (Huss et al., 2022). As a nature-based solution, intercropping supports biodiversity both above and below ground, contributing to more resilient agroecosystems.

Organic and Conservation Agriculture

Organic farming and conservation agriculture represent holistic approaches to sustainable cropping. Organic systems emphasize the use of compost, organic fertilizers and biopesticides, minimizing reliance on synthetic inputs (Rosset & Altieri, 1997). Long term studies have demonstrated that organic practices can enhance soil microbial biomass and activity, particularly in diverse cropping systems (Lazicki et al., 2016). Conservation agriculture, characterized by minimal soil disturbance, permanent soil cover and crop rotation, helps maintain soil structure, reduce erosion and conserve water (Hobbs et al., 2007). Together, these systems promote ecosystem stability and climate resilience while supporting food security.

Reduced and No-till practices

Reduced and no-till practices are key components of conservation agriculture, aimed at minimizing soil disturbance to enhance soil health and sustainability. No till farming involves planting crops directly into undisturbed soil and crop residue, eliminating plowing and reducing the number of field passes (Bayer Crop Science, 2026). This practice helps preserve soil structure, increases organic matter, and reduces erosion by maintaining protective residue cover (Srivastava et al., 2025; USDA Climate Hubs). Studies show that no till systems improve water infiltration, reduce evaporation and enhance carbon sequestration, particularly when combined with cover cropping and crop rotation (Lazicki et al., 2016; Ogle et al., 2019).

Agro forestry in context to sustainability

Agroforestry enhances sustainability by integrating trees with crops and livestock, improving soil health, carbon sequestration and biodiversity. It increases soil organic carbon (SOC) by 20% to 30% compared to monocultures and sequesters 2 to 4 mg C ha^{-1} $year^{-1}$, depending on species and climate (Udawatta & Jose, 2011) contributing to climate resilience and food security (Abebaw, 2025). They also support biodiversity by 25% to 40% and reduce greenhouse gas emissions through improved nitrogen use and microclimate regulation (Abebaw et. al., 2025; Sharma et al., 2021). Despite benefits, adoption is hindered by land tenure issues and policy gaps. Agroforestry systems enhance water retention, reduce erosion and improve nutrient cycling.

Challenges and Pathways to Adoption

Despite their benefits, the adoption of sustainable cropping practices faces significant barriers. These include policy incentives favoring conventional systems, lack of market infrastructure for diverse crops and farmers' dependence on specialized equipment (Boody et al., 2005; Bowman & Zilberman, 2013). Overcoming these challenges requires coordinated efforts from policymakers, researchers and the private sector. Supportive policies, extension services and financial incentives can encourage the transition to diversified, sustainable systems. Additionally, consumer demand for sustainably produced food can drive market transformation.

Conclusion

Rethinking cropping systems from soil to sustainability is not merely an agronomic imperative but a necessity for planetary health. By embracing diversified, ecologically sound practices, agriculture can regenerate degraded soils, enhance biodiversity and contribute to climate change mitigation. The evidence is clear: sustainable cropping systems can maintain or even improve productivity while reducing environmental impact. The path forward lies in scaling these practices through innovation, collaboration and a shared commitment to long term resilience.

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Integrated Farming System (IFS): A Practical Pathway to Sustainable and Resilient Agriculture in India

Abstract

Integrated Farming System (IFS) is emerging as a sustainable and a practical option for farmers, especially small and marginal farmers, who are facing rising cultivation costs, uncertain weather, and unstable market prices. Instead of depending on only one crop, IFS encourages farmers to combine different farm activities such as crops, livestock, poultry, fisheries, horticulture, beekeeping, and composting, IFS creates a self-sustaining and resource-efficient farming model. The system is based on the principle that the by-products of one enterprise serve as inputs for another, thereby reducing waste, lowering input costs, and enhancing overall farm productivity. In the context of climate variability, rising cultivation costs, and market uncertainty, IFS offers a resilient strategy to improve farm income, ensure nutritional security, and strengthen livelihood stability. This article discusses the principles, components, benefits, and practical relevance of IFS in Indian agriculture, highlighting its role as a farmer-centric model for sustainable and climate-resilient farming.

Introduction

Indian agriculture is increasingly challenging day by day. Farmers today are dealing with smaller landholdings, rising input costs, uncertain weather, and frequent changes in market prices. For small and marginal farmers, who make up most of India's farming community, depending on only one crop is becoming more risky and less reliable. In such situations, Integrated Farming System (IFS) offers a practical way forward by helping farmers combine different farm activities and make better use of the resources they already have.

IFS is a holistic farming approach in which different agricultural enterprises are combined and managed in a complementary manner within the same piece of land. Instead of depending on a single crop, farmers integrate crops with livestock, poultry, fishery, horticulture, beekeeping, agroforestry, and organic recycling units. This integration improves resource use efficiency, diversifies income sources, and reduces dependence on external inputs. More importantly, IFS helps farmers maintain year-round income and build resilience against climatic and market-related risks.

One of the practical advantages of IFS is that it keeps farm families engaged throughout the year. In regular crop farming, work is usually concentrated during sowing and harvesting, while in the remaining months there is often less work and fewer income opportunities. IFS helps overcome this gap by spreading farm activities across seasons. Enterprises such as dairy, poultry, kitchen gardening, mushroom cultivation, vermicomposting, and small-scale value addition provide regular work even during the off-season. This helps farm families make steady income opportunities, and reduces the need to migrate in search of work.

Integrated Farming System also supports better nutrition for farm families. In many cases, regular farming is mainly focused on growing crops for sale, with less attention given to the variety of foods needed for a healthy diet. IFS helps improve this by bringing together different farm components such as pulses, vegetables, fruits, milk, eggs, and fish, which can directly support household food needs. This gives farm families better access to fresh and nutritious food throughout the year. It is especially important for rural families facing hidden hunger and micronutrient deficiencies. In this way, IFS not only helps farmers produce more, but also helps families eat better, stay healthier, and improve food security, especially for women and children.

On the other hand, IFS helps farmers in two important ways, one it improves income and also keeps the farm healthy. Instead of depending on just one crop and one harvest, farmers can earn from different sources throughout the year. At the same time, IFS is also better for the farm environment. Growing only one crop repeatedly and depending too much on chemicals can weaken the soil and increase pest problems over time. IFS helps avoid this by encouraging crop diversity, recycling farm waste, and reducing the need for external chemical-based inputs. It improves soil fertility, supports useful insects, reduces nutrient loss, and keeps the farm more balanced and sustainable in the long run.

Principle Behind Integrated Farming System

The core principle of Integrated Farming System is **resource recycling and enterprise integration**. It functions on the concept that every enterprise on the farm should support another, creating a circular and self-sustaining production system.

For example:

- Crop residues can be used as fodder, mulch, or compost
- Livestock dung can be converted into farmyard manure, vermicompost, or biogas slurry
- Poultry droppings can be utilized in fish ponds
- Horticultural waste can be composted and returned to the soil
- Beekeeping improves pollination and increases crop productivity

Thus, the output or waste of one enterprise becomes a valuable input for another. This reduces resource wastage, lowers production costs, improves nutrient cycling, and enhances ecological balance on the farm.

Major Components of IFS

The components of IFS may vary depending on agro-climatic conditions, farm size, and farmer resources. However, below are the few commonly integrated enterprises include:

- Crop production (cereals, pulses, oilseeds, fodder crops)
- Horticulture (fruits, vegetables, flowers, spices)
- Livestock (dairy, goat, sheep)
- Poultry and duckery
- Fishery
- Beekeeping (Apiculture)
- Agroforestry / boundary plantations
- Vermicomposting and composting
- Mushroom cultivation
- Value addition and on-farm processing

These enterprises are selected and linked based on farm conditions and market opportunities.

IFS Models Developed in India

IFS in India is not merely a conceptual approach; it is a scientifically developed and region-specific farming model validated by the Indian Council of Agricultural Research (ICAR) through its network of institutes and coordinated research programmes. The ICAR-Indian Institute of Farming Systems Research (ICAR-IIFSR), Modipuram, formerly Project Directorate for Farming Systems Research (PDFSR), has played a central role in designing, standardizing, and evaluating IFS models across different agro-climatic regions of the country.

Recognizing that farming systems vary widely across India, ICAR developed location-specific IFS models based on rainfall, resource availability, farm size, and market opportunities. These models were designed for irrigated, rainfed, coastal, hill, tribal, and peri-urban production systems to improve productivity, profitability, employment, and livelihood security.

According to the Council on Energy, Environment and Water (CEEW), based on ICAR evidence, 45 climate-resilient IFS models have been developed and are demonstrated in different regions through Krishi Vigyan Kendras (KVKs).

ICAR's IFS models are broadly structured around dominant farming situations and natural resource conditions. For example, in areas receiving 500–700 mm annual rainfall, ICAR recommends integrating low water-requiring crops with livestock and trees. In 700–1100 mm rainfall zones, crop + horticulture + livestock systems are considered more profitable. In regions receiving more than 1100 mm rainfall, fisheries can be effectively integrated along with crops and livestock for enhanced system productivity.

Several region-specific IFS models have been developed and tested under ICAR institutions:

Crop–Livestock based IFS models were developed for dryland and rainfed regions by ICAR-Central Research Institute for Dryland Agriculture, focusing on drought resilience, fodder security, and risk reduction in low-rainfall ecologies.

Rice-based IFS models integrating fishery, poultry, ducks, and vegetables were developed for eastern India by ICAR-National Rice Research Institute to improve productivity and profitability in water-abundant ecosystems.

Pond-based IFS models were developed for the North Eastern Hill region by ICAR Research Complex for North Eastern Hill Region, where integration of crops, fishery, livestock, and horticulture significantly improved system productivity and livelihood security.

Integrated crop–livestock–horticulture systems were standardized for the western plain and Indo-Gangetic regions by ICAR-Indian Institute of Farming Systems Research to enhance income and employment among smallholders.

Coastal IFS models integrating crops, livestock, fishery, and horticulture were developed for west coast ecosystems to improve resource recycling and income diversification under humid tropical conditions.

These models demonstrate that IFS in India is not a one-size-fits-all recommendation, but a regionally adaptable and research-backed farming approach. The strength of IFS lies in its flexibility: farmers can adopt enterprise combinations suited to their local ecology, available resources, and livelihood needs while following scientifically validated integration principles.

Key Benefits of Integrated Farming System

1. Efficient Resource Recycling: IFS promotes efficient utilization of on-farm resources by converting waste into useful inputs. This reduces dependence on external inputs and lowers cultivation costs.

2. Year-Round Income Generation: Unlike seasonal crop farming, IFS ensures continuous income through milk, eggs, vegetables, honey, fish, mushrooms, and other farm products.

3. Risk Reduction and Resilience: IFS minimizes the impact of crop failure, market fluctuations, and climate variability by diversifying enterprises and income streams.

4. Improved Soil Health: Organic recycling through compost, farmyard manure, mulching, and crop residues improves soil fertility, organic carbon, and moisture retention.

5. Better Labour Utilization: IFS provides employment opportunities throughout the year, ensuring better use of family labour and reducing seasonal unemployment.

6. Reduced Market Dependency and Nutritional Security: Farmers become less dependent on external markets for inputs such as manure, fodder, and bio-inputs, thereby reducing input costs and risks and at the same time with the inclusion of different components resulting - fruits, vegetables, milk, eggs, fish, and pulses can improve household nutrition and dietary diversity.

7. Environmental Sustainability: IFS promotes biodiversity, ecological balance, reduced pollution, and sustainable use of land and water resources.

Practical Tips for Farmers to Adopt IFS

Farmers planning to adopt IFS should begin with available resources and gradually integrate suitable enterprises.

Some practical tips include:

- Start with 2–3 compatible enterprises instead of many at once
- Select enterprises based on farm size, water availability, and market access
- Prioritize low-cost and locally adaptable enterprises
- Recycle crop residues and livestock waste effectively
- Integrate fodder crops for livestock support
- Use composting and vermicomposting to reduce fertilizer costs
- Include nutrition-oriented components such as vegetables, poultry, and pulses
- Explore local market opportunities for value-added products
- Seek technical guidance from Research stations, KVKs and extension agencies

Challenges in Adoption

Despite its advantages, IFS is not without challenges. Initial investment for different enterprise set up such as livestock sheds or fish ponds or beekeeping units, compost pits, or fodder blocks etc., may be difficult for resource-poor farmers. Managing multiple enterprises also requires knowledge, skill, and labour coordination. Market linkages for perishable products such as milk, vegetables and mushrooms, remain weak in many rural areas. Farmers may also need support in enterprise selection, credit access, risk planning, and value addition. These constraints are real, but they are not reasons to reject IFS. Rather, they highlight the need for stronger extension, institutional convergence, and localized IFS planning.

The future of Indian agriculture lies not in maximizing one crop, but in optimizing the whole farm. That is the central promise of Integrated Farming System. For small and marginal farmers, IFS offers more than diversification, it offers stability, reduces risk, improves recycling, generates year-round income, and builds resilience against climate and market uncertainty. In a country where farm sustainability must go hand in hand with livelihood security, IFS is not merely an alternative model; it is an essential pathway toward resilient and sustainable agriculture in India.

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ROBOTIC WEEDING SYSTEMS FOR PRECISION WEED MANAGEMNT

1. Introduction

Weeds continue to be one of the major challenges faced by farmers, as they compete directly with crops for essential resources such as water, nutrients, sunlight, and space, often leading to yield losses of around 20–30% worldwide. Traditional weed control methods, however, have significant limitations. Manual weeding requires a great deal of labour and time, making it difficult and costly, especially during peak seasons. On the other hand, the excessive use of chemical herbicides, while effective in the short term, can harm the environment, degrade soil health and contribute to the development of herbicide-resistant weed species.

With the rise of Precision Agriculture (PA), technology-driven solutions are transforming weed management. Robotic weeding systems, which combine robotics, artificial intelligence (AI) and advanced sensors, are emerging as an effective alternative. These systems can accurately distinguish between crops and weeds and apply targeted treatments-mechanical, thermal, or minimal chemical-only where needed. This improves efficiency while reducing input waste and environmental impact. Robotic weeders also reduce dependence on manual labor, which is especially valuable in labor-scarce regions. Additionally, they collect real-time field data that supports better farm decisions. A typical system integrates sensors (such as RGB cameras, LiDAR, and MEMS), actuators, processing units, and autonomous mobility platforms. As the global population is expected to reach 9 to 10 billion by 2050, food production must increase by at least 70% (Lottes et al., 2017). Sustainable weed management is therefore critical. Reducing pesticide use while maintaining productivity remains essential (Rani et al., 2021), making robotic weeding a promising solution.

2. Weeding Methods

1. Traditional Methods

a. Manual Weeding

Manual weeding involves physically removing weeds by hand or using simple tools. This method is prevalent in small-scale and organic farming due to its precision and minimal environmental impact.

Advantages:

- **Precision:** Allows for selective removal of weeds without disturbing crops.
- **No Chemical Use:** Ideal for organic farming practices.
- **Low Initial Investment:** Requires minimal equipment.

Disadvantages:

- **Labor-Intensive:** Requires significant human effort and time.
- **Time-Consuming:** Limited area can be covered in a day.
- **Physical Strain:** Can lead to fatigue and health issues among workers.

b. Mechanical Weeding

Mechanical weeding utilizes tools like hoes, cultivators, and power weeders to uproot or cut weeds.

Types of Mechanical Tools:

- **Hand Hoes:** Simple tools for small-scale weeding.
- **Rotary Hoes:** Powered equipment for larger areas.
- **Power Weeders:** Motorized devices that reduce manual labor.

Advantages:

- **Increased Efficiency:** Covers larger areas faster than manual methods.
- **Reduced Labor Costs:** Less human labor required.
- **No Chemical Use:** Suitable for organic farming.

Disadvantages:

- **Imprecision:** Risk of damaging crops if not carefully operated.
- **Soil Disturbance:** Can disrupt soil structure and health.
- **High Initial Cost:** Investment in equipment can be substantial.

2. Chemical Weeding

Chemical weeding involves the application of herbicides to control weed growth.

Common Herbicides:

- **Glyphosate:** Broad-spectrum herbicide.
- **Paraquat:** Fast-acting herbicide with high toxicity.
- **2,4-D:** Selective herbicide for broadleaf weeds.

Advantages:

- **Effectiveness:** Rapid control of a wide range of weeds.
- **Labor Savings:** Reduces the need for manual labor.
- **Cost-Effective:** Lower immediate costs compared to mechanical methods.

Disadvantages:

- **Environmental Impact:** Potential contamination of soil and water sources.
- **Health Risks:** Exposure can lead to respiratory issues and other health problems.
- **Resistance Development:** Overuse can lead to herbicide-resistant weed populations.

3. Emerging Robotic Methods

a. Mechanical Robots

Mechanical robots are autonomous machines equipped with tools to remove weeds.

Features:

- **AI Integration:** Uses computer vision to identify weeds.
- **Precision Tools:** Equipped with blades or tines to uproot weeds.
- **Autonomous Operation:** Can work independently in fields.

Advantages:

- **Labor Reduction:** Minimizes the need for human workers.
- **Precision:** Targets weeds without harming crops.
- **Scalability:** Suitable for large-scale operations.

Disadvantages:

- **High Initial Cost:** Expensive to purchase and maintain.
- **Technical Complexity:** Requires skilled operators and maintenance.
- **Field Limitations:** Performance can be affected by soil conditions and terrain.

b. Chemical Robots

Chemical robots apply herbicides directly to weeds using precision technology.

Features:

- **Targeted Application:** Delivers herbicides only to weeds.
- **Reduced Chemical Use:** Minimizes overall herbicide application.
- **AI Guidance:** Uses sensors and algorithms to identify weeds.

Advantages:

- **Environmental Benefits:** Reduces chemical runoff and pollution.
- **Cost Savings:** Lower herbicide usage leads to cost reductions.

- **Efficiency:** Faster than manual application methods.

Disadvantages:

- **Chemical Dependency:** Still relies on herbicides.
- **Regulatory Concerns:** Must comply with agricultural regulations.
- **Maintenance Needs:** Requires regular upkeep and calibration.

c. Laser Robots

Laser robots use high-intensity lasers to vaporize weeds without chemicals.

Features:

- **Laser Technology:** Uses focused beams to destroy weeds.
- **AI Detection:** Identifies weeds using computer vision.
- **No Herbicides:** Chemical-free weed control.

Advantages:

- **Sustainability:** No chemical use reduces environmental impact.
- **Precision:** Targets weeds with high accuracy.
- **Labor Savings:** Autonomous operation reduces labor needs.

Disadvantages:

- **High Cost:** Expensive technology and maintenance.
- **Fire Risk:** Potential fire hazards in dry conditions.
- **Energy Consumption:** High energy requirements for operation.

2.1 Components of a Weeding Robot

A weeding robot is a complex system that integrates sensing, decision-making, and actuation to perform precise and efficient weed control. Its architecture is typically divided into functional layers, each responsible for a specific task in the operation process. Understanding these components is essential for designing and improving robotic weeding systems (Fig 1).

1. Perception Layer

The perception layer acts as the sensing system of the robot, helping it observe and understand what is happening in the field in real time. It collects important environmental information so that the robot can make correct and timely decisions during operation. In this layer, sensors function like the robot's eyes and awareness system. Cameras, including RGB and multispectral types, capture detailed images of the field and help differentiate crops from weeds based on their color, shape, and health condition. LiDAR sensors create a three-dimensional view of the surroundings using laser pulses, which helps the robot detect obstacles, estimate plant height, and move safely. Thermal sensors identify temperature differences among plants, which can indicate stress or disease and sometimes help distinguish weeds from crops. Ultrasonic sensors use sound waves to measure distances and are useful for avoiding obstacles, especially in uneven or complex terrains. GPS provides accurate location information, allowing the robot to navigate properly, plan its path, and cover the entire field without missing or repeating any area.

2. Decision Layer

The decision layer works as the "brain" of the robot, where data from the perception layer is processed to decide appropriate actions. It uses artificial intelligence and control systems to make real-time decisions. Deep learning models, such as Convolutional Neural Networks (CNNs), help the robot identify and differentiate crops and weeds from images, while machine learning methods like SVMs and Random Forests offer alternative ways for classification. Sensor fusion combines data from different sensors, improving accuracy in detection and navigation.

The control system then converts these decisions into actions. Microcontrollers manage sensor inputs and control the robot's movements. Path planning algorithms like A* and Dijkstra help the robot move efficiently through the field while avoiding obstacles. Continuous feedback from sensors allows the robot to adjust its actions in real time, ensuring accurate and efficient weed removal.

3. Actuation Layer

The actuation layer is responsible for carrying out the decisions made by the robot, performing the actual task of weed removal in the field. It uses different tools and systems depending on the method of control. Mechanical tools such as rotary blades, tines, hoes, and cutter wheels physically remove weeds by cutting or uprooting them from the soil, making them suitable for various field conditions and crop arrangements. In addition to mechanical methods, chemical applicators are used for precise weed control. Selective sprayers and micro-sprayers apply herbicides only to identified weeds, reducing chemical usage and environmental impact, while modified drip systems can deliver herbicides directly to the base of weeds with minimal wastage.

Advanced systems like laser-based weed control are also being explored, where high-intensity laser beams target and destroy weed tissues without the use of chemicals. Laser scanners help in detecting weeds accurately, and built-in cooling systems ensure the equipment operates safely and efficiently. Overall, the actuation layer transforms intelligent decisions into practical actions, enabling effective and targeted weed management.

4. Power Supply

The power supply system ensures that the robot can operate smoothly and continuously in the field. It mainly relies on batteries and, in some cases, renewable energy sources like solar power. Lithium-ion batteries are commonly used due to their high energy density and long life, making them suitable for autonomous operation, while Nickel-Metal Hydride (NiMH) batteries serve as an alternative that performs better under varying temperatures. A Battery Management System (BMS) plays an important role by monitoring battery health, charge levels, and temperature to ensure safe and efficient functioning.

In addition, solar panels can be integrated to provide a sustainable energy source. Photovoltaic cells convert sunlight into electricity, and any excess energy generated can be stored in batteries for later use, especially during low-light conditions. Power management systems regulate how energy is distributed among sensors, actuators, and other components, helping to optimize energy usage and extend the robot's operating time.

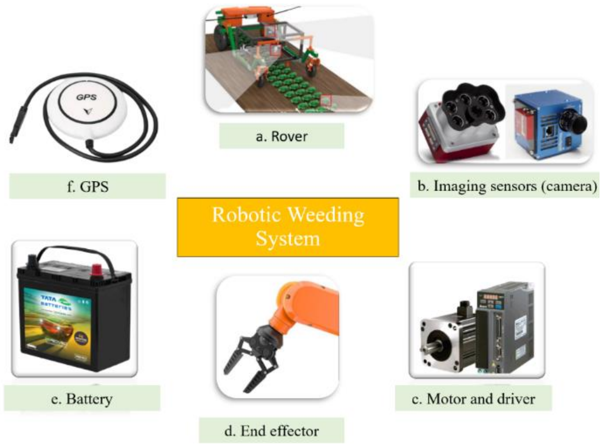

Fig 1. Components of a Weeding Robot

2.2 Different Types of Weeding Robots

Robotic weeding technologies are rapidly transforming modern agriculture by enabling precise, efficient, and sustainable weed management. These systems integrate artificial intelligence, advanced sensors, and automation to reduce labor dependency and minimize chemical usage. Various types of weeding robots have been developed to suit different farm sizes, crop types, and management practices (Table 1).

1. Farm Wise Titan FT-35

The Farm Wise Titan FT-35 is an autonomous, tractor-mounted robot designed for precision weeding in row crops. It utilizes machine learning and computer vision to differentiate between crops and weeds, enabling targeted weed removal without the use of herbicides.

Key Features:

- AI-Powered Weed Detection: Employs deep learning algorithms to identify weeds with high accuracy.
- Mechanical Weeding: Equipped with robotic arms that use blades to mechanically remove weeds.
- Chemical Application: Capable of applying fungicides and insecticides as needed, offering flexibility in pest management.
- Autonomous Navigation: Utilizes GPS and sensors for precise field navigation.
- Real-Time Data Processing: Processes sensor data in real-time to make immediate weeding decisions.

Applications:

Ideal for organic and conventional farming, particularly in crops like lettuce, broccoli, and celery. The Titan FT-35 helps reduce labor costs and herbicide use, promoting sustainable farming practices.

2. Carbon Robotics Laser Weeder

The Laser weeder is an autonomous robot that uses high-powered lasers to eliminate weeds without chemicals. It integrates AI, computer vision, and robotics to identify and target weeds with precision.

Key Features:

- Laser Technology: Equipped with multiple high-powered lasers to destroy weeds by vaporizing them.
- AI-Driven Weed Identification: Utilizes deep learning models to distinguish between crops and weeds.
- High Efficiency: Capable of eliminating up to 300,000 weeds per hour with sub-millimeter accuracy.
- All-Weather Operation: Designed to operate day and night, in various weather conditions.
- Modular Design: Available in different models to suit various farm sizes and crop types.

Applications:

Suitable for large-scale farms growing crops like corn, soybeans, and vegetables. The LaserWeeder offers a chemical-free alternative to traditional weed control methods, enhancing sustainability and reducing labour costs.

3. Ecorobotix AVO

Ecorobotix's AVO is a lightweight, solar-powered robot designed for selective herbicide application. It uses AI and GPS to identify and target weeds, applying herbicides only where necessary.

Key Features:

- Selective Spraying: Applies herbicides directly to weeds, minimizing chemical use.
- Solar-Powered: Operates autonomously for extended periods without the need for external charging.
- AI-Powered Weed Detection: Utilizes machine learning to accurately identify weeds.
- Lightweight Design: Easy to transport and maneuver in fields.
- Cost-Effective: Offers a more affordable solution compared to traditional sprayers.

Applications:

Ideal for small to medium-sized farms, especially those practicing organic farming. The AVO helps reduce herbicide usage, lowering costs and environmental impact.

4. FarmBot Genesis

FarmBot Genesis is an open-source, CNC (Computer Numerical Control) farming machine designed for small-scale precision agriculture. It automates tasks like sowing, watering, and weeding with high precision.

Key Features:

- Open-Source Platform: Allows users to customize and modify the system according to their needs.
- Precision Weeding: Equipped with a rotary tool for light-duty weed control, ensuring minimal soil disturbance.
- Automated Operations: Performs tasks like seed planting, watering, and soil milling autonomously.
- Customizable Tools: Users can design and 3D-print their own implements for specific tasks.
- User-Friendly Interface: Operated via a web-based interface, making it accessible for users with varying technical skills.

Applications:

Perfect for small-scale urban farms, educational institutions, and research purposes. FarmBot Genesis promotes sustainable farming practices and serves as an educational tool for learning about automation in agriculture.

2.3 Weed Detection Models:

Weed detection models play a crucial role in enabling precision weeding by accurately distinguishing crops from weeds using advanced deep learning techniques. Models such as ResNet and DenseNet are used for feature extraction, while YOLO and DetectNet enable real-time object detection in field conditions (Fig 2). Semantic segmentation models like SegNet and DeepLab v3 provide pixel-level classification for precise weed localization. Area-based CNN approaches further enhance detection by focusing on region-specific analysis. Together, these models improve the accuracy, speed, and efficiency of automated weeding systems, especially under varying agricultural environments

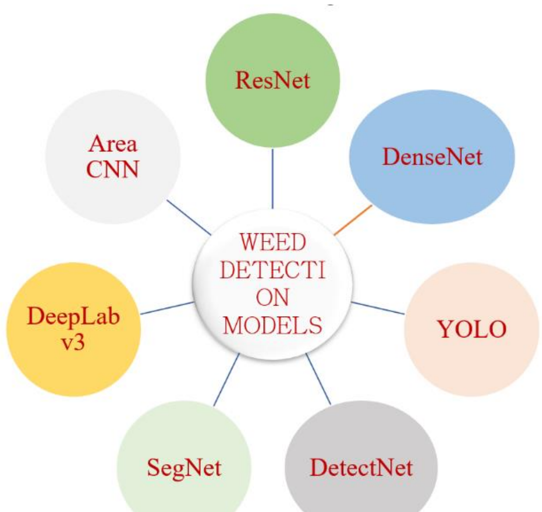

Fig 2. Weed detection modules

2.4 Working of a Weeding Robot

Robotic weeding systems integrate advanced sensors, artificial intelligence, and actuation mechanisms to autonomously identify and eliminate weeds while minimizing crop damage. The workflow of a weeding robot can be divided into four main stages: Navigation, Weed Detection, Weed Removal, and Feedback Mechanisms (Fig 3).

1. Navigation

Navigation is crucial for a robot to traverse fields efficiently and precisely without damaging crops.

a. GPS (Global Positioning System) and IMU (Inertial Measurement Unit)

- GPS: Provides geolocation data to determine the robot's exact position in the field. High-precision GPS (RTK-GPS) allows centimetre-level accuracy, which is essential for row crop weeding.
- IMU: Measures acceleration, orientation, and angular velocity using accelerometers and gyroscopes. This data is critical for maintaining stability and detecting slope changes in uneven terrains.
- Integration: GPS provides global positioning while IMU ensures smooth motion and precise heading adjustments, even when GPS signals are weak.

Table 1. Comparison Table:

Feature	FarmWise Titan FT-35	Carbon Robotics LaserWeeder	Ecorobotix AVO	FarmBot Genesis
Technology	AI, Machine Learning	AI, Laser Technology	AI, GPS	CNC Automation
Power Source	Diesel	Diesel	Solar	Electric
Weeding Method	Mechanical & Chemical	Laser	Herbicide	Mechanical
Scale	Large Farms	Large Farms	Small Farms	Small Farms
Customization	Limited	Limited	Limited	High
Open-Source	No	No	No	Yes

b. Path Planning Algorithms

- Robots use algorithms to create efficient coverage paths for the entire field, avoiding both overlap and missed spots.
- Common algorithms:
  - A*: Optimizes shortest path while avoiding obstacles.
  - Dijkstra's Algorithm: Calculates shortest distance from start to target positions.
  - Coverage Path Planning (CPP): Ensures every row is traversed without missing areas.
- Obstacle Avoidance: Sensors detect objects like rocks, irrigation systems, or humans. The robot adjusts its path in real-time to avoid collisions.

2. Weed Detection

Weed detection differentiates crops from weeds and decides where removal is needed.

a. Image Processing

- Camera Systems: RGB, multispectral, or hyperspectral cameras capture high-resolution images of the field.
- Image Preprocessing: Includes filtering, contrast enhancement, and segmentation to isolate plants from soil background.
- Feature Extraction: Detects characteristics such as color, shape, leaf texture, and height differences between crops and weeds.
- Vegetation Indices: Algorithms like NDVI (Normalized Difference Vegetation Index) can highlight plant growth and health, helping distinguish weeds from crops.

b. Machine Learning and AI

- Model Training: Supervised machine learning models (e.g., CNNs – Convolutional Neural Networks) are trained with datasets of crop and weed images.
- Real-Time Inference: Once trained, the robot uses these models to classify plants in real-time while moving through the field.
- Adaptive Learning: Robots can update their models with new data to improve detection accuracy over time.

Example: A robot may identify a weed growing between two lettuce rows and mark its location for targeted removal.

3. Weed Removal

Once weeds are detected, the robot applies appropriate removal methods depending on its design.

a. Mechanical Methods

- Tools Used: Rotating blades, tines, hoes, or cutter wheels uproot weeds or slice them at the soil surface.
- Precision: Actuators adjust the tool's position using real-time sensor data to avoid damaging nearby crops.
- Soil Considerations: Mechanical weeding may loosen soil, improving aeration but requiring careful depth control to avoid crop roots.

b. Chemical Methods

- Targeted Spraying: Robots equipped with micro-sprayers or selective herbicide applicators release chemicals only on weed foliage.
- Reduced Herbicide Usage: Minimizes environmental impact and lowers operational costs compared to conventional blanket spraying.
- Safety Measures: Sensors monitor spray volume and direction to prevent drift onto crops.

c. Laser Methods

- Focused Laser Beams: High-intensity lasers target and destroy weed tissues by burning or vaporizing them.
- Precision: Sub-millimeter targeting ensures crops are unharmed.
- Efficiency: Rapid treatment allows high-speed operations in large fields, especially in organic or chemical-free farming.

4. Feedback Mechanisms

Feedback systems continuously monitor performance and adjust actions to optimize efficiency.

a. Sensors

- Force Sensors: Detect resistance during mechanical weeding to ensure tools are effectively removing weeds.
- Camera/Optical Sensors: Verify if weeds were successfully eliminated.
- Chemical Sensors: Ensure correct herbicide application rates.
- Laser Sensors: Confirm if laser intensity is sufficient to destroy weeds.

b. Adjustments and Real-Time Control

- Adaptive Control Systems: Modify tool depth, laser intensity, or spraying volume based on sensor feedback.
- Path Corrections: If obstacles are detected or weed clusters are denser than anticipated, robots adjust their routes dynamically.
- Data Logging: Field maps are updated in real-time, recording treated areas and missed spots for future optimization.

Workflow Summary

1. Start Navigation: Robot moves along predefined paths using GPS and IMU.

2. Capture Images: Cameras and sensors continuously scan the field.
3. Detect Weeds: AI analyzes images and identifies weeds in real-time.
4. Execute Removal: Mechanical, chemical, or laser actuators remove the identified weeds.
5. Monitor & Adjust: Sensors provide feedback; robot adjusts actions if needed.
6. Log Data: Field coverage, weed density, and treatment results are recorded.

Advantages of Robotic Weed Removal Workflow

- Reduces labor costs and human error.
- Minimizes herbicide use and environmental impact.
- Ensures high precision in weeding, even in densely planted crops.
- Operates autonomously with minimal supervision.

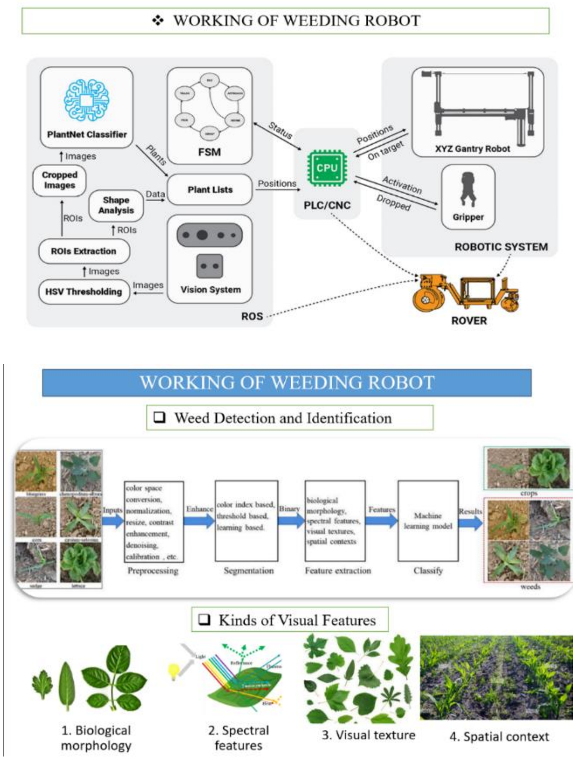

Fig 3. Working of weeding robot

Conclusion

The study concludes that image processing techniques are effective in distinguishing crops from weeds, especially under controlled laboratory conditions. However, their accuracy decreases in real-time field environments due to varying factors such as lighting, soil background, and plant overlap. Robotic weeding systems demonstrate strong potential for site-specific weed management, offering a sustainable alternative to conventional chemical methods by reducing herbicide usage. Despite these advantages, challenges remain in field implementation, particularly in minimizing crop damage and improving the precision and speed of weed removal. Therefore, further refinement is required to enhance system reliability, efficiency, and adaptability under diverse field conditions.

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"Harnessing Renewable Energy to Overcome Fuel and Fertilizer Shortages: A Roadmap for the Upcoming Kharif Season"

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1. Introduction: a barrier to pathway of revolution

As India is working towards forthcoming *Kharif* season, its agricultural sector faces a critical juncture. The juncture is caused by the confluence of persistent fuel and fertilizer shortages compounded by global supply chain disruptions and volatile energy markets. Ongoing geopolitical situations, conflicts, raging wars, volatile energy markets and climatic uncertainties continue to impose a major curb. These factors have seriously taken down input supply and hiked prices. As of, India is navigating real and severe energy supply disruption towards agricultural sector. The "vicious cycle" created due to above situations is significantly and undeniably hampering Indian Agriculture by targeting its most critical energy-linked inputs. The blockade in West Asia disrupting supply of LNG, crude oil and fertilizers.

India, being a major energy importer faces direct challenge for agricultural sector as it is heavily reliant on energy for various processes including farm machinery, irrigation and fertilizer production. This necessitates a strategic pivot towards sustainable energy solutions for curbing the situation. The weak monsoon predictions and climate change are stressing already fragile farming systems, particularly in vulnerable regions of North Eastern Hill (NEH) region comprising Arunachal Pradesh, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim and Tripura where steep terrains, heavy rainfall, landslides and *Jhum* cultivation amplify risks.

Fig.1. Solar energy: immediate and scalable solution (Ref-AI generated image)

In this dire of escalating fuel and fertilizer shortages, erratic monsoons and climate extremes, Indian agriculture faces an alarming tipping point; yet this crisis heralds a golden opportunity. Renewable energy technologies and organic nutrient management approaches offer not just alternatives, but a transformative and reformative pathway to resilient, self-reliant farming brimming with potential in the biodiversity rich, unique rainfed agriculture in NEH region. This approach is crucial for mitigating greenhouse gas emissions associated with conventional agriculture and is enough for fostering a second to none green revolution that prioritizes both productivity and ecological integrity.

1. Renewable energy: a revolution from farms

Being bestowed with vast potential for renewable energy, India has focused towards decentralized RET's especially for rural and agricultural landscapes. The harnessment of renewable energy resources at farm can boost agricultural economy through reduction of inputs which are affected highly due to recurring and non-recurring constraints. Use of renewable energy not only eases energy and input burden but also improves sustainability. The NEH region amongst offers unique opportunities due to abundant resources like solar insolation (Approx. 4–5.5 kWh/m²/day), hydropower from perennial rivers, and biomass resources etc.

1.1. Solar energy: immediate and scalable solution

Solar energy, being the most abundant and accessible source of energy, can be scaled for farmers with technologies such as:

- Solar Water Pumping
- Solar Drying technologies
- Solar-based cold storage and processing units
- Solar cooking systems for feed/fodder
- Solar insect traps
- Solar lighting systems
- Solar fencing systems
- Portable solar spraying systems

These equipments foremost reduce dependency on costly fossil fuels and bring energy sources and have liberty to use farm-level energy sources. Solar pumps are being promoted through PM-KUSUM scheme by government, reducing operational costs especially in remote NEH hill regions where grid extension is challenging. Solar dryers help reduce post-harvest losses and increase shelf life of perishable products, enhancing value addition and market value. The other small-scale appliances mentioned above can be useful for marginal and small land holding farmers; thus, improving the income of farmers.

1.2. Biomass energy: turning waste into wealth

Being enormous quantity of agricultural residues generated in Indian agricultural system is wasted through burning causing environmental pollution. These wastes can be used for energy production through bioenergy systems. The useful bioenergy conversion systems can provide both fuel and fertilizer. Key conversion systems are:

1. Gasification
2. Incineration
3. Anaerobic digestion (Biogas technology)
4. Pyrolysis
5. Torrefaction
6. Fermentation
7. Liquefaction
8. Transesterification
9. Densification
10. Combustion
11. Carbonization

Biomass gasifiers can be used for generation of heat and electricity for farm operations and small agro-industries using waste residues. Biogas technology using animal dung and organic waste for production of clean cooking fuel and energy for rural households. Further processing and conditioning of biogas can provide compressed biogas and also hydrogen fuel can also be synthesized secondarily. The bottled Compressed biogas (CBG) can serve as alternative to LPG. Also, biogas spent slurry acts as a nutrient-rich organic manure promoting organic and natural farming system. Biochar produced from agricultural residues can have remedial action on soil with nitrogen adsorption, water retention and minimization of leaching. In NEH region, abundant livestock's and *Jhum* residues play important role for applying ideal bioenergy systems aligning with traditional waste recycling practices.

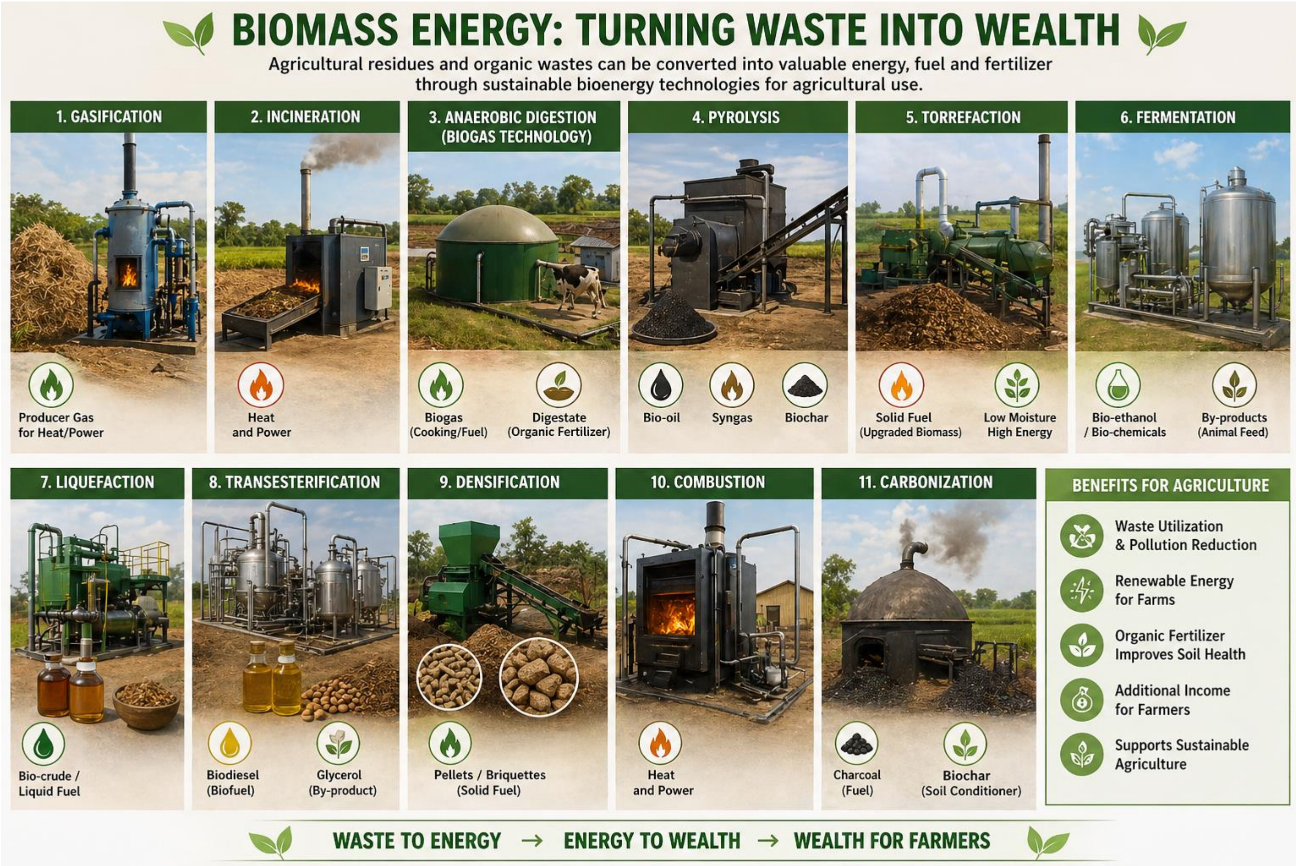

Fig.2. Biomass energy: turning waste into wealth (Ref-AI generated image)

1.3. Wind and Small hydro: location-specific solutions

In various agro-climatic zones, small-scale wind turbines and micro-hydel systems can supply energy for farm needs. These technologies are location specific; they are major decentralized and diversified energy systems enhancing resilience. NEH region has strong potential for micro-hydel plants.

2. Addressing fertilizer shortages: a way through organic innovations

As energy challenges and fertilizer shortages demand a shift towards efficient and sustainable nutrient management practices resonating deeply with NEH's indigenous organic traditions. The organic and biological inputs popularly can be used are composting and vermicomposting, green manuring and bio-fertilizers. These approaches not only reduce input costs but also improve soil structure, microbial activity and long-term fertility vital for restoring *Jhum* degraded terraces.

The emerging sustainable practices like 1) biochar application enhances soil carbon, improves water retention and increases nutrient use efficiency; 2) integrated nutrient management combines organic and inorganic sources and 3) microbial consortia and liquid bio inputs improve efficiency. These innovations are crucial under changing climate conditions, ensuring soil health and crop resilience in flood and landslide vulnerable NEH landscapes.

3. Bridging the gap: from technology to adoption

Despite development of various technologies, their widespread adoption is the challenge unhindered due to factors like lack of awareness, lack of technical skills, lack of financial support and all compounded in the NEH region by remoteness, hilly terrain and ethnic diversity. Major keys for enabling adoption are:

a) **Capacity Building & Training:** Farmers need hands-on training and demonstrations to understand the benefits and operation of renewable energy technologies tailored to NEH farming.

b) **Institutional Support:** Support from universities, KVKs and research institutes can enhance the dissemination of technologies.

c) **Policy & Incentives:** Government schemes, subsidies and credit support can significantly enhance and accelerate the adoption through NEH specific programs

d) **Demonstration Projects:** Field demonstrations can build confidence among farmers and peer learning and leveraging community *Jhum* groups with focus on strengthening existing community institutions.

4. Future preparedness: self-resilient and self-reliant farming systems

The future of Indian agriculture lies in decentralized, integrated and climate-resilient systems. The renewable energy interventions combined with precision agriculture, digital advisory tools (DSS and AI based tools) and climate-smart practices can provide a platform for a robust agricultural ecosystem capable of withstanding uncertainties.

Community-based models like FPOs, farmer's cooperatives and self-help groups with energy sharing systems can further enhance accessibility and affordability of renewable energy technologies. Additionally, *Public-Private Partnerships* (PPP) can play a vital role in scaling innovations and ensuring last-mile delivery in NEH regions.

5. Conclusion: turning crisis into opportunity

The crisis across globe and post covid reforms halting the economy due to fuel and fertilizer shortages and bans for purchase from certain countries with trade fears India has to reimagine Indian agriculture. With constant increment in use of RET's and sustainable practices can reduce dependency on external inputs, lowering operational costs and mitigating climate change impacts providing a Agri-ecosystem for NEH region. As the Kharif season approaches, proactive planning and timely adoption of these technologies can ensure uninterrupted agricultural operations. This transition can provide a benchmark for greener, resilient and self-sufficient agricultural future. India stands at a critical juncture where decisions taken today will shape the future sustainable food system. Harnessing renewable energy is not just an option but a necessity and strict imperative for ensuring sustainable agriculture, especially in biodiversity-rich NEH regions.

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LOW-CARBON AGRICULTURE IN INDIA: DESIGNING SUSTAINABLE AND CLIMATE-RESILIENT CROPPING SYSTEMS

Abstract:

Low-carbon agriculture is essential for reducing greenhouse gas emissions while maintaining sustainable crop production. This study explores the design of climate-resilient cropping patterns across different agroclimatic regions of India. It highlights key practices such as crop diversification, conservation tillage, integrated nutrient management, and efficient water use to enhance carbon sequestration and resource-use efficiency. The study emphasizes that region-specific low-carbon strategies can improve soil health, reduce environmental impacts, and strengthen farm resilience. Adoption of such approaches is crucial for achieving long-term agricultural sustainability under changing climate conditions.

Keywords: Low-carbon agriculture, cropping systems, carbon sequestration, climate-smart agriculture, India

Introduction

Today, the food system is in a crucial state and is responsible for both a large part of the ongoing climate change and for its negative impacts.

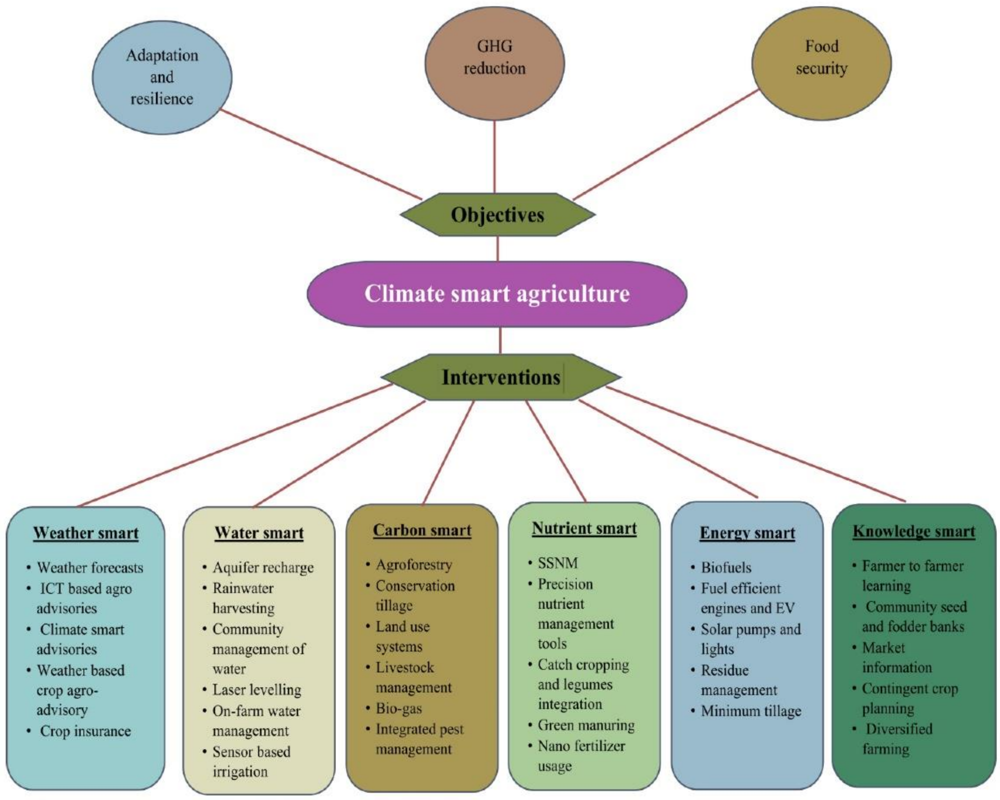

Figure 1. Concept of Low-Carbon Agriculture

The agriculture sector accounts for 10-12% of total anthropogenic GHGs globally, largely due to methane (CH4) emissions from both livestock and rice production and nitrous oxide (N2O) emissions produced from the use of synthetic fertilizers. In an effort to achieve "net zero" emissions, transitioning to low-carbon agriculture is no longer an option; it has become foundational to the next green revolution. Changing from 'extractive' farming to 'regenerative' design is essential to create a sustainable cropping system. Optimising the carbon cycle through farming means reducing the carbon output of farm inputs whilst increasing the soil's ability to hold carbon (or 'sink'). Low-carbon agriculture includes using precision technology, conservation tillage practices, and planting more diverse crop rotations to separate agricultural productivity from agricultural degradation in India, which supports millions of smallholder farming households who will be severely impacted by climate change and who can benefit both from reducing greenhouse gases that lead to climate change and improving farmer resiliency.

Concept of Low-Carbon Agriculture

Agriculture with low carbon emissions is an approach to growing food that reduces fossil-fuel-based greenhouse gas emissions and increases carbon stored in the land. Low-carbon agriculture is based on:

1. Reducing the use of fertilizer, water and energy and therefore reducing greenhouse gas emissions.
2. Increasing the amount of carbon sequestered in both soils and above-ground biomass.
3. Improving the efficiency of resource use to sustain productivity over the long-term.

This idea correlates with sustainability and/or climate-smart agricultural techniques within the Sustainable Development Goals, with a goal of increasing production while minimizing ecological disruption; all while helping the world community achieve its objective to combat climate change through transforming agricultural practices into carbon-efficient agronomic methods.

Key Practices and Features of Low-Carbon Agriculture Components

1. Conservation Farming

By encouraging the use of cereal and legume crop rotations and practising minimal tillage and leaving behind residue from harvested crops, conservation agricultural practices promote viable cropping systems that will help reduce greenhouse gas emissions and increase soil. These agricultural practices support sustainable farming and help to improve the sustainability of cropping systems.

2. Blue Carbon

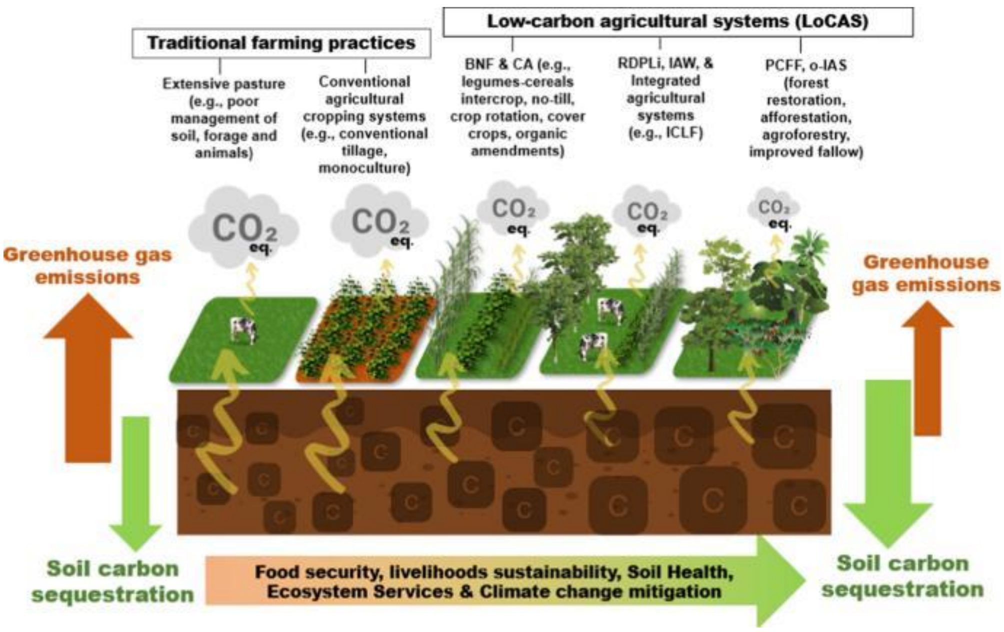

Figure 2. Sustainable Cropping System Framework

In coastal areas where cropping occurs, cropping systems (including rice in the water and fish swimming beneath) are examples of how integrating agriculture with the use of mangrove forests can enhance the types of crops produced as well as provide additional carbon storage capacities.

3. Agroclimatic Zone-wise Cropping Pattern

i. Western Himalayas

For instance, Himachal and Uttarakhand

The cropping patterns of this region are coded maize-wheat or rice-wheat with a horticulture pattern based on apples. Carbon-friendly improvements are agroforestry, growing crops on terraces to prevent soil erosion, and increasing organic farming to improve soil carbon levels.

ii. Eastern Himalayas

For instance, Sikkim, Arunachal Pradesh

This region is typically characterized by rice-based systems and jhum or shifting cultivation. Transition to settled agriculture by increasing the number of farms, increasing organic farming, and implementing soil conservation practices will provide significant emission reductions.

iii. Lower Gangetic Plain

For example, West Bengal

The majority of rice-rice-rice and rice-jute-vegetable systems are practised, has developed some low-carbon strategies, such as alternate wetting and drying (AWD) for rice, integration of fish with rice, and diversification of crops with pulses.

iv. Middle Gangetic Plain

For example, Bihar

The system of cropping is usually characterized by rice-wheat and maize-wheat. Planting direct-seeded rice (DSR), integrated nutrient management (INM), and the inclusion of legumes into cropping systems will improve carbon efficiencies.

v. Upper Gangetic Plain

For example, Uttar Pradesh

The system of cropping usually consists of rice-wheat and sugarcane. Replacing rice with either maize or pulses, using zero tillage, and managing crop residues will result in significant reductions in emissions.

vi. Trans-Gangetic Plain

For example, Punjab and Haryana

The cropping Systems are typically comprised of rice-wheat and cotton-wheat, which are historically common. Some strategies to reduce carbon emissions are precision farming, minimum tillage practices, and diversification in crop production.

vii. Eastern Plateau and Hills

For example, Jharkhand and Chhattisgarh

The predominant form of agriculture in this region is through rice monoculture. Agricultural sustainability can be supported by improving water management, promoting diverse cropping systems, and using conservation agriculture.

viii. Central Plateau and Hills

For example, Madhya Pradesh)

The dominant systems are based on soya bean and wheat, and sorghum and chickpeas. This is getting progressively less due to improved integrated nutrient management and efforts to reduce the use of chemicals.

ix. Western Plateau and Hills

For example, Maharashtra

Systems are based primarily on cotton and sorghum. By promoting drought-resistant crops, expanding micro-irrigation and reducing the use of tillage, carbon balances can be improved.

x. Southern Plateau and Hills

For example, Karnataka and Tamil Nadu

Systems are primarily based on finger millet and pulses, with groundnuts a distant third. Finger millet promotion, crop diversification and improving water management are among the ways of achieving low-carbon agriculture.

xi. East Coast Plains and Hills

For example, Andhra Pradesh and Odisha

The predominant system in these two states is based heavily on rice and other crops, with rice being the most widely produced crop by far. Integrating fish into rice production, using aerated wet irrigation practices, and developing varieties that tolerate saline soil are among the benefits of this growing region.

xii. West Coast Plains and Ghats

For example, Kerala

The only way to have successful production is to reforest and implement mixed cropping systems, instead of growing coconut, rice, and plantation crops.

xiii. Gujarat Plains and Hills

For example Gujarat

The predominant types of farming are those that produce groundnuts and wheat, with cotton produced to a lesser extent. By implementing micro-irrigation, expanding crop diversification, and conserving soil moisture, farmers could access better quality produce and use fewer inputs.

xiv. Western Dry Region

For Example: Rajasthan

The Dominant Crops this region are Pearl Millet, Mustard Seed and Guar. Through Increased Rainwater Harvesting, Increasing the Use of Pearl Millet, and Implementing Conservation Tillage, the Carbon Footprint is Reduced.

xv. Islands region

For example, Andaman and Nicobar Islands

The Dominant Crops in the Islands Region are Rice and Coconut Trees. Integrated Farming Systems, Organic Agriculture and Blue Carbon Strategies (Mangrove Conservation) all Increase Sustainability.

Benefits of Low-Carbon Cropping Patterns

• Low-Carbon Cropping Patterns can help reduce greenhouse gas emissions.

• Low-Carbon Cropping Patterns also improve soil health and carbon sequestration.

• Get better water and nutrient use efficiency with Low-Carbon Cropping Patterns.

• Low-Carbon Cropping Patterns make our farms more resilient to climate variability.

Conclusion

Designing carbon cropping patterns is a really important thing for sustainable agriculture. We can change the way we plant crops and use methods that work well in regions to cut down on emissions a lot and still get a lot of food from the land. We need to start planting different kinds of crops and include things like legumes and millets in low-carbon cropping patterns. We also need to think about the environment and use low-carbon cropping patterns that work with nature, not against it, to have systems that can handle climate change and are sustainable.

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BEYOND RICE–WHEAT DOMINANCE: STRATEGIES FOR SUSTAINABLE CROPPING SYSTEM DIVERSIFICATION IN PUNJAB

ABSTRACT

Punjab, the backbone of India's food security, has long relied on the rice–wheat cropping system due to the success of the Green Revolution. Although this system has ensured high productivity, its continuous cultivation has led to serious environmental concerns, including groundwater depletion, soil degradation, and declining biodiversity. Crop diversification has emerged as a sustainable alternative to address these challenges. This review examines the current cropping pattern in Punjab, the need for diversification, potential alternative cropping systems, associated benefits, constraints, and policy interventions. The study highlights that diversification towards maize, pulses, oilseeds, and horticultural crops can enhance resource-use efficiency, improve soil health, and increase farmers' income. However, lack of assured procurement, inadequate infrastructure, and farmer risk aversion hinder its adoption. The paper concludes that a combination of policy support, technological innovation, and market development is essential to promote sustainable agricultural diversification in Punjab.

INTRODUCTION

Punjab has played a central role in transforming India into a food-secure nation, primarily due to the large-scale adoption of high-yielding varieties of rice and wheat during the Green Revolution. The rice–wheat cropping system dominates the agricultural landscape, covering nearly 80% of the cultivated area. While this system has ensured stable production, its long-term sustainability has become questionable due to overexploitation of natural resources and environmental degradation. Continuous monocropping has resulted in declining soil fertility, increased pest incidence, and heavy reliance on chemical inputs. Moreover, intensive irrigation practices have led to a sharp decline in groundwater levels, making Punjab one of the most water-stressed regions in India. In this context, crop diversification is increasingly being recognized as a viable strategy to achieve ecological balance and economic stability.

Figure 1: Illustration of Crop Diversification through Multiple Cropping Systems.

CONCEPT AND IMPORTANCE OF CROP DIVERSIFICATION

Crop diversification refers to the practice of growing a variety of crops instead of relying on a single cropping system. It includes both horizontal diversification, which involves introducing different crops into the existing system, and vertical diversification, which focuses on value addition and allied activities such as processing and dairy farming. Diversification is essential for reducing production risks, improving soil health, and ensuring efficient use of resources. It also contributes to nutritional security by promoting the cultivation of diverse food crops. In Punjab, diversification is particularly important to reduce the excessive dependence on rice and wheat and to mitigate the associated environmental and economic challenges.

CURRENT CROPPING PATTERN IN PUNJAB

The existing cropping pattern in Punjab is highly skewed towards rice and wheat due to favorable government policies, including minimum support price (MSP), assured procurement, and input subsidies. The widespread availability of irrigation infrastructure has further reinforced this system. However, this pattern has resulted in significant ecological imbalances. The excessive use of groundwater for paddy cultivation has led to alarming declines in water tables, with many regions classified as over-exploited. Additionally, the imbalance in nutrient application, particularly the overuse of nitrogen fertilizers, has degraded soil quality. Crop residue burning, a common practice in the rice–wheat system, contributes to severe air pollution and loss of soil organic matter.

NEED FOR CROPPING SYSTEM DIVERSIFICATION

The need for diversification in Punjab arises from environmental, economic, and social concerns. Environmentally, the declining groundwater levels and soil degradation necessitate a shift towards less resource-intensive crops. Economically, rising input costs and stagnating yields have reduced profit margins for farmers, making diversification essential for improving income stability. Socially, dependence on a single cropping system increases vulnerability to market and climate risks. Diversification can provide alternative livelihood opportunities and reduce the overall risk associated with farming.

Figure 2: Conceptual Framework showing the Need for Crop Diversification.

ALTERNATIVE CROPPING SYSTEMS

A. Maize-Based Systems:
   1. Rice → Maize replacement
   Benefits:
      a. Requires less water (70–80% less than rice)
      b. Suitable for diversification
B. Pulses-Based Systems:
   1. Crops: Green gram, black gram, chickpea
   Benefits:
      a. Nitrogen fixation
      b. Improves soil fertility

GOVERNMENT INITIATIVES AND POLICY SUPPORT

The government has implemented various initiatives to promote crop diversification in Punjab. Programs such as the Crop Diversification Programme aim to encourage farmers to adopt alternative crops. Financial incentives and subsidies for micro-irrigation systems and farm machinery are also provided. The promotion of Direct Seeded Rice (DSR) technology helps reduce water usage in paddy cultivation. However, these efforts need to be complemented with strong policy support, including assured procurement and price incentives for diversified crops, to ensure widespread adoption.

STRATEGIES FOR PROMOTING DIVERSIFICATION

A comprehensive approach is required to promote crop diversification in Punjab. Policy reforms should focus on extending MSP and procurement facilities to alternative crops. Investment in infrastructure, including storage, transportation, and processing facilities, is essential to strengthen market linkages. Technological interventions such as improved crop varieties, precision farming, and water-saving techniques can enhance productivity and resource efficiency. Capacity building through farmer training and extension services is crucial to increase awareness and adoption of diversified cropping systems. Encouraging contract farming and public–private partnerships can also facilitate market access and reduce risks for farmers.

CONCLUSION

Crop diversification is a critical pathway for achieving sustainable agriculture in Punjab. The continued dominance of the rice–wheat system is no longer viable due to its adverse environmental and economic impacts.

Diversification towards maize, pulses, oilseeds, and horticultural crops can improve resource use efficiency, enhance soil health, and increase farmers' income. However, successful implementation requires coordinated efforts involving policy support, infrastructure development, technological innovation, and farmer participation. A holistic approach will enable Punjab to transition towards a more resilient and sustainable agricultural system. Future policies must align sustainability goals with farmer profitability to ensure long-term adoption.

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PLANT IDEOTYPES FOR DRYLAND AGRICULTURE: DESIGNING CLIMATE-RESILIENT CROPS

Abstract

Dryland Agriculture is facing significant challenges due to scarcity of the water, climate variability, erratic rainfall and soil erosion. Traditional crop varieties are unable to obtain stable yield under these drought conditions, making it essential to develop climate resilient crops for future environmental constraints. Under such conditions, Plant Ideotypes are emerging as a strategy to develop climate resilient crops. Recent advancement in the breeding, crop modelling and modern techniques enhanced the development of the crops of the future with drought tolerance, water use efficiency and yield stability. This article examines the concepts, traits, and applications of plant ideotypes for dryland agriculture. It highlights morphological, physiological and genetic characteristics that enabled the designing of crops. The study highlights how designing the crop of the future can enhance productivity, sustainability, and resilience in dryland agriculture. By integrating modern breeding techniques with ecological understanding, plant ideotypes offer a pathway toward resilient and future-ready cropping systems.

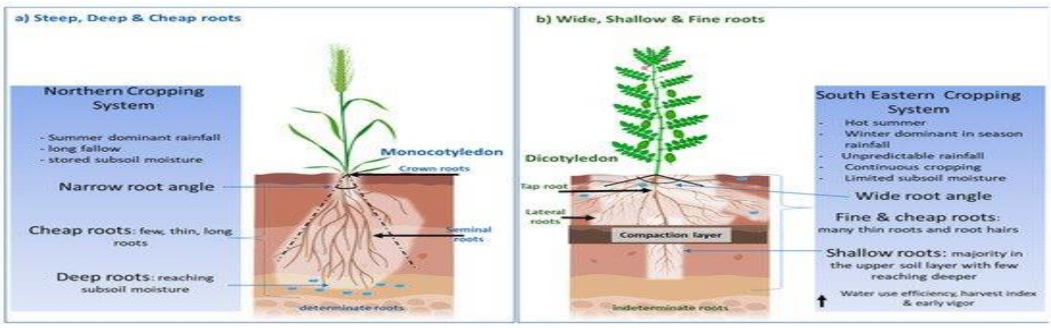
Key words: Dryland agriculture, plant ideotypes, climate resilient crops, water use efficiency, sustainability, crop modelling.

1. Introduction

Dryland agriculture constitute nearly 40% of the world's agricultural land. However, these regions are characterized by erratic rainfall, high evaporation, poor soil fertility and drought conditions. These characters limit the crop growth and productivity. Climatic variability is increasing water scarcity and severity of drought conditions, causing a major threat to the global food security. As a result, traditional crop varieties fail to produce optimum yield under such stress conditions.

In response, the concept of plant ideotypes is an emerging strategy that can enhance crop productivity while ensuring sustainability. These are theoretical models of plants with desirable traits required for particular environmental conditions. In Dryland agriculture, plant ideotypes are designed to enhance water use efficiency, drought tolerance and produce stable yields under

limited available resources. This article examines the designing strategies, key plant traits and potential ideotypes in Dryland agriculture systems.



1. Concept of Plant ideotypes

The concept of plant ideotype was first proposed by Donald (1968). A plant ideotype is a theoretical model of an ideal plant with specific morphological, physiological, and biological traits that improves the performance under defined set of environmental conditions. Unlike traditional breeding, which only focuses on the yield, ideotype breeding integrates traits such as deep root system, canopy cover, water use efficiency, drought tolerance that contribute to increased production in a defined environment.

2. Key Traits of plant ideotypes for Dryland

Plant ideotype breeding provides a solution by designing plants with traits that improves survival and productivity under Dryland agricultural conditions.

2.1 Morphological Traits

2.1.1 Deep root system

A well-developed root system is essential under dryland conditions. Deep roots enable the plant to absorb moisture from deeper layers of the soil, while lateral roots enhance water and nutrient absorption. Crops like sorghum and pear millet has such traits which are able to serve as models for ideotype development. Pulse crop studies have shown that root architecture as a key trait for drought adaptations. (Rao *et al*., 2021)

2.1.2 Reduced leaf area and canopy cover

Decreased leaf area reduces transpiration losses. Compact canopy structures and erect leaves improves light penetration and reduce water requirement, enhancing the plant efficiency under limited moisture conditions.

2.1.3 Early seedling vigour and rapid establishment

Early germination and growth allow crops to utilize available soil moisture more efficiently. Early vigour also helps in weed suppression and improves seedling establishment. Early maturity avoids late drought, this mechanism is known as drought escape and rapid establishment causes early ground cover reduces evaporation losses.

2.2 Physiological Traits

2.2.1 Drought tolerance mechanism

Dryland ideotypes have phenological adaptations such as, osmotic adjustment, stomatal regulation, leaf rolling and waxy cuticles. Osmotic adjustment - cell maintain turgor under stress. Stomatal regulation - reduces water loss through transpiration. These mechanisms improve cellular function under drought stress. (Gracia-Romero *et al*., 2023)

2.2.2 High water use efficiency

Ideotypes combine efficient biomass partitioning, stomatal control, osmotic adjustment and photosynthetic efficiency to maximize the yield under arid and semi-arid conditions. (Mashouqi *et al*., 2025)

2.2.3 Stay green trait of ideotypes

The stay green trait refers to the ability of the plant to maintain photosynthetic activity under drought stress. This supports in better grain filling and yield stability in crops like sorghum.

2.3 Phenological Traits

2.3.1 Early flowering and maturity

This is one of most important phenological trait, which helps the crops to complete their life cycle before the terminal drought. This mechanism is knowns as drought escape, which has been widely reported in cereal crops such as wheat and sorghum, where early maturing genotypes show increased yield stability under water stress.

Table 1. Comparison of Conventional Crops vs Future Ideotype Crops

Parameter	Conventional Crops	Future Ideotype Crops
Yield Stability	Low	High
Water Productivity	Low	High
Climate Adaptability	Poor	Strong
Resource Efficiency	Low	Optimized
Technology Integration	Minimal	High (AI, genomics)

2.3.2 Synchronized flowering with moisture availability

This is an important phenological trait in dryland ideotypes as it helps the crop to use available moisture at most critical stage. Flowering stage and grain setting are highly sensitive to drought, any changes in soil moisture reduces the crop yield. Studies have shown that adjusting flowering time with seasonal rainfall patterns significantly improves yield stability under drought conditions. (Passioura, 2012), (Kirkegaard & Hunt, 2010)

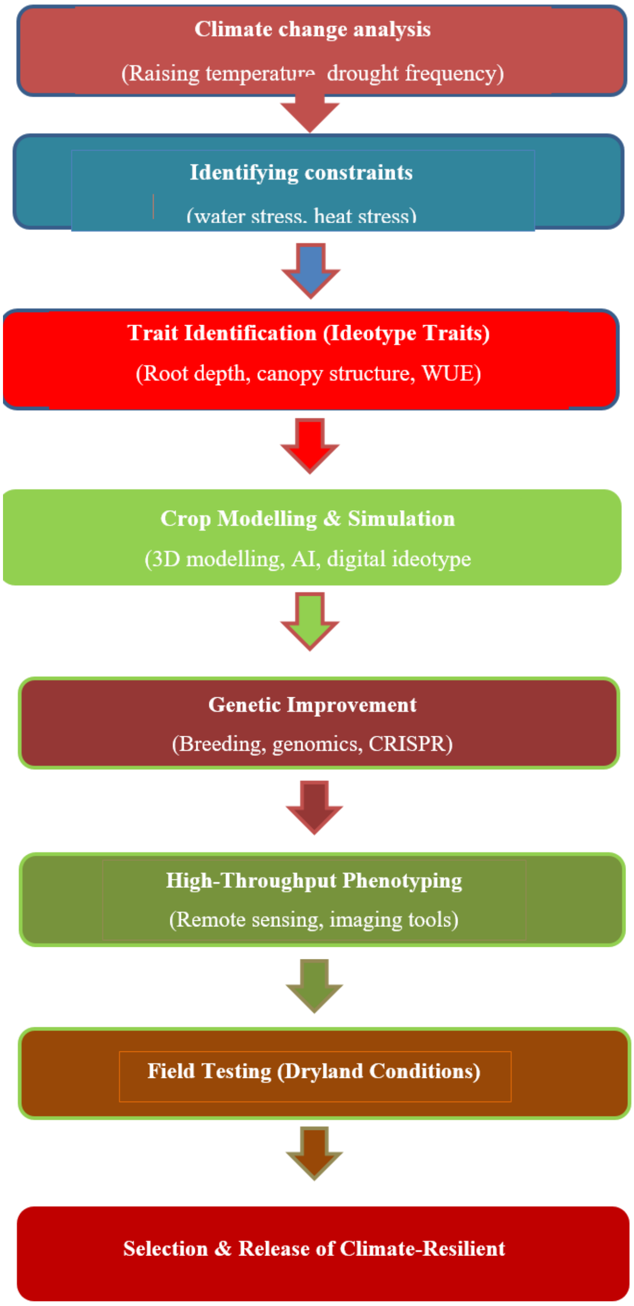


Figure: Designing the crop of the future

This figure represents how crops resilient to climatic conditions are designed for dryland farming. It emphasizes the process whereby scientific study, recent technology, and practical experimentation are combined in designing crops capable of enduring environmental stress. It outlines the transformation from identifying problems to developing efficient crops of the future

Designing the crop of the future

Crop design is the science of developing ideotypes of plants having certain morphological, physiological, and genetic features, which helps to function optimally in varying environmental conditions and contribute to increasing productivity, particularly in dry farming, which is affected greatly by drought and heat stresses. While conventional plant breeding is concerned primarily in producing highly productive varieties under optimal growing conditions, designing aims at creating resilient, stable, and resource-efficient crops. This process starts with predicting future climatic problems in which crop have to be adjusted, choosing the most relevant adaptive traits, such as a deep root system, optimum canopy structure, water-use efficiency, and stay green. Then these traits should be combined in one plant. The emergence of crop simulation models enables scientists to estimate the effectiveness of the chosen combination of adaptive traits for certain climates and make the designing process more precise. Besides, genomics, gene editing technology, for example, using CRISPR, high-throughput phenotyping, and other innovations associated with artificial intelligence can significantly speed up breeding processes and lead to the creation of climate-resilient plants.

Conclusion:

The design of the crop of the future through ideotypes in plants is key to ensuring sustainability in agriculture for arid land. It is feasible for researchers to breed crops using scientific techniques coupled with knowledge of ecology, which lead to crops thriving in extreme environmental conditions. This approach plays a crucial role in addressing global food security challenges in the face of climate change.

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