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Vermicomposting: An Eco-Friendly Tool for Enhancing Soil Fertility and Health

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1. Introduction

The escalating global population and intensified agricultural practices have placed immense pressure on soil resources, leading to widespread degradation, nutrient depletion, and diminished productivity. Conventional agriculture, heavily reliant on synthetic fertilizers and pesticides, often exacerbates these issues, contributing to environmental pollution, biodiversity loss, and a decline in soil health. Consequently, there is an urgent need for sustainable agricultural strategies that can restore and enhance soil fertility without compromising ecological integrity.

Vermicomposting, a promising biotechnological process, offers a viable solution to these challenges. It involves the synergistic action of various species of earthworms, along with a diverse community of microorganisms, to decompose organic waste materials into a dark, humified, and nutrient-rich product known as vermicompost. This process not only diverts organic waste from landfills, thereby reducing greenhouse gas emissions and leachate production, but also generates a valuable organic amendment that significantly improves soil properties and plant growth.

This article aims to provide a comprehensive overview of vermicomposting, focusing on its mechanisms, the characteristics of vermicompost, its impact on soil fertility and health, and its implications for sustainable agriculture.

2. The Process of Vermicomposting

Vermicomposting is an aerobic and mesophilic process that mimics the natural decomposition of organic matter in forest ecosystems. The key players in this process are epigeic earthworm species, such as *Eisenia fetida* (red wiggler) and *Lumbricus rubellus*, which are particularly adapted to living in the upper layers of soil rich in organic matter.

2.1. Earthworm Biology and Role

Earthworms consume organic waste, digest it with the aid of their powerful gizzard and a diverse microbial community in their gut, and excrete it as vermicasts. During their passage through the earthworm gut, organic materials undergo significant physical and biochemical transformations:

a. **Mechanical Grinding:** The gizzard grinds the organic matter into finer particles, increasing its surface area for microbial colonization.
b. **Microbial Enhancement:** The earthworm gut provides an ideal environment for microbial proliferation, with gut microbes actively breaking down complex organic compounds.
c. **Enzymatic Activity:** Earthworms secrete various enzymes (e.g., cellulase, chitinase, lipase, protease) that further aid in the breakdown of organic polymers.
d. **Mucus Secretion:** Earthworm mucus, rich in nitrogenous compounds, contributes to microbial activity and aggregate stability.

2.2. Factors Influencing Vermicomposting

The efficiency of vermicomposting is influenced by several environmental and substrate-related factors:

a. **Temperature:** Optimal temperature for most vermicomposting earthworms is between 20-30°C.

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b. **Moisture Content:** A moisture content of 70-80% is crucial for earthworm activity and microbial decomposition.

c. **pH:** Earthworms thrive in a slightly acidic to neutral pH range (6.0-7.5).

d. **C: N Ratio:** An ideal Carbon to Nitrogen (C: N) ratio of the feedstock is between 25:1 to 30:1 for efficient decomposition.

e. **Aeration:** Adequate aeration is necessary to maintain aerobic conditions and prevent the buildup of harmful anaerobic byproducts.

f. **Substrate Type:** Various organic wastes, including agricultural residues, animal manures, food waste, and sewage sludge, can be vermicomposted. Pre-composting or shredding may be required for certain materials.

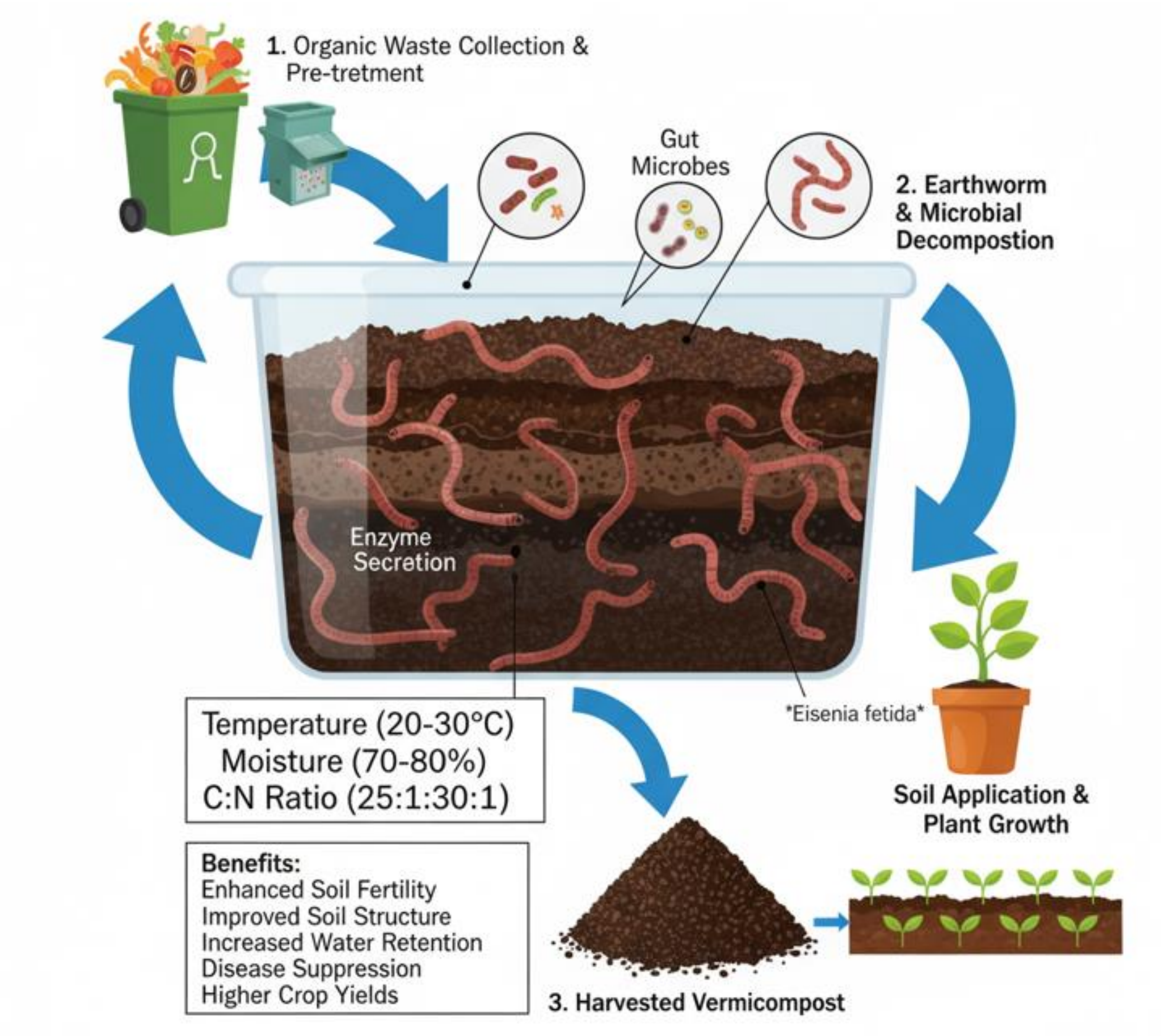

Figure 1. Schematic Diagram of the Vermicomposting Process

3. Characteristics of Vermicompost

Vermicompost is a heterogeneous mixture of earthworm casts, organic matter in various stages of decomposition, and a diverse microbial population. Compared to traditional compost and raw organic materials, vermicompost exhibits superior physicochemical and biological properties.

3.1. Chemical Properties

- **Nutrient Enrichment:** Vermicompost is richer in essential plant nutrients (Nitrogen, Phosphorus, Potassium, Calcium, Magnesium, micronutrients) in readily available forms. The humification process stabilizes nitrogen, reducing leaching losses.
- **Humic Substances:** They contain a higher proportion of humic acids and fulvic acids, which contribute to nutrient chelation, soil aggregation, and plant growth stimulation.
- **C: N Ratio Reduction:** The C: N ratio is significantly lower than the original feedstock, indicating a stable and mature product.
- **Increased Cation Exchange Capacity (CEC):** The high content of humic substances and fine organic matter particles contributes to an elevated CEC, enhancing the soil's ability to retain and supply nutrients to plants.
- **Neutral pH:** Vermicompost typically has a near-neutral pH, making it suitable for a wide range of crops and helping to buffer soil pH.

Table 1. Comparative Chemical Properties of Feedstock, Traditional Compost, and Vermicompost

Property	Raw Feedstock (e.g., Cow Dung)	Traditional Compost	Vermicompost
Organic Carbon (%)	30-45	20-35	15-25
Total Nitrogen (%)	1.0-2.0	1.5-2.5	2.0-3.0
Total Phosphorus (%)	0.5-1.0	0.8-1.5	1.0-2.0
Total Potassium (%)	0.3-0.8	0.6-1.2	0.8-1.5
C: N Ratio	20-35:1	15-25:1	10-15:1
pH	6.5-8.0	6.0-7.5	6.5-7.0
Humic Acid (%)	Low	Moderate	High
CEC (meq/100g)	Low-Moderate	Moderate-High	High

3.2. Biological Properties

a. Microbial Diversity: Vermicompost harbours a richer and more diverse population of beneficial microorganisms, including bacteria (e.g., nitrogen fixers, phosphate solubilizers), fungi, actinomycetes, and protozoa.

b. Plant Growth-Promoting Substances: It contains plant growth regulators such as auxins, gibberellins, and cytokinins, produced by microorganisms and earthworm gut activity.

c. Enzymatic Activity: High levels of various enzymes (dehydrogenase, urease, phosphatase, cellulase) indicate active microbial communities and contribute to nutrient cycling.

4. Impact of Vermicompost on Soil Fertility and Health

The application of vermicompost to agricultural soils results in a myriad of benefits, collectively contributing to enhanced soil fertility and overall health.

4.1. Improvement of Soil Physicochemical Properties

a. Soil Structure and Aggregation: The fine particulate matter, mucus secretions from earthworms, and microbial glues in vermicompost promote the formation and stability of soil aggregates. This improves soil aeration, water infiltration, and reduces soil compaction.

b. Water Holding Capacity: The high organic matter content of vermicompost acts like a sponge, significantly increasing the soil's water-holding capacity, which is particularly beneficial in drought-prone regions.

c. Nutrient Availability and Retention: Vermicompost slowly releases plant-available nutrients, reducing nutrient leaching and making them accessible over a longer period. Its high CEC further enhances nutrient retention.

d. Buffering Capacity: Vermicompost helps stabilize soil pH, buffering against drastic changes that can stress plants and inhibit nutrient uptake.

4.2. Enhancement of Soil Biological Properties

a. **Microbial Biomass and Activity:** Application of vermicompost leads to a substantial increase in soil microbial biomass carbon and nitrogen, indicating a healthier and more active microbial community. This invigorated microbial life drives nutrient cycling and organic matter decomposition.

b. **Suppression of Plant Diseases:** Vermicompost often contains beneficial microorganisms that can suppress soil-borne plant pathogens through mechanisms like antibiosis, competition for nutrients, and induced systemic resistance in plants. This can reduce the reliance on chemical fungicides.

c. **Biodiversity Enhancement:** By improving soil structure and providing a rich food source, vermicompost can support a more diverse array of soil macro- and microorganisms, contributing to a robust soil food web.

5. Benefits for Crop Productivity

The multifaceted improvements in soil health provided by vermicompost translate directly into robust and sustainable enhancements in crop productivity. These benefits stem not just from improved nutrient supply but also from hormonal stimulation and increased plant resilience.

5.1. Direct Yield and Quality Enhancement

The application of vermicompost consistently results in higher crop yields across diverse agricultural systems, including horticulture, cash crops, and cereals. This boost is a consequence of the product's ability to provide nutrients in slow-release, readily available forms.

- **Nutrient Synergism:** Unlike synthetic fertilizers that often supply only 3-4 major nutrients, vermicompost delivers a balanced spectrum of macro- and micronutrients (N, P, K, S, Zn, Mn, Cu, and Fe) essential for optimal plant metabolism. The high Cation Exchange Capacity (CEC) of vermicompost prevents these nutrients from leaching, ensuring prolonged availability.
- **Improved Crop Quality:** Beyond biomass, vermicompost improves the intrinsic quality of the harvest. Studies report increases in total soluble solids (brix), vitamin content, protein levels, and dry matter accumulation in fruits and vegetables, which directly enhances their market value and nutritional density.

5.2. Hormonal Stimulation and Root Vigor

A critical advantage of vermicompost over traditional compost is the presence of naturally produced Plant Growth Regulators (PGRs).

- **Auxins and Gibberellins:** Earthworm gut activity and the associated microbial community synthesize significant quantities of phytohormones, particularly auxins and gibberellins. Auxins promote cell elongation and differentiation, leading to dramatically enhanced root system development (increased root length, volume, and surface area). A dense, healthy root network is crucial for maximizing the uptake of water and nutrients, especially less mobile elements like Phosphorus (P).
- **Cytokinins:** These PGRs promote cell division and delay senescence (aging). Their presence contributes to greater vegetative growth, increased leaf area for photosynthesis, and more vigorous shoot development. This hormonal effect leads to better resource partitioning within the plant.

5.3. Enhanced Nutrient and Water Use Efficiency

By improving the soil's physical properties and nutrient retention, vermicompost optimizes how plants utilize scarce resources.

- **Water Use Efficiency (WUE):** The higher organic matter and stable aggregate structure significantly increase the soil's water-holding capacity. This provides a buffer against intermittent drought, allowing plants to maintain transpiration and photosynthesis for longer periods under water stress, thereby improving WUE.
- **Nutrient Uptake Mechanisms:** The humic and fulvic acids present in vermicompost effectively chelate (bind) micronutrient cations like Zn, Mn, Cu, and Fe. This chelation makes these elements more stable, soluble, and accessible for root absorption, overcoming common micronutrient deficiencies often encountered in high-pH soils.

5.4. Increased Stress and Disease Tolerance

Plants grown in vermicompost-amended soils exhibit greater resilience against biotic and abiotic stresses.

- **Disease Suppression:** Vermicompost often acts as a bio-pesticide. Its rich microbial community includes antagonists (e.g., certain *Bacillus* species and *Trichoderma* fungi) that compete with or directly inhibit soil-borne pathogens like *Fusarium* and *Pythium*. Furthermore, vermicompost can trigger Induced Systemic Resistance (ISR) in the plant, activating the plant's natural defence mechanisms against diseases.
- **Tolerance to Abiotic Stress:** The improved soil structure and water regulation help mitigate the impacts of salinity and drought. Healthier, hormone-stimulated roots are better equipped to navigate challenging soil conditions, ensuring plant survival and productivity even in marginal environments.

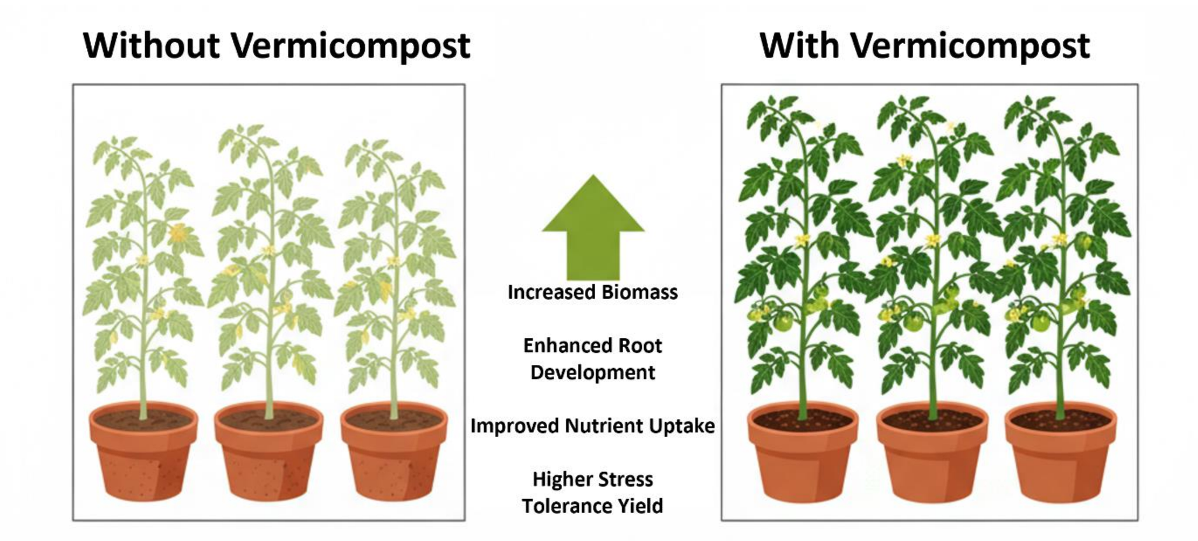

Figure 2. Impact of Vermicompost on Plant Growth

6. Environmental and Economic Benefits

Beyond enhancing soil and crop productivity, vermicomposting offers significant ecological and economic advantages, aligning perfectly with the principles of the circular economy and sustainable development.

6.1. Sustainable Waste Management

Vermicomposting serves as a highly efficient and decentralized method for the sustainable management of vast quantities of organic waste (manures, crop residues, municipal solid waste). By diverting this waste from landfills, it helps to:

a. **Reduce Landfill Burden:** Decreasing the volume of waste requiring disposal, thus saving valuable land space.

b. **Mitigate Greenhouse Gas Emissions:** Anaerobic decomposition in landfills releases potent greenhouse gases like methane (CH_4). Vermicomposting, being an aerobic process, significantly reduces CH_4 production.

c. **Minimize Water Pollution:** It stabilizes organic matter, reducing the potential for leachate formation, which can contaminate groundwater and surface water bodies.

6.2. Economic Viability

For farmers and entrepreneurs, vermicomposting can be a source of income generation and reduced input costs:

a. **Value-Added Product:** Vermicompost and vermiwash (the liquid extract) are high-value organic soil amendments that can be sold.

b. **Reduced Input Costs:** Farmers can substantially cut down on expenditure for synthetic fertilizers and chemical pesticides, improving their profit margins.

c. **Job Creation:** The establishment of vermicomposting units, especially at the community and commercial levels, fosters local employment.

7. Challenges and Future Directions

Despite its clear advantages, the widespread adoption of vermicomposting faces several hurdles that require focused research and policy interventions.

7.1. Operational and Technical Challenges

a. **Scaling Up:** Moving from small-scale household or farm units to large-scale commercial operations requires standardized and mechanized methods for feeding, harvesting, and quality control.
b. **Feedstock Variation:** The quality of vermicompost can vary significantly depending on the initial feedstock. Proper pre-treatment and blending are necessary to ensure a consistent, high-quality end product.
c. **Temperature and Climate Control:** Maintaining the optimal temperature and moisture level (20-30°C and 70-80% moisture) can be challenging in extremely cold or hot climatic regions, necessitating controlled-environment systems.
d. **Heavy Metal and Pathogen Concerns:** When processing sewage sludge or certain industrial wastes, the presence of heavy metals or pathogens requires careful monitoring and verification that the vermicomposting process effectively reduces their toxicity and viability.

7.2. Future Research Focus

Future research should be directed towards:

a. **Process Optimization:** Developing predictive models and sensor technologies to monitor and automate critical parameters like temperature, pH, and moisture in large-scale vermireactors.
b. **Vermicompost Standardization:** Establishing internationally recognized quality standards and certification for vermicompost based on nutrient content, microbial load, and absence of contaminants, to build farmer confidence.
c. **Application-Specific Formulations:** Tailoring vermicompost and vermiwash recipes for specific soil types, crop requirements, and nutrient deficiencies (e.g., using it to remediate micronutrient deficiencies like Zinc, Manganese, and Iron, which are often monitored in soil science research).
d. **Mechanisms of Disease Suppression:** Further elucidating the exact microbial and biochemical pathways by which vermicompost suppresses pathogens to enhance its biocontrol efficiency.

Table 2: Economic and Environmental Impact of Vermicomposting

Aspect	Conventional Waste Disposal (Landfill)	Vermicomposting	Significance
Product Value	Negative (Disposal Cost)	High (Soil Amendment)	Converts cost into revenue.
GHG Emissions	High (CH_4, CO_2)	Low (CO_2 from respiration)	Major climate change mitigation potential.
Nutrient Cycling	Interrupted (Nutrients are locked up)	Complete (Nutrients are mineralized)	Recycles N, P, and K back to the soil.
Input Dependency (Fertilizer)	High	Low	Reduces reliance on fossil fuel-derived inputs.
Soil Quality	No Impact /Detrimental	Significant Improvement	Enhances soil health and resilience.

8. Conclusion

Vermicomposting is redefined not merely as a waste management practice but as a crucial component of ecological agriculture and circular economy principles. The resulting vermicompost serves as an exceptional soil amendment, enhancing the soil's physical, chemical, and biological properties. With high levels of plant-available nutrients, increased Cation Exchange Capacity, and stable humic acid content, vermicompost significantly improves soil fertility, structure, and water retention while reducing erosion and compaction risks. Its role as a biological inoculant introduces a wealth of beneficial microorganisms, fostering nutrient cycling, disease resistance, and promoting higher crop yields and quality. Furthermore, its capacity to sequester and stabilize Soil

Organic Carbon (SOC) positions vermicomposting as vital for soil carbon management and mitigating climate change.

For widespread adoption, challenges such as standardization and large-scale production must be addressed, necessitating research on optimizing feedstock processes and developing specific application protocols. By integrating vermicomposting with precision agriculture technologies, it can become a cornerstone of sustainable intensification, promoting robust crop productivity while improving soil health and lessening the environmental footprint of farming. The future of resilient agro-ecosystems is closely tied to the acceptance and application of such eco-friendly and biologically driven practices.

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"Power on Your Plate: How Vegetables Fuel a Healthier Tomorrow"

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Abstract

Vegetables form a very important part of human nutrition and are immensely crucial for achieving all health and environmental sustainability objectives. They are rich in vitamins, minerals, dietary fiber and phytochemicals. They offer protective effects for chronic diseases such as cardiovascular disorders, diabetes, obesity and cancer. In the present scenario of increased lifestyle diseases and ecological degradation, vegetables assume a dual role: they improve human health while promoting planetary health with low carbon footprints and efficient use of resources. Contemporary vegetable science research emphasizes their potentiality as functional foods, nutraceutical sources and climate-resilient crops suitable for adaptation under sustainable production systems. Apart from that, emerging technologies like hydroponics, aeroponics and vertical farming have reinvented the way vegetables can be produced in a very sustainable manner within city environments. Despite such scientifically proven benefits, global consumption of vegetables remains well below the World Health Organization's minimum recommended intake of 400 grams per person per day. This article discusses the many facets of vegetables-from nutritional and biochemical importance to their economic, ecological and social contribution. It also explores vegetable production innovation, postharvest challenges and a greater focus on plant-based diets regarding global health and sustainability. Through this synthesis, the article underlines that empowering communities with knowledge and access to vegetables will alter dietary trends, reverse climate change and build back a healthier tomorrow-putting "power on your plate."

Keywords: vegetables, nutrition, sustainability, functional foods, phytochemicals, health, vertical farming.

1. Introduction

Vegetables have nourished humanity since the dawn of civilization, standing intrinsically connected with diets across regions, cultures and generations. They are much more than a side dish-they provide essential nutrients, health-promoting bioactive compounds and ecological resilience. In today's fast-changing world, with non-communicable diseases such as diabetes, obesity, hypertension and cancer increasing at alarming rates, vegetables cannot be overemphasized in everyday diets (Slavin & Lloyd, 2012; Willett *et al*., 2019).

Although the WHO, 2020, recommends a minimum daily intake of 400 grams of fruits and vegetables, global surveys reveal that average consumption is much below this level, especially in developing countries where diets are shifting toward refined carbohydrates and processed foods. The Food and Agriculture Organization reports that in most Asian and African countries, vegetable consumption ranges between 100–250 grams per day, which reflects not only economic constraints but also lifestyle and awareness gaps.

Vegetables provide a unique combination of macronutrients and micronutrients that contribute to growth, metabolism and immunity. They contain minimal fat and are energy-dense yet low in calories, making them ideal for maintaining healthy body weight. Moreover, they are rich sources of dietary fiber, which aids digestion, enhances gut microbiota balance and prevents constipation and colorectal cancer (Liu, 2013). Vitamins like A, C and K, along with minerals such as iron, magnesium and calcium, are abundantly supplied by a diverse range of vegetables. Their phytonutrient content — including flavonoids, carotenoids and glucosinolates — acts as a natural defense system against oxidative stress and inflammation, thus lowering disease risk (Pandey & Rizvi, 2009).

Apart from health benefits, vegetables nurture sustainable food systems in that they require less of the available natural resources than animal-based foods. For example, while a kilogram of beef requires upwards of 15,000 litres of water, the same is less than 300 litres for leafy vegetables (FAO, 2022). Meanwhile, vegetables produce far less greenhouse gas, and their place in climate-smart agriculture and sustainable diets is vital (Springmann *et al*., 2018).

Besides nutrition and sustainability, vegetables contribute to socio-economic development. They are the main sources of jobs and financial resources for millions of smallholder farmers, particularly women and contribute to household food security in both rural and urban areas. The International Horticultural Congress declared vegetables as “the most promising gateway crop for achieving nutrition-sensitive agriculture” in 2022.

However, there are various issues that need consideration in the global vegetable sector, such as limited storages, postharvest losses estimated at 20–40%, erratic supply chains and a lack of awareness among consumers about the need to consume a variety of vegetables (FAO, 2021). Furthermore, the pressure due to rapid urbanization has diminished arable land availability, impelling scientists and farmers to explore hydroponics, aeroponics and vertical farming as novel cultivation systems that maximize efficient use of space and resources (Despommier, 2020).

As an interdisciplinary field, vegetable science encompasses genetics, physiology, postharvest technology and socio-economics, with the ultimate objectives of developing high-yielding, nutrient-rich, climate-resilient varieties, among others and promoting sustainable production practices. The vegetables will have to play a pivotal role in ensuring nutritional and ecological security with the global population projected to reach 9.7 billion by 2050. UN, 2022. Thus, the phrase "Power on Your Plate" is not just metaphorical but real because vegetables transform bodies, ecosystems, and societies. This article explores that power through scientific, social and technological lenses-illustrating how vegetables fuel a healthier tomorrow.

2. Nutritional Powerhouse: The Science Behind Vegetables

Vegetables are biological powerhouses packed with nutrients essential for human growth, maintenance, and disease prevention. The science behind their health-promoting properties lies in their biochemical composition, which includes carbohydrates, proteins, dietary fiber, vitamins, minerals and an array of bioactive phytochemicals. Unlike processed foods, which are high in sugar, salt, and unhealthy fats, vegetables provide nutrition in a natural, balanced and bioavailable form that supports long-term wellness.

2.1. Macronutrient Composition

Although often perceived as being low in calories, vegetables contain key nutrients that sustain physiological processes.

Carbohydrates: The major source of energy in most vegetables exists as complex carbohydrate forms like starch, cellulose, and pectins. Root vegetables include potatoes, sweet potatoes and carrots, which consist of slow-releasing carbohydrates that sustain blood glucose levels.

Proteins: Leguminous vegetables such as peas and beans are rich in plant-based proteins, offering an alternative to animal protein sources and supporting muscle development and metabolic functions.

Fats: Most vegetables are made of negligible fats, with some exceptions like avocado and soybean that provide fats having healthy unsaturated fatty acids beneficial to heart health (Wang *et al*., 2019).

2.2 Dietary Fiber: The Digestive Regulator

Dietary fiber is a non-digestible carbohydrate found in abundance in leafy greens, legumes, and tubers that plays a paramount role in digestive health. The soluble fibers include pectin and β-glucans, which delay digestion and regulate blood sugar levels, while insoluble fibers, such as cellulose, add bulk to the stool, preventing constipation. Regular intake of fiber-rich vegetables has been associated with reduced risks of coronary heart disease, stroke and Type-2 diabetes.

Table 1. Fiber Content of Common Vegetables

Vegetable	Fiber (g/100g)	Type of Fiber	Health Benefit
Spinach	2.2	Insoluble	Improves bowel movement
Carrot	2.8	Soluble	Lowers cholesterol
Broccoli	2.6	Insoluble/Soluble	Regulates blood sugar
Green peas	5.7	Soluble	Enhances gut microbiota
Sweet potato	3.3	Insoluble	Prevents constipation

(**Source:** USDA Food Database, 2023)

2.3. The Role of Water Content

These vegetables contain a high percentage of water, hence are highly hydrologic, ranging between 70–95%. Vegetables are vital for maintenance of body fluids and body temperature regulation. High-moisture vegetables, like cucumber, tomato and lettuce, also make them more important in hot tropics due to high prevalence of dehydration and heat stress. Water-rich vegetables maintain kidney health by diluting toxins and preventing stone formation (Popkin *et al.*, 2010).

2.4. Low-Calorie, High-Volume Advantage

Low energy density enables an individual to eat more vegetables without a very high intake of calories, a property that supports weight management and will help combat obesity as one of the major risk factors of metabolic diseases. It has been illustrated from studies that the replacement of 20% of energy by vegetables reduces BMI and visceral fat accumulation significantly (Ledikwe *et al.*, 2006).

2.5. Vegetable Protein as a Sustainable Nutrient Source

As global concerns about animal-based diets grow due to their environmental burden, plant-based proteins from vegetables offer a sustainable alternative. Green peas, soybeans, lentils and leafy greens contain high-quality amino acids essential for human metabolism. Moreover, advances in breeding and biotechnology are enhancing protein yield and digestibility in vegetables, making them integral to the future of food security (FAO, 2022).

3. Vitamins, Minerals and Phytochemicals: The Hidden Nutrients

The true nutritional magic, however, lies in the micronutrients of vegetables: vitamins, minerals, and secondary metabolites responsible for protecting and healing the human body. Though these compounds are needed in minute quantities, they play outsized roles in maintaining health, immunity and longevity.

3.1. Vitamins: Nature's Catalysts

Vitamins in vegetables serve as cofactors for enzymatic reactions and antioxidants that neutralize free radicals.

Vitamin	Key Sources	Function	Deficiency Effect
Vitamin A (β-carotene)	Carrot, pumpkin, spinach	Vision, cell growth, immunity	Night blindness
Vitamin C (ascorbic acid)	Amaranthus, broccoli, bell pepper	Collagen synthesis, antioxidant	Scurvy, weak immunity
Vitamin K	Kale, spinach, cabbage	Blood clotting, bone metabolism	Bleeding disorders
Vitamin E (tocopherol)	Green leafy vegetables	Protects cell membranes	Oxidative stress
Folate (B_9)	Lettuce, beetroot, amaranth	DNA synthesis, fetal development	Neural tube defects

Source: National Institutes of Health, 2023

Especially important are vitamin C and β-carotene because of their antioxidant action in fighting oxidative stress, which is considered a basic factor that determines aging and the development of chronic diseases.

3.2. Vegetables and its Mineral Content

Minerals have a diverse set of structural and regulatory roles. Vegetables are rich in the mineral's potassium, magnesium, calcium, iron and zinc, all important for physiological homeostasis. High levels of potassium in vegetables such as amaranth and spinach can regulate blood pressure through the balance of sodium within the body. Magnesium supports various enzymatic activities and muscle functions and iron from leafy greens contributes to the synthesis of haemoglobin, highly important for oxygen transportation.

Nutritional value (per 100 g)	Examples of common vegetables					
	Spinach	Tomato	Onion	Cucumber	Lettuce	Broccoli
Energy (kcal)	23	18	40	16	13	34
Carbohydrate (g)	3.6	3.9	9.34	3.63	2.23	6.64
Starch (g)	0.4	2.6	4.24	1.67	1.9	1.7
Dietary fibre (g)	2.2	1.2	1.7	0.5	1.1	2.6
Fat (g)	0.4	0.2	0.1	0.11	0.22	0.37
Protein (g)	2.9	0.9	1.1	0.65	1.35	2.82
Vitamins						
Thiamine (B1) (mg)	0.08	0.042	0.046	0.027	0.057	0.031
Riboflavin (B2) (mg)	0.078	0.449	0.027	0.033	0.062	0.361
Niacin (B3) (mg)	0.724	0.123	0.116	0.098	0.15	0.071
Pantothenic acid (B5) (mg)	0.296	0.037	0.123	0.0259	0.082	0.117
Vitamin B6 (mg)	0.195	0.594	0.12	0.04	0.184	0.639
Folate (B9) (μg)	194	80.0	19	7	73	175
Vitamin C (mg)	28	14	7.4	2.8	3.7	0.063
Vitamin E (mg)	2	0.57	–	–	0.18	89.2
Vitamin K (mg)	0.483	7.9	–	0.0164	0.1023	0.78
Minerals					–	–
Calcium (mg)	99		23	16	35	0.47
Iron (mg)	2.71	–	0.21	0.28	1.24	0.73
Magnesium (mg)	79	11	10	13	13	21
Manganese (mg)	0.897	0.114	0.129	0.079	0.179	0.21
Phosphorous (mg)	49	24	29	24	34	66
Potassium (mg)	558	237	146	174	238	316
Sodium (mg)	7.9		–	2	5	0.58
Zinc	0.53		0.17	0.2	0.27	33
Other elements					–	–
Water (g)	91.4	94.5	89.11	95.23	95.63	89.3

Fig 1: Nutritional Composition of Common Vegetables

3.3. Phytochemicals: The Protective Compounds

Phytochemicals are bioactive compounds produced by plants that give colour, flavour and protection. They include carotenoids, flavonoids, glucosinolates, polyphenols and alkaloids.

Carotenoids such as lycopene, lutein and β-carotene protect cells against oxidative stress, lowering the risk of cardiovascular disease and prostate cancer (Giovannucci, 2002).

Flavonoids-onions, kale, and tomatoes-can help decrease inflammation and improve vascular function.

Glucosinolates, abundant in cruciferous vegetables like cabbage and broccoli, are precursors of isothiocyanates that help detoxify carcinogens.

Polyphenols are associated with the improvement of gut microbiota composition and cognitive function (Manach *et al*., 2004).

Table 2. Major Phytochemical Classes in Vegetables and Their Health Effects

Class	Key Vegetables	Major Compounds	Health Benefit
Carotenoids	Carrot, tomato	β-carotene, lycopene	Antioxidant, cancer prevention
Flavonoids	Onion, kale	Quercetin, kaempferol	Anti-inflammatory
Glucosinolates	Cabbage, broccoli	Sulforaphane	Detoxification, anticancer
Polyphenols	Spinach, lettuce	Resveratrol, catechin	Heart and brain health
Alkaloids	Eggplant	Solanine	Antimicrobial properties

These compounds often act synergistically-meaning the health benefits of whole vegetables are far greater than isolated supplements. Regular intake of phytochemical-rich vegetables reduces the incidence of oxidative DNA damage, atherosclerosis and neurodegenerative diseases (Liu, 2013).

3.4. Antioxidant Mechanisms and Human Immunity

The compounds of vegetables enhance immune competence by antioxidant and anti-inflammatory mechanisms. Their activity involves scavenging ROS, lipid peroxidation inhibition and maintaining cellular integrity. For instance, vitamin C regenerates oxidized vitamin E; polyphenols modulate the gene expression associated with immune cell signalling (Pandey & Rizvi, 2009). This is of particular relevance during infectious disease outbreaks such as COVID-19, where nutrition-based immunity has gained a renewed focus.

4. The Role of Vegetables in Disease Prevention

The connection between vegetable consumption and disease prevention has been one of the most extensively researched topics in nutritional science. A growing body of evidence confirms that individuals who consume ample amounts of vegetables have a significantly lower risk of chronic non-communicable diseases (NCDs) such as cardiovascular disease, diabetes, obesity and certain cancers. This section elaborates on the preventive and therapeutic properties of vegetables in modern health management.

4.1. Cardiovascular Health

CVDs remain the leading cause of mortality globally, accounting for more than 18 million deaths annually (WHO, 2023). Vegetables contribute to cardiovascular health through many mechanisms:

- **Antioxidant compounds** include vitamin C, β-carotene, and polyphenols, which decrease oxidative stress and prevent endothelial damage.
- **Dietary fiber** lowers LDL cholesterol levels and improves HDL concentrations.
- **Potassium-rich vegetables**, such as spinach, amaranth, and beet greens help in regulating blood pressure by counteracting the body's sodium level (Appel *et al*., 2011).

According to the long-term study of Joshipura *et al*. (2001), those subjects who consumed more than five servings daily had a 25% lesser risk of coronary heart disease than the subjects with lower intake. Leafy greens have also been shown to promote nitrate-based vasodilation, which will improve blood circulation and oxygen delivery.

4.2 Diabetes and Regulation of Blood Sugar

Specifically, vegetables are important in maintaining Type-2 diabetes, especially non-starchy ones such as bitter gourd (*Momordica charantia*), okra and leafy greens. Due to their low glycemic index, they prevent sudden increases in the levels of blood glucose. Bioactive compounds such as charantin found in bitter gourd and polysaccharide fractions found in okra increase insulin sensitivity and glucose uptake (Grover & Yadav, 2004).

Indeed, diets heavy with vegetables and whole plant foods are associated with reduced diabetes risk by 35% (Satija *et al*., 2016). In addition, the soluble fiber found in legumes and leafy vegetables delays carbohydrate digestion and results in slowing the rise of postprandial glucose.

4.3. Obesity and Weight Management

Obesity is a complex metabolic disorder driven by excessive intake of calories and sedentary lifestyle. Vegetables help in weight management by:

- Low caloric density and high fiber content that increase satiety.
- Phytochemicals that modulate lipid metabolism.
- Prebiotic fibers involve changes in gut microbiota composition toward improving metabolic efficiency (Turnbaugh *et al*., 2009).

Clinical trials have demonstrated that substituting vegetables for refined carbohydrates and fats significantly decreases body fat percentage, BMI and waist circumference (Ledikwe *et al*., 2006). Daily intakes of vegetables, such as cucumber, cabbage and spinach, inhibit metabolic syndrome.

4.4. Cancer Prevention

Antimutagenic and anticarcinogenic compounds represented by carotenoids, flavonoids, glucosinolates and isothiocyanates are present in vegetables. These compounds exert a protective action on DNA from oxidative damage; they control cell proliferation and induce apoptosis in malignant cells.

Cruciferous vegetables (broccoli, cabbage, cauliflower) are especially known for their role in detoxification of carcinogens through the activation of phase II detoxifying enzymes (Hecht, 2000). Lycopene in tomatoes and β-carotene in carrots are associated with reduced risks of cancers of the prostate, lung and stomach (Giovannucci, 2002).

Table 3. Anticancer Compounds Found in Common Vegetables

Vegetable	Active Compound	Type of Cancer Prevented	Mechanism of Action
Broccoli	Sulforaphane	Breast, colon	Induces detoxifying enzymes
Tomato	Lycopene	Prostate	Antioxidant, inhibits cell growth
Carrot	β-carotene	Lung, skin	Free radical scavenging
Garlic	Allicin	Stomach, colon	Anti-inflammatory, apoptosis
Spinach	Lutein	Eye, skin	Prevents oxidative damage

4.5 Gastrointestinal Health

A high level of fiber in vegetables promotes gut health, thus developing a very healthy microbiota containing Lactobacillus and Bifidobacterium. These microbes enhance nutrient absorption and prevent colon diseases. Polyphenols in leafy greens have prebiotic properties, improving microbial diversity and intestinal barrier integrity (Cardona *et al*., 2013).

4.6. Immunity and Anti-inflammatory Properties

Vegetables are powerful immunomodulators. Phytochemicals, such as quercetin and kaempferol, inhibit inflammatory cytokines, while vitamins A, C and E act directly to potentiate white blood cell function. High vegetable diets during viral outbreaks relate to superior immune outcomes and shortening the recovery period of symptoms associated with (Carr & Maggini, 2017).

5. Vegetables for a Sustainable Planet

Not only are vegetables a healthy addition to the diet, but they are also at the heart of any effort to sustainably build a food system. They represent a confluence of environmental conservation with economic opportunity and social welfare and align with the United Nations SDGs, particularly **SDG 2, Zero Hunger; SDG 3, Good Health and Well-being; and SDG 13, Climate Action.**

5.1. Environmental Sustainability

When vegetable farming is managed well, it exerts a lower environmental impact compared with livestock or cereal-based operations.

Food Type	Carbon Footprint (kg CO_2-eq/kg)	Water Requirement (L/kg)
Beef	27.0	15,400
Poultry	6.9	4,300
Rice	2.7	2,500
Vegetables (avg.)	1.1	300

Source: FAO, 2022

Vegetables also play a vital role in carbon sequestration and soil fertility restoration when integrated into crop rotations. Leguminous vegetables, such as cowpea and French bean, fix atmospheric nitrogen, reducing fertilizer dependency and greenhouse gas emissions.

5.2. Urban Agriculture and Food Security

Urban farming, in all its variations, including hydroponics, aquaponics and rooftop gardens, illustrates how vegetable science is meeting both the challenges of space and those of food supply during all seasons. These systems are optimizing the use of water and land resources: up to 90% less water and 80% less land compared to traditional agriculture. Despommier (2020). For example, vertical farming enables local production in urban environments, reducing the need for transport emissions and providing fresh produce closer to the consumer. This will support resilient urban food systems and food sovereignty within growing cities.

5.3. Socio-economic Benefits of Vegetable Production

Vegetables contribute substantially to livelihood diversification and women's empowerment. Small-scale vegetable enterprises often represent the entry points for women into agricultural markets in so many developing nations. According to the World Vegetable Center in 2021, vegetable farming has the potential to generate 2-3 times as much income per hectare than cereal crops.

The drying, pickling, and freezing of vegetables add to value addition, employment and market linkages, thereby reinforcing rural economies. Equally, the sector supports nutrition-sensitive agriculture that not only ensures communities produce the food but consume it for better health outcomes.

5.4 Climate Resilience and Crop Diversity

Vegetable species show good genetic diversity and adaptability. Crops such as amaranthus, moringa and pumpkin are some which thrive best under heat and drought stresses-these are definitely crops best suited for climate-smart farming systems. Rana and Yadav, 2020 confirm breeding programs focus on the resilience against biotic and abiotic stresses for maintaining regular yield despite erratic weather patterns.

5.5. Postharvest Management and Food Waste Reduction

Poor handling, transportation and storage lead to loss of 30–40% of vegetable produce between harvest and consumption worldwide. Innovations in postharvest management, including MAP technology, low-cost evaporative coolers and solar dryers, are changing this and extending shelf life with minimal losses reported (Kader, 2005).

Table 4. Common postharvest technologies for vegetable preservation

Technology	Function	Example
Cold storage	Extends freshness	Refrigerated warehouse
MAP	Reduces respiration	Polyethylene pouches for leafy greens
Edible coatings	Prevents moisture loss	Aloe vera coating for tomatoes
Solar drying	Reduces microbial growth	Amaranthus leaf powder production

6. Technological Innovations in Vegetable Science

Advancements within vegetable science and technology have transformed the cultivation, management and consumption of vegetables. New varieties developed through biotechnology combine precision farming, protected cultivation and digitization in agriculture to bring improvements in productivity, nutritional quality and sustainability. These technologies will ensure that vegetables can meet the nutritional demands of a growing population while minimizing environmental impact.

6.1. Biotechnology and Genetic Improvement

Plant biotechnology opens new frontiers for vegetable breeding, allowing for the development of high-yielding, pest-resistant and nutrient-enriched varieties.

- Hybrid breeding has resulted in improved varieties with superior vigor, uniformity, and shelf life.
- Marker-Assisted Selection (MAS) speeds up the identification of desirable traits like disease resistance or drought tolerance.
- Transgenic and genome-edited crops enabled by CRISPR-Cas9 have proven to afford precise changes in genes controlling yield, quality and abiotic stress tolerance (Zhang *et al*., 2018).

For instance, biofortified vegetables like **"Golden Tomato"** (rich in β-carotene) and iron-enriched spinach are being developed to combat micronutrient deficiencies. Gene editing also enhances postharvest durability, reducing losses and maintaining market value.

6.2. Precision and Smart Farming

Precision agriculture employs sensor-based, data-driven technologies for optimized field management. Tools include drones, IoT-based sensors and remote imaging, which monitor soil moisture, nutrient levels and pest populations in real time.

- Smart irrigation systems vary water delivery according to soil conditions.
- Similarly, automated fertigation guarantees efficient nutrient use, reducing waste and cost.
- AI and machine learning predict disease outbreaks and recommend timely interventions.

This technological integration ensures resource efficiency and higher productivity, which is an essential component in farming vegetables through sustainable means.

6.3. Protected Cultivation Systems

Protected cultivation, such as through polyhouses, net houses and greenhouses, insulates crops from unfavorable weather conditions and infestations, thus prolonging the growing seasons and assuring quality output. Hydroponic and aeroponic systems housed in these facilities further optimize nutrient delivery regardless of soil conditions.

Technology	Function	Example
Cold storage	Extends freshness	Refrigerated warehouse
MAP	Reduces respiration	Polyethylene pouches for leafy greens
Edible coatings	Prevents moisture loss	Aloe vera coating for tomatoes
Solar drying	Reduces microbial growth	Amaranthus leaf powder production

Source: FAO, 2022

The protected cultivation is specifically advantageous to the high-value crops, such as tomatoes, capsicum and lettuce, yielding up to 2–3 times more compared with open-field cultivation.

6.4. Postharvest and Processing Technologies

The integration of technology does not stop at cultivation but continues into storage, processing, and distribution. Techniques such as controlled atmosphere storage, cold chain logistics and nano-based packaging enhance shelf life and nutritional integrity (Kader, 2005).

The emerging processing technologies, such as freeze-drying, high-pressure processing and microwave-assisted dehydration, preserve maximum nutrients and provide convenient product forms like vegetable powders, snacks and ready-to-cook mixes.

6.5 Digital and Climate-Smart Agriculture

Mobile apps and cloud platforms are increasingly connecting farmers directly with markets and advisory services. For instance, digital tools provide real-time information on weather updates, pest alerts and crop management practices. Such platforms empower smallholders, reduce information gaps and promote climate-resilient decisions (FAO, 2021). Collectively, these vegetable science innovations epitomize an emerging new order of data-driven sustainable and resilient horticulture in tune with nutrition and technology.

7. The Future of Plant-Based Diets

The global transition toward plant-based diets represents a profound shift in both nutritional awareness and environmental consciousness. Vegetables are the core of this transformation-driving dietary patterns toward human and planetary health synchronically.

7.1. Global Trends in Plant-Based Consumption

Across the world, consumers are increasingly embracing vegetarian, vegan, and flexitarian diets. The global plant-based food market was valued at USD 52 billion in 2023 and is projected to exceed USD 160 billion by 2030 (Bloomberg Intelligence, 2023). This surge is propelled by growing evidence linking plant-rich diets with lower chronic disease risks and ecological sustainability.

This is evidenced by significant increases in demand within countries such as India, the UK, and the Netherlands for vegetable-based products, ranging from plant proteins and smoothies to vegetable-based snacks. This is indicative of a redefinition of food culture and shifting priorities toward sustainability.

7.2. Health Implications of Plant-Based Diets

Plant-based diets emphasize the intake of vegetables, legumes, whole grains and nuts while limiting animal-based foods. Research has shown that such diets are associated with:

- Lower cholesterol and blood pressure
- Reduced risk of type-2 diabetes and cancer
- Improved gut health and longevity (Willett *et al*., 2019)

Vegetable-based diets provide adequate protein, fiber, vitamins, and minerals if they are well balanced. However, awareness of nutrient diversity, in particular the sources of vitamin B_{12}, calcium and iron, remains important to avoid deficiencies in strict vegan diets.

7.3. Environmental and Ethical Dimensions

Shifting toward vegetable-based diets considerably minimizes environmental impact. The EAT–Lancet Commission estimated in a 2019 report that the adoption of plant-forward diets may reduce food-related GHGs by up to 50% and liberate substantial land resources. These diets also involve fewer animals, consistent with concerns for animal welfare and biodiversity conservation.

7.4. Functional Foods and Nutraceuticals from Vegetables

Now, vegetables are not only known as foodstuffs but also recognized as active ingredients that have physiological functions besides nutrition. Nutraceutical formulations containing lycopene, lutein, sulforaphane and quercetin provide support for cardiovascular health, vision and immune function (Granato *et al*., 2020).

The development of functional vegetable-based products includes fortified soups, juices, powders and capsules, representing a junction between agriculture, nutrition and pharmaceutical science. Such innovations could revolutionize the global health food sector by offering preventive solutions to nutrition-related disorders.

7.5. Policy and Public Awareness

Government and international agencies are also important facilitators, not only in nutrition education but also through school garden programmes and urban vegetable initiatives. Public health policy can stimulate dietary diversity, as demonstrated by campaigns such as **"Eat 5 a Day" (UK) and "Poshan Abhiyaan" (India).** Public health education highlighting the environmental and health benefits of vegetable consumption creates behavioural shifts in populations.

8. Challenges and Opportunities in the Vegetable Sector

Vegetables are essential for human health and environmental sustainability, yet the global vegetable sector is beset by interconnected challenges. These barriers extend throughout the value chain from production to consumption and involve agronomic, economic, infrastructural and social aspects. But within these challenges are also considerable opportunities for innovation, policy reform and public engagement.

8.1. Production Issues

Vegetable cultivation is highly sensitive to climatic variability, pest infestations and degradation of the soil. Due to climate change, increased frequency of droughts, floods and heat waves seriously impacts productivity and quality. For instance, temperature stress at the time of flowering leads to yield reduction in crops like tomato and capsicum. Besides, the high cost of inputs of quality seeds, fertilizers, and irrigation systems limits their adoption by smallholders. Every year, billions of dollars in damage is caused by pests and diseases such as whiteflies, thrips, and leaf curl viruses (FAO, 2021). Integrated Pest Management (IPM) and biological control offer eco-friendly alternatives but require farmer training and support.

8.2. Postharvest and Supply Chain Limitations

Vegetables are perishable commodities with short shelf lives. In developing nations, 20–40% of vegetables are lost postharvest due to poor storage, packaging and transportation infrastructure (Kader, 2005). Inadequate cold-chain systems, unreliable electricity and long market chains exacerbate these losses. Moreover, market volatility and seasonal gluts often lead to price crashes that discourage farmers. Enhancement in aggregation centres, value chains and cooperative marketing can raise stability and farmer income.

8.3. Consumer Awareness and Accessibility

A big paradox exists: though vegetables have been identified as vital to health, in many regions, consumption is insufficient. Small awareness of nutritional benefits, cultural preferences for meat-based diets, and urban lifestyles dominated by processed foods have decreased vegetable intake. According to the World Health Organization (2020), educational campaigns, media outreach and community programs should help to fill this knowledge gap. Accessibility also poses a problem. The urban poor in general face "vegetable deserts," where fresh produce is not available at affordable prices. Policies support urban agriculture, kitchen gardens, and local farmers' markets to ensure equitable access.

8.4. Opportunities for the Future

In spite of these constraints, the vegetable sector presents tremendous opportunities:

- Technological Advancement
- Value Addition and Export Potential
- Health and nutrition movements
- Sustainable Development Goals
- Policy and Institutional Support

8.5. Research and Education: Building the Next Generation of Vegetable Scientists

To sustain progress, investment in research, extension and education is crucial. Breeding climate-resilient varieties, optimization in nutrient management and eco-friendly post-harvest technologies must be addressed by universities and research institutions. Introduction at school levels may motivate youths toward agri-entrepreneurship to ensure long-term sectoral vitality.

9. Conclusion

Vegetables are much more than colourful meal additions; they represent the lifeblood of a healthier, more sustainable and equitable future. As this article highlights, vegetables provide essential nutrients and phytochemicals that help with the prevention of diseases, acting as the backbone of sustainable food systems that protect our planet's health.

The phrase "Power on Your Plate" articulates it succinctly. Vegetables decrease the global burden of chronic diseases through their vitamins, minerals, antioxidants and fibers. Environmentally, they demand fewer natural resources, emit less carbon and enhance soil health. Economically, they empower millions of small farmers and offer resilient livelihood opportunities, particularly for women and youth.

But most of the potential of vegetables will be realized only through collective action-from policymakers who can ensure equity in access and infrastructure, to scientists who can further develop sustainable cultivation techniques, to consumers who make conscious dietary choices. Promotion of vegetable-based diets in the 21st century is a nutritional necessity, a moral imperative, and an ecological imperative.

A healthier tomorrow starts with what we plant, grow, and eat today. It is only by centering vegetables in human diets and agricultural systems that humankind will truly be able to put power onto every plate, nourishing people and the planet.

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The Hidden Weight of Teenage Stress on Physical Health

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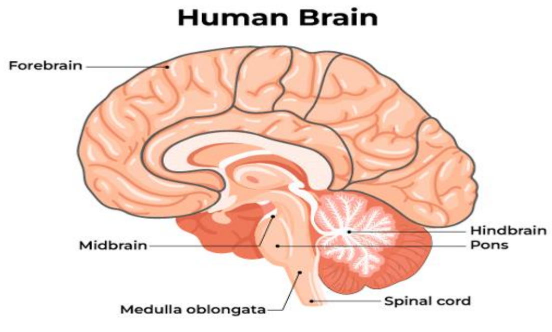
Abstract

Adolescence is a critical period of growth and brain development, yet it is also marked by heightened vulnerability to stress. Persistent stress from academics, peers, family, and social media can affect both mental and physical health, including sleep, immunity, and emotional regulation. Chronic stress elevates cortisol levels, impacting key brain regions such as the hippocampus, amygdala, and prefrontal cortex, which can lead to memory difficulties, emotional instability, and impaired decision-making. Over time, these changes may increase the risk of anxiety, depression, and cognitive challenges. This paper explores the mechanisms through which stress affects adolescent brain development and outlines strategies for promoting mental well-being. Early interventions can help adolescents build resilience, cope effectively with stress, and maintain long-term physical and mental health.

Introduction

The teenage years are often celebrated as a stage of growth and discovery, but for many adolescents, they also bring a hidden weight. Pressures from academics, peers, family, and social media combine with hormonal changes to make stress more than just an emotional challenge. It can leave lasting marks on the body, contributing to high blood pressure, obesity, weakened immunity, and poor sleep. These physical effects not only disrupt normal growth and development but also increase the risk of long-term health issues. Recognizing how deeply stress affects the body is vital for creating supportive environments. With timely care and healthy coping strategies, adolescents can be guided toward resilience and well-being.

How Stress Impacts Brain Development in Adolescence



1. Stress Hormones and the Adolescent Brain:

During adolescence, the brain continues to develop, particularly in areas related to emotion and decision-making. Chronic stress leads to excessive release of cortisol, the body's main stress hormone. While cortisol is useful in small doses, prolonged exposure disrupts the balance of neurotransmitters and alters brain structure. This can impair learning, memory, and emotional regulation

- Prolonged high cortisol levels disrupt the normal pruning and strengthening of synapses, which are crucial for efficient brain networks.

- Adolescents under persistent stress often show altered connectivity between emotional and cognitive brain regions.

2. Hippocampus (Memory and Learning)

The hippocampus, vital for memory formation and learning, is highly sensitive to cortisol. Chronic stress reduces neurogenesis (the growth of new neurons) and can shrink hippocampal volume. This may result in memory problems, difficulties with concentration, and lower academic performance. Neuroimaging studies show that adolescents exposed to chronic stress or trauma often display smaller hippocampal volumes, which are linked to poorer learning outcomes.

3. Amygdala (Emotion Regulation)

The amygdala, which governs emotional responses like fear and anxiety, becomes hyperactive under stress. Excessive cortisol and emotional strain heighten amygdala activity, making adolescents more vulnerable to anxiety disorders, mood swings, and heightened fear responses. This can lead to emotional instability and difficulties in managing stress later in life.

4. Prefrontal Cortex (Decision-Making and Impulse Control)

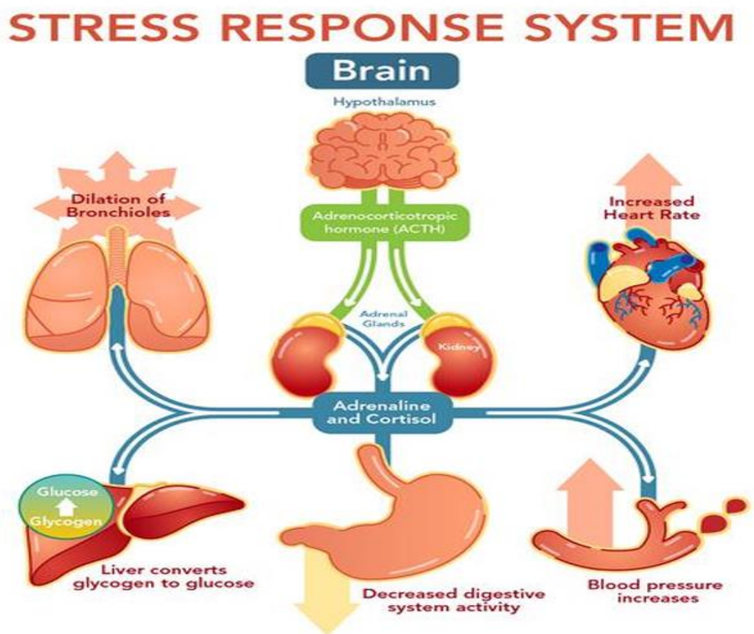
The prefrontal cortex, responsible for planning, judgment, and impulse control, continues to mature into the mid-20s. Chronic stress disrupts the wiring of this region, weakening its ability to regulate emotions and control impulses. This may manifest as risk-taking, poor decision-making, and attention problems, often seen in stressed adolescents. Stress-related dysfunction in this area has been linked to conditions such as ADHD and conduct issues.

5. Neural Connectivity and Cognitive Control

Stress interferes with the integration of different brain regions, particularly the connections between the prefrontal cortex and the amygdala. This imbalance means that emotional reactions (from the amygdala) can overpower rational decision-making (from the prefrontal cortex). Adolescents under chronic stress may therefore struggle with impulse regulation, emotional control, and resilience in the face of challenges.

6. Long-Term Effects on Brain Development

Because adolescence is a critical period of brain plasticity, chronic stress during this stage can "rewire" the brain in ways that persist into adulthood. Long-term consequences include heightened risk for anxiety, depression, cognitive impairments, and vulnerability to substance abuse. These effects underscore the need for supportive environments that help adolescents cope with stress in healthy ways.



Strategies to Support Teenagers Mental Health

Problem-Focused Coping Strategies:

These strategies aim to directly address the stressor by finding a solution.

- Time Management
- Goal Setting and Planning
- Seeking Information and Help

Emotion-Focused Coping Strategies

These techniques help adolescents regulate emotions and reduce stress levels.

- Mindfulness and Meditation
- Journaling and Expressive Writing

Social Support Strategies

Adolescents cope better when they have strong social connections.

- Talking to Trusted People
- Healthy Peer Relationships

Physical Activity and Healthy Lifestyle

Physical well-being directly impacts mental resilience against stress.

- Regular Exercise
- Proper Sleep Hygiene

Professional Help and Therapy

When stress becomes overwhelming, professional support is essential.

- Counseling and Therapy
- Support Groups and Helplines

Conclusion

Stress during adolescence affects both mental and physical health, including brain development, sleep, and emotional well-being. Supportive families, healthy habits, mindfulness, and social connections can help teens cope effectively. Professional guidance, when needed, strengthens resilience and promotes positive mental health. By addressing stress early, we can help adolescents thrive now and in the future.

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Discharge of Nutrient waste from Integrated aquafarms

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Abstract:
Integrated aquaculture production was differentiated as a concept from polyculture which involves farming of terrestrial and aquatic species together in the same area to get double production by the farmers. The aim of this farming is to recycle the animal wastes (faeces, urine and spoiled feeds) and serve it as manures, sometimes as food for fish raised in ponds, enclosures and cages. There are different Integrated farming systems which were practiced by the farmers of India. The nutrient discharge rate determined as the amount of nutrients discharged per unit of aquaculture production. The nutrient discharge into the environment may leads to several impacts such as landscape modification and biodiversity loss**,** Eutrophication etc. Reducing the nutrient input into the ponds and by increasing the efficiency of nutrient retention are important aspects of managing nutrient loads within the harvested animals. To manage this nutrient load we can utilize integrated farming system models.
Keywords: Integrated farming, Nutrient discharge, impacts

Introduction:

Integrated aquaculture production was differentiated as a concept from polyculture which involves farming of terrestrial and aquatic species together in the same area to get double production by the farmers. The aim of this farming is to recycle the animal wastes (faeces, urine and spoiled feeds) and serve it as manures, sometimes as food for fish raised in ponds, enclosures and cages. There are different Integrated farming systems which were practiced by the farmers of India. The amount of organic matter that can be recycled in ponds as manures is up to 5g C.m2d-1 , corresponding to 100 kg of dry manure ha-1 d-1. Fish farm releases carbon (C), nitrogen (N) and phosphorus (P) waste. Dissolved inorganic N (i.e. NH3+) and P (i.e. PO43−) are released through excretion, and inorganic C as CO2 is released through respiration (Wang, X. *et al.,* 2012). Nutrient use efficiency, emphasizes mostly the macronutrients such as nitrogen (N) and phosphorus (P), which is defined as the proportion of all nutrient inputs that are removed in the harvested products, including both crop and animal products. In general, nutrient use is much lower for animal products than comparing with crops. Unused nutrients can be lost through the common mechanisms includes ammonia volatilization, N2O emission, nitrate leaching, and runoff into the soil, water, and atmosphere. Detrimental effects may result from the nutrient-enriched water discharged from farms which affect the aquatic ecosystem health. Managing the waste nutrients discharged from freshwater and marine pond aquaculture is a global challenge (FAO).

Nutrient inputs and outputs in an aquaculture production pond:

Nutrient inputs:

It denotes the amount of substances that has been used for the production of the fishes in ponds. The substances include

- Water used for the system
- Fertilizers used for algal blooms and secondary production within the pond
- Animals stocked initially
- Rainfall and runoff entering the pond
- Erosion of earthen ponds
- Formulated feeds
- Nitrogen fixation by cyanobacteria

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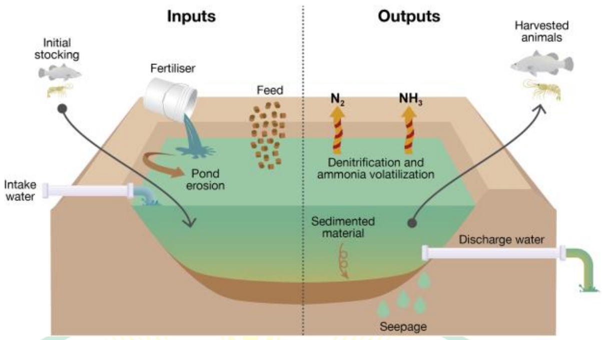
Nutrient Outputs:

It denotes the amount of nutrient substances that has been removed through various activities in the aquaculture production systems in the natural water bodies.

- Soil sediments and sludges of aquaculture pond
- Discharging water from the pond after harvesting of fishes
- Nitrogen can be discharged to atmosphere the process of volatization and sublimation
- Seepage loss



(TABRETT ET AL 2024)

Pond discharge loads:

Nutrients discharged from the pond can be achieved through routine water exchanges or final draining at harvest. Proportion of input nutrient that is discharged will depend on the effectiveness of other outputs, that is, harvested animals, sedimentation, gaseous exchange, in removing nutrients from the water column (TABRETT ET AL 2024)

Discharge	Nitrogen budget	Phosphorus budget
Fish pond	1% to 59%	5% to 72%
Shrimp pond	3% and 57%	2% and 45%

Nutrient use efficiency

Nutrient use efficiency as the percentage difference between nutrients withdrawn from the system by harvesting and contents in the juveniles when they were first introduced into the system as a proportion of the total nutrient inputs (Ying Zhang et al 2015)

Nutrient inputs were defined as follows:

$$I_t = I_f + I_j + I_r + I_p$$

I_t is the total input of N or P,

I_f is the input from and fertilizer

$I_p$is the input from water pumped into the system

I_r is the input from rainfall

Nutrient discharge

The nutrient discharge rate as the amount of nutrients discharged per unit of aquaculture production. It was calculated by multiplying the average nutrient discharge rate by the total aquaculture production for that system, and the total nutrient discharge from aquaculture equaled the sum of the nutrient discharge from each system (Ying Zhang et al 2015):

$$DR = D/H$$

$$D_t = \sum_{i=1}^{i} DR + H_i \times 10^{-6}$$

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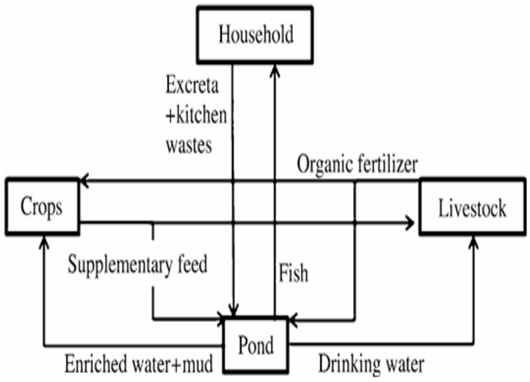
DR is the discharge rate for N(NDR)or P (PDR), in kgt−1
D is the output of N or P in water discharged from the system, in kg
H is the aquaculture production(harvest),
Dt is the total discharge of N or P, in Gg;
I - is the aquaculture group

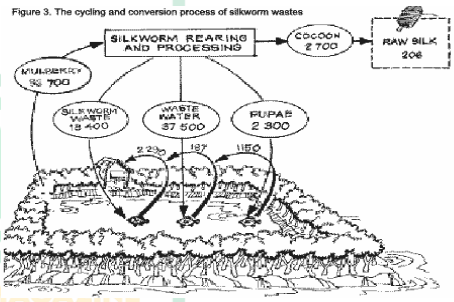
Integrated Agri-Aquaculture Systems:

Agri-aquaculture systems are generally family farming systems, comprised of three major sub-systems: aquaculture, agriculture and house hold, the discharged from the one system can be used as a source for the another system which reduce the nutrient discharge into the environment. Waste utilization cycle ivolves the use of animal manure as pond fertilizer, the use of crop by-products as supplementary feed for fish, the use of pond sediments as terrestrial crop fertilizers, the use of aquaculture wastewater for crop irrigation. On small-holder farms, these inputs are available mainly in the form of wastes from crops or animals. By products of aquaculture such as enriched waste water and sediments can be used as inputs for other agricultural activities.



Integrated Fish cum sericulture farming:

Silkworm frass (excreta and sloughed skins) and pupae are fed to fish or applied to ponds. It has been determined that 36 700 kg/ha of mulberry leaves can be produced which can yield 2700 kg of cocoons. One Chinese mulberry–silkworm–fish model generated ~18,400–18,750 kg/ha of silkworm excreta, which were used directly as fish feed and fertilizer. These waste if directly discharged into the ecosystem can cause severe effects to minimize this integrated farming along with the aquaculture plays a major role in reducing this problem.



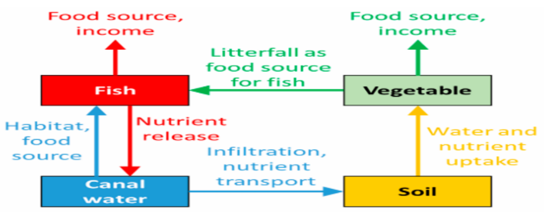
Integrated duck–fish–vegetable system:

In this closed-loop model, duck waste and uneaten feed become natural, nutrient-rich inputs that fertilize the pond ecosystem, promoting the growth of phytoplankton and zooplankton which feed the fish. Duck droppings fertilize the pond, fish absorb nutrients (directly or via plankton), and fish effluent water is used to irrigate vegetables. The pond sediment (enriched with fish waste and decayed feed) is dredged and applied to fields or gardens, boosting soil fertility.

Integrated Fish-Vegetable Farming Systems:

Potential benefits of integrated fish and cucumber production

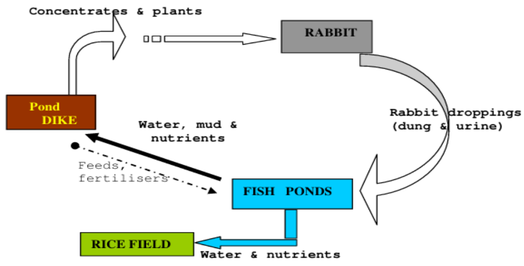
The final body weight of the giant gourami grown for eight months in the canal surrounding the cucumber plots was 459.3g/ fish with a total yield of 0.387kg/m2.



Pathway provides the utilization of nutrients by other integrated systems (Thi Da et al., 2020)

Integrated Rabbit–Fish–Rice System

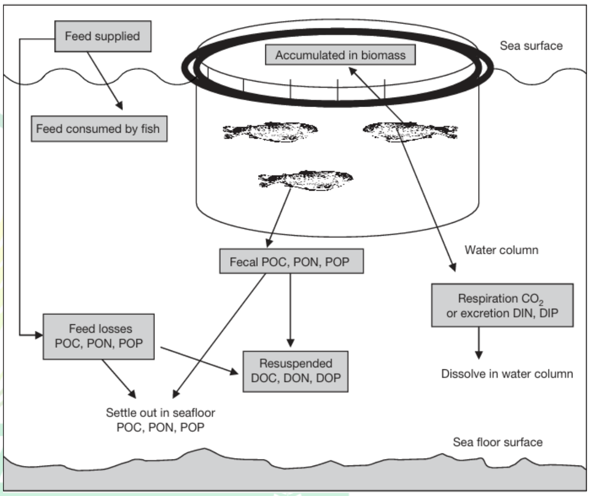
Rabbit droppings accounting for up to 27% N and 79% P of the total N and P in total fish pond inputs. Rabbit droppings allowed for a fertilising rate of 3.98 kg N and 1.94 kg P. ha-1.day-1, capable of causing a net fish yield of 2.0 – 3.3 t.ha-1.yr-1 without any feed supplement. The system improved rice production that was, 5.87 t.ha-1.crop-1 of rice paddy and 9.97 t.ha-1.crop-1 of rice straw (fresh weight) without any other input.



(Tabaro, S. R. et al.,2011)

Discharge of Effluents from salmon farms – cage culture:

In this Salmon cage culture farms the nutrients has been discharged in the following ways: Dissolved inorganic nitrogen and phosphorus (DIN and DIP, respectively) were released in the process of excretion, and inorganic carbon (CO2) through respiration. Particulate organic C, N and P (POC, PON and POP, respectively) are released through defecation and feed loss. Dissolved organic C, N and P (DOC, DON and DOP, respectively) resuspended from faeces and feed particle. 48% of feed C was respired as CO2, 45% of feed N excreted as dissolved inorganic N (DIN), and 18% of feed P excreted as dissolved inorganic P (DIP). The salmon aquaculture industry has taken a number of steps to reduce nutrient release from salmon farming facilities. These efforts include optimizing feed composition and improvements in feed digestibility and feeding technology. These measures reduced nutrient loading and mitigated pressure on the environment. (Wang, X. *et al.,* 2012).



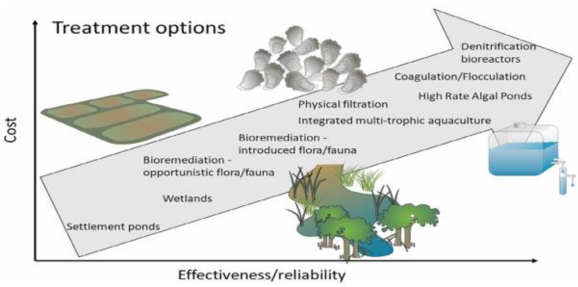
The flow and fate of nutrient components from a salmon cage system

Impacts:

The nutrient discharge into the environment may leads to several impacts such as landscape modification and biodiversity loss**,** Eutrophication**,** Environmental pollution**,** Biological oxygen demand (BOD)**,** oxygen depletion. Integrated farms, if over-fertilized, have seen fish kills.Water-quality impacts include turbidity and microbial proliferation**,** Nitrate in effluents also risks of groundwater contamination or harmful algae if discharged to open waters.

Mitigation Measures and Best Practices:

There are several mitigation measures to reduce the impact of the nutrient discharge. They are Optimal Feeding and Fertilization, Optimized stocking density, Partial harvesting and sludge removal, Water and Effluent Management, Polyculture within Ponds, Sediment Utilization, Anaerobic Digestion and Composting, Nutrient Monitoring and Farm Planning etc…



Treatment options scaled according to relative cost and effectiveness/reliability (TABRETT ET AL 2024)

Conclusion:

Reducing the nutrient input into the ponds and by increasing the efficiency of nutrient retention are important aspects of managing nutrient loads within the harvested animals and reducing the potential impact of aquaculture on the surrounding aquatic environment. Aquaculture operations releases waste in the form of carbon, nitrogen, and phosphorus, Integrated aquaculture systems focus on transforming this waste into a valuable resource for agricultural production, nutrient discharge can be significantly reduced through various integrated models, like fish-poultry, fish-vegetable, rabbit-fish-rice, and Sericulture- fish etc. By recycling wastes into a resource, integrated systems becoming a more sustainable and efficient way to produce food and help to protect our water, land for the future.

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Vertical Farming of Vegetable Crops: Integrating Soilless Cultivation and Biostimulants for Sustainable Urban Agriculture

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Abstract

Facing global pressures from population growth, climate change, and land degradation, agriculture requires transformative solutions. Vertical farming (VF) offers a promising approach by enabling high-density crop production in controlled, indoor environments. This review examines the core technologies powering VF: soilless cultivation systems like hydroponics, aeroponics, and aquaponics. These systems facilitate precise integrated nutrient management (INM), drastically improving resource efficiency and enabling year-round harvests. Furthermore, the use of biostimulants is explored as a key strategy to boost plant growth, stress resilience, and nutritional quality within VF systems. While challenges like high startup costs and energy use remain, ongoing innovation is solidifying VF's role in building sustainable and resilient urban food systems for the future.

Keywords: Controlled Environment Agriculture, Hydroponics, Aeroponics, Aquaponics, Biostimulants, Resource Use Efficiency, Urban Food Security.

Introduction

The global agricultural sector is under unprecedented strain, tasked with feeding a growing population amidst shrinking arable land, water scarcity and the escalating impacts of climate change (Ali *et al.,* 2024). Hence, the prime objective is no longer merely maximizing productivity but optimizing across a "complicated terrain of production, environmental and social justice outcomes." Traditional agriculture's reliance on chemical inputs has led to significant environmental degradation, including greenhouse gas emissions and eutrophication of water bodies. In this context, Controlled Environment Agriculture (CEA) and particularly Vertical Farming (VF), has gained prominence as a transformative approach to food production.

Vertical farming can be defined as the practice of growing crops in vertically stacked layers, often within buildings such as warehouses, skyscrapers, or repurposed urban structures. This system leverages CEA technologies to meticulously control environmental factors such as light, temperature, humidity and carbon dioxide levels. A foundational element of VF is the adoption of soilless cultivation methods, which align with the principle of Integrated Nutrient Management (INM) by allowing for precise delivery and recycling of nutrients (Chaubey *et al.,* 2023). INM aims to "integrate traditional and contemporary nutrient management techniques into an environmentally sound and commercially optimal agricultural system," a goal that VF is uniquely positioned to address.

This review manuscript will explore the scientific and technological foundations of vertical farming for vegetable crop production. It will delve into the primary soilless cultivation systems viz. hydroponics, aeroponics and aquaponics and evaluate their role in efficient resource management. Furthermore, it will discuss the emerging application of bio stimulants to enhance crop performance within VF systems. Finally, the review will address the current challenges and future perspectives, highlighting how VF can contribute to a more sustainable and resilient agricultural future.

The Pillars of Vertical Farming: Soilless Cultivation Systems

At the heart of vertical farming lies the principle of soilless cultivation, which is defined as “any technique for cultivating plants that does not include the use of soil as a rooting medium and uses irrigation water to provide the inorganic nutrients for the roots to absorb”. This approach is critical for VF as it eliminates soil-borne diseases, allows for extreme spatial efficiency and enables unparalleled control over the plant's root zone environment. Success in these systems is "highly dependent on accurate nutrition management", directly embodying the INM approach.

1. Hydroponics

As the predominant soilless system in vertical farming (VF), hydroponics cultivates plants with their roots in a nutrient-rich solution, categorized into solid inert media and water medium cultures (Putra and Yuliando, 2015).

- **Solid Inert Media:** Utilizes supportive substrates like coco coir, perlite and rockwool, which vary in water retention, aeration and pH buffering.
- **Water Medium Culture:** Suspends plant roots directly in nutrient solution using techniques such as:
  - ✓ **Nutrient Film Technique (NFT):** A continuous, shallow nutrient flow ideal for lettuce and microgreens.
  - ✓ **Deep Flow Technique (DFT):** Roots submerged in a deeper, aerated reservoir for increased system buffering.
  - ✓ **Ebb and Flow System:** Periodic flooding and draining of the grow tray to ensure hydration and aeration.
- **Key Benefits:** Hydroponics offers substantial advantages for VF, including "a yield increase, better space and energy utilization," and immunity to soil-borne diseases. Its controlled conditions enable cultivation in non-traditional spaces like "shipping containers," while precise management of pH and electrical conductivity in the nutrient solution minimizes environmental impact.

2. Aeroponics

Aeroponics represents a more advanced soilless technique particularly suited for VF due to its high efficiency. In this system, plant roots are suspended in the air within a closed chamber and are periodically misted with a nutrient solution. This method "combines ecological control, plant physiology and nutrition; it benefits from minimal maintenance requirements, superior growth processes, automatic monitoring, protected cultivation and high yields".

The key advantage of aeroponics is the maximization of oxygen availability to the roots. As highlighted in the source material, roots require oxygen for cellular respiration, which produces the energy (ATP) necessary for "nutrient intake, root growth and other essential processes". Aeroponics provides this optimal oxygen environment, leading to accelerated growth rates and reduced water and nutrient requirements compared to other systems. The "reduced nutrient and water requirements, minimal cost and a decrease in damage and disease are some of the potential advantages of this strategy". Aeroponics has been successfully used for a variety of VF-suited crops, including tomato, lettuce, arugula and leafy herbs.

3. Aquaponics

Aquaponics integrates hydroponic plant production with aquaculture (fish farming) in a symbiotic, recirculating ecosystem. In this closed-loop system, "plants act as a biofilter and recycle water to ponds or containers containing fish, where fish produce ammonia, which is later converted into nitrate and provides necessary nutrients to plants". This integration offers the dual benefit of producing both vegetables and fish protein, enhancing the sustainability profile of a VF operation.

However, a significant challenge in aquaponics is nutrient balance. The system, "which only uses fish feed as a source of nutrients for the plants, is lacking in some nutrients, such as K, Fe and Ca, which are necessary for plant growth". This disparity is compounded by differing pH requirements; plants thrive at a pH of 5–6, while fish prefer 7–9. Therefore, to prevent deficiencies and maximize yield, "nutrient supplementation is necessary via foliar application, into the culture water/fertigation, or through supplementation in the fish diet". Despite these challenges, aquaponics remains a compelling model for resource circularity within VF, with successful cultivation of plants like spinach, basil, lettuce and tomatoes alongside various fish species.

Enhancing Vertical Farming through Biostimulant Application

The controlled environment of a vertical farm, while offering many advantages, can also present abiotic stresses to plants, such as high light intensity, sub-optimal humidity, or nutrient imbalances. The application of biostimulants offers a potent tool to mitigate these stresses and further optimize crop performance. Biostimulants are defined as "substance(s) and/or micro-organisms whose function when applied to plants or the rhizosphere is to stimulate natural processes to enhance/benefit nutrient uptake, nutrient efficiency, tolerance to abiotic stress and crop quality".

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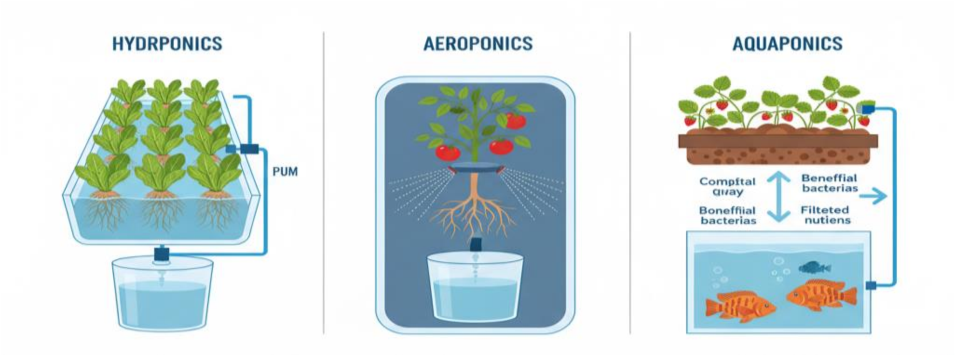

Fig. 1. Soilless Cultivation Systems of Vegetable Crops

a) Categories and Modes of Action

Biostimulants can be categorized as either non-microbial or microbial.

- **Non-microbial biostimulants** include seaweed extracts, humic and fulvic acids, protein hydrolysates and plant extracts (e.g., Moringa leaf extract). These substances often act by enhancing nutrient uptake, improving chlorophyll synthesis and acting as antioxidant agents.
- **Microbial biostimulants** consist of beneficial microorganisms such as plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF) and *Trichoderma* fungi. These microbes form symbiotic relationships with plants, improving nutrient solubilization (particularly phosphorus) and water uptake and inducing systemic resistance to stresses.

The physiological effects of biostimulants are comprehensive. They are "known to improve nutrient availability, nutrient uptake efficiency, productivity, flowering, fruit development and plant growth and tolerance of biotic and abiotic stress" (Wu and Ma, 2015). For example, a seaweed extract (*Ascophyllum nodosum*) has been shown to induce "reduction in stomatal closure, improved water stress tolerance and gas exchange" in broccoli and spinach. Similarly, an amino-acid-based biostimulant (FOLIAR) caused a "95% increased photochemical efficiency (Fv/Fm)" in perennial ryegrass.

b) Applications in the Vertical Farming Workflow

The use of biostimulants can be integrated at multiple stages within a VF operation:

- **Seed Germination and Seedling Establishment:** Biostimulant seed treatments enhance germination, radicle emergence and seedling vigor under optimal and stressful conditions. Coatings with extracts like vermicompost result in plants with "significantly higher" biometric growth and nitrogen uptake.
- **Vegetative Growth and Photosynthesis:** Biostimulants, including Moringa and seaweed extracts, boost the growth and yield of leafy greens by improving photosynthetic efficiency and leaf gas exchange, as indicated by a higher SPAD index.
- **Fruit Set and Quality Enhancement:** For fruiting crops, biostimulants like seaweed extracts and protein hydrolysates improve yield and quality, linked to "improved antioxidant activity, TSSs, anthocyanins and total polyphenols," which is vital for producing nutrient-dense, high-value produce.

By incorporating biostimulants, vertical farms can reduce their reliance on mineral fertilizers, enhance crop resilience to the slight environmental stresses inherent in indoor systems and ultimately improve the nutritional quality and marketability of their produce.

Synergy with Integrated Nutrient Management (INM) and Technological Integration

Vertical farming is a physical manifestation of advanced INM principles. The core objectives of INM include "controlling and maintaining agricultural productivity while simultaneously increasing farmers' profitability through the rational and effective use of its components such as chemical fertilizers, organic manures... and biofertilizers". VF achieves this by creating a closed-loop system where nutrient inputs are meticulously calculated and waste is minimized.

The INM principle of "coordinating the regional and temporal distributions of crop demand and soil nutrient delivery" is directly executed in VF through the real-time monitoring and adjustment of nutrient solutions. This leads to high Nutrient Use Efficiency (NUE), a critical metric for sustainability. Furthermore, the use of biostimulants, particularly microbial ones like PGPR and AMF, aligns with the INM component of utilizing "biofertilizers" to enhance the biological capacity of the cultivation system.

Modern VF is also deeply intertwined with digital agriculture. The technologies such as "sensors, drones and inexpensive satellite imaging for better fertilization and pest control," which, while some are field-oriented, the sensor technology is directly applicable. Machine learning (ML) algorithms can "forecast yields based on genetic information, environmental and land management variables, fertilizer rates and genetic data". In a VF context, this translates to AI-powered systems that adjust nutrient recipes and environmental parameters in real-time based on plant phenotyping data, pushing the boundaries of precision agriculture.

Challenges and Future Perspectives

Despite its significant promise, the widespread adoption of vertical farming faces several hurdles.

- **High Costs:** Substantial initial investment and ongoing operational expenses, primarily for energy-intensive lighting and climate control (Ali *et al.,* 2023).
- **Energy Footprint:** Significant electricity consumption contributes to its carbon footprint, though this can be offset with renewable energy sources.
- **Skill Gap:** A shortage of professionals with expertise in horticulture, engineering and data science hinders adoption.
- **Limited Crop Variety:** Economically viable only for high-value, fast-growing crops like leafy greens and herbs, not for staples or large trees.

The future of vertical farming hinges on overcoming its challenges via targeted innovation. Key priorities include developing more energy-efficient technologies like advanced LED lighting and powering operations with renewable energy to address high electricity demands.

Conclusion

Vertical farming represents a radical and necessary evolution in agricultural production, particularly for vegetable crops. By integrating advanced soilless cultivation system hydroponics, aeroponics and aquaponics within controlled environments, VF achieves unprecedented levels of resource use efficiency and productivity per unit area. The synergistic application of biostimulants further enhances this model by bolstering plant health, stress tolerance and nutritional quality, reducing the need for synthetic inputs. While challenges related to economics and energy use persist, the trajectory of technological advancement is clear. Vertical farming, grounded in the principles of Integrated Nutrient Management and empowered by digital technologies and plant science, is poised to become an indispensable component of a decentralized, resilient and sustainable food system for urbanizing world.

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Circular Economy in Agriculture: From Waste to Wealth

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Abstract:

The circular economy in agriculture aims to transform waste into valuable resources by promoting sustainable, resource-efficient, and economically viable practices. By reusing agricultural residues, recycling nutrients, and generating renewable energy, this model minimizes waste and environmental degradation while enhancing farmers' profitability. The adoption of circular strategies such as composting, biogas production, and nutrient recovery supports soil health, reduces greenhouse gas emissions, and fosters climate resilience. However, implementing a circular economy faces challenges including high initial costs, limited awareness, and inadequate policy support. Overcoming these barriers requires technological innovation, stakeholder collaboration, and enabling regulatory frameworks. Successful case studies demonstrate that transitioning from a linear to a circular model can strengthen sustainability and create a regenerative agricultural system that benefits both the environment and the economy.

Keywords: Circular economy, Agriculture, Waste management, Sustainability, Resource efficiency, Renewable energy, Nutrient recycling

Introduction:

The concept of a circular economy in agriculture focuses on transforming waste into wealth by optimizing resource use, minimizing waste, and creating value from agricultural by-products. This approach not only addresses environmental concerns but also enhances economic viability for farmers. By integrating circular economy principles, agriculture can significantly reduce its environmental footprint while boosting profitability and sustainability. The following sections explore the key aspects of implementing a circular economy in agriculture, including its benefits, challenges, and practical applications.

Benefits of Circular Economy in Agriculture

Economic Gains: Circular strategies can create substantial value from waste, decrease input costs, and enhance farmers' revenues and profits. By utilizing residues from crops and animal products, farmers can produce renewable energy and organic manure, thus reducing dependency on external inputs and increasing profitability (Hasan, 2024) (Ali & Peerzada, 2025). This shift not only promotes sustainable practices but also contributes to ecological improvements and resilience in agricultural systems (Hasan, 2024). Moreover, the adoption of circular economy practices can lead to improved soil health and biodiversity, fostering long-term sustainability in agricultural ecosystems.

Environmental Impact: The circular economy helps in reducing greenhouse gas emissions by promoting sustainable waste management practices such as composting and anaerobic digestion. These practices not only improve soil health but also contribute to the production of bioenergy, thereby reducing reliance on fossil fuels (Bollam, 2025) (Sharma et al., 2024). This multifaceted approach ultimately supports the transition to a more sustainable agricultural system, aligning economic growth with environmental stewardship.

Resource Efficiency: By closing the loop in food systems, the circular economy maximizes the value of resources and minimizes waste. This involves reusing food, recycling nutrients, and using by-products, which helps in conserving natural resources and reducing environmental degradation (Ali & Peerzada, 2025). Implementing these strategies requires collaboration among farmers, policymakers, and businesses to overcome barriers and realize the full potential of a circular agro-economy (Ajayi et al., 2024).

Challenges in Implementing Circular Economy

High Initial Costs: The transition to a circular economy requires significant investment in new technologies and infrastructure, which can be a barrier for many farmers (Hasan, 2024). To address these challenges, it is essential to provide financial support, enhance awareness, and improve infrastructure to facilitate the adoption of circular practices in agriculture (Hasan, 2024).

Low Awareness and Knowledge: There is a general lack of awareness and understanding of circular economy principles among farmers, which hinders widespread adoption (Hasan, 2024). To overcome this barrier, targeted education and training programs should be established to inform farmers about the benefits and practical applications of circular economy practices in agriculture.

Policy and Regulatory Barriers: Inadequate policies and regulations can impede the implementation of circular economy practices. Supportive policies and laws are crucial to promote sustainable waste management techniques and encourage the adoption of circular economy models (Sharma et al., 2024) (Ajayi et al., 2024). To facilitate this transition, it is vital to engage stakeholders across the agricultural sector, ensuring collaborative efforts that foster innovation and sustainable practices.

Practical Applications and Solutions

Technological Innovations: The development of technologies for nutrient reuse, such as nitrogen and phosphorus recovery, is essential for closing nutrient cycle loops in agriculture. These technologies can help in efficiently managing livestock waste and other agricultural residues ("Circular Economy Approaches in the Livestock Waste Area," 2023). Additionally, integrating biogas technology can further enhance waste management by converting livestock manure into renewable energy, thereby supporting sustainable agricultural practices and improving farmers' livelihoods (Pata et al., 2024).

Collaborative Efforts: Successful implementation of circular economy practices requires collaboration among farmers, policymakers, and businesses. This includes sharing knowledge, investing in innovation, and creating exemplary models to demonstrate the benefits of circular agriculture (Bollam, 2025) (Ajayi et al., 2024). Effective collaboration can drive the adoption of circular economy practices, ensuring that all stakeholders benefit from sustainable agricultural systems.

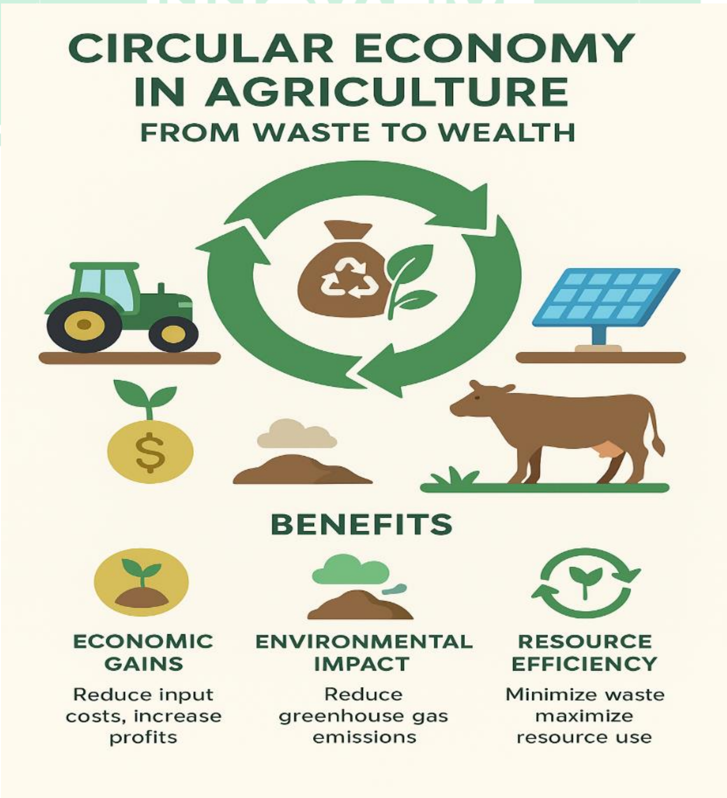

Fig. 1: Circular Economy Concept

Real-World Examples: Initiatives like the World Economic Forum's 'Shaping the Future of Food' highlight the potential of circular economy practices in creating sustainable and efficient food systems. These examples serve as models for other regions to follow (Bollam, 2025). Furthermore, addressing the challenges of low awareness and high initial costs is crucial for fostering a successful transition to circular practices in agriculture (Marku et al., 2024). By fostering collaboration and innovation, the agricultural sector can effectively address the challenges posed by resource scarcity and environmental degradation (Jain & Virk, n.d.).

While the circular economy in agriculture presents numerous benefits, it is important to consider the broader context of its implementation. The transition from a linear to a circular model is complex and requires overcoming significant challenges, including financial, technological, and policy-related barriers. However, with the right support and collaboration, the agricultural sector can successfully adopt circular economy principles, leading to a more sustainable and profitable future.

Conclusion:

Adopting a circular economy in agriculture turns waste into valuable resources, promoting sustainability, resource efficiency, and profitability. Though challenges like high costs and limited awareness exist, collaborative efforts, innovation, and supportive policies can drive the successful transition toward a sustainable and resilient agricultural system.

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The Secret Life Beneath Our Feet: Soil Microbes and the Future of Plant Growth

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Introduction

Beneath our feet lies a hidden, thriving world a teeming universe of microscopic life known as soil microbes. These tiny organisms include bacteria, fungi, archaea, protozoa, algae, and even viruses, all living in a fine balance that makes soil one of the most complex ecosystems on Earth. Though invisible to the naked eye, soil microbes are among the most important life forms for the planet's health and ours.

In response, the recruited microbes offer critical services: Some break down organic materials, releasing essential nutrients like nitrogen, potassium, and phosphorus. Others form protective barriers against harmful pathogens, acting like a biological defence system. Certain fungi, called mycorrhizae, extend far beyond the root zone, effectively increasing a plant's access to water and minerals. What makes this relationship even more impressive is its mutualistic nature both the plant and the microbe benefit. Scientists now recognize that healthy plant growth depends not just on soil nutrients but on the quality and diversity of microbial life in the soil.

In essence, soil microbes act as nature's invisible caretakers, constantly working to support life above ground. Their presence turns dirt into fertile, living soil and their absence can leave land barren and lifeless. Understanding and protecting these organisms is one of the keys to a more sustainable future in agriculture, climate resilience, and global food security.

Agriculture's Forgotten Allies

In modern agriculture, when we think of tools for boosting crop production, we often picture tractors, fertilizers, pesticides, and irrigation systems. Yet beneath our boots lies a powerful force that has been working silently for millennia — soil microbes. These microscopic organisms are often overlooked and underappreciated, but they are some of the most important allies a farmer can have. Soil microbes naturally perform many of the functions that synthetic inputs try to replicate — only they do it more efficiently, more sustainably, and with far fewer side effects.

Why They Matter More Than Ever

Without these microbial services, the entire soil ecosystem would grind to a halt. Plants would struggle to access key nutrients, organic matter would accumulate without decomposing, and water cycles would be disrupted. In short, soil would become a lifeless medium, unable to support farming, forests, or food production.

In today's era of soil degradation, over-farming, and climate stress, preserving and enhancing microbial life is no longer optional — it is essential. These hidden engineers are the silent allies we must protect if we want to grow food sustainably, restore ecosystems, and secure a future for generations to come.

Why We Must Acknowledge Them Now

Despite their incredible contributions, soil microbes are rarely mentioned in policy discussions, extension programs, or even academic curricula. Chemical inputs continue to dominate the narrative, while the living soil remains an afterthought. This oversight comes at a high cost — ecological, economic, and nutritional. By recognizing soil microbes as partners rather than background characters, we open the door to a new kind of agriculture: one that is biologically rich, self-renewing, and less dependent on external inputs. It's a shift in thinking that is not just about sustainability — it's about survival.

Nature's Hidden Engineers

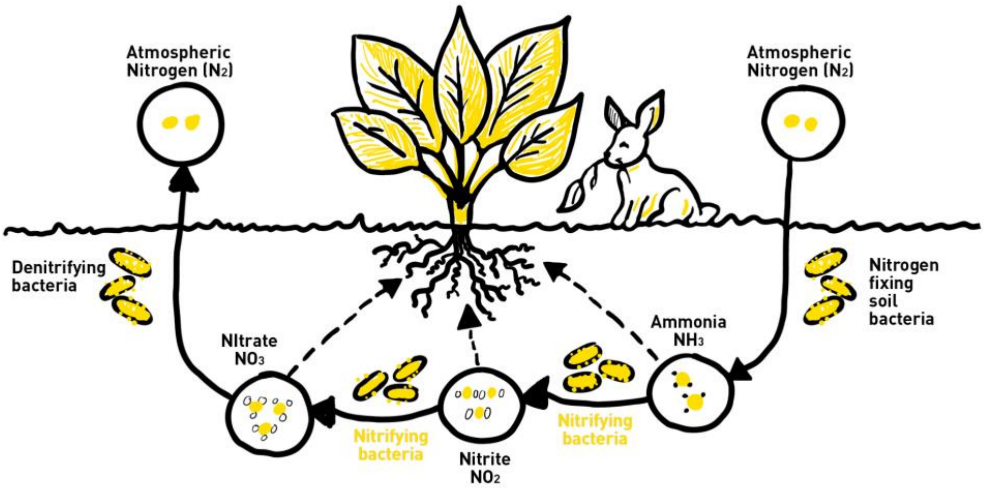
If the soil were a complex biological factory, microbes would be its master engineers — managing its operations, repairing damage, and fueling productivity. These microscopic organisms may be invisible, but they run the show below ground, powering the very processes that make life above ground possible. From fixing nitrogen to recycling dead organic matter, soil microbes form the backbone of natural fertility and ecological balance.

Let's explore how these tiny engineers keep our soil alive and productive:

Nitrogen Fixation: Making Air Useful for Plants

Nitrogen is essential for plant growth — it's a key ingredient in proteins, enzymes, and chlorophyll. Ironically, although nitrogen makes up about 78% of the Earth's atmosphere, most plants cannot use it in its gaseous form (N_2). This is where certain soil microbes come to the rescue. Nitrogen-fixing bacteria, such as Rhizobium, form a symbiotic relationship with leguminous plants like beans, peas, and lentils. They colonize the plant's root system and create small swellings called nodules. Inside these nodules, the bacteria convert atmospheric nitrogen into ammonia, a form that plants can readily absorb and use.

This natural process acts as a biological fertilizer, enriching the soil with nitrogen and reducing the need for chemical inputs. That's why crop rotations involving legumes are so beneficial — they literally leave the soil richer than before, thanks to their microbial partners.



Phosphorus Solubilization: Unlocking Hidden Nutrients

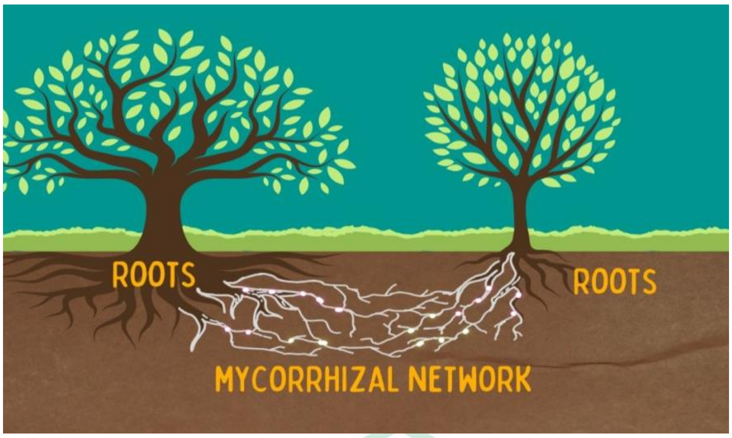
Phosphorus is another critical nutrient for plant development, especially for root growth and flowering. However, much of the phosphorus in soil exists in forms that are chemically bound to minerals, making it unavailable to plants. Certain soil fungi and bacteria, like Aspergillus, Bacillus, and Pseudomonas, have developed the remarkable ability to solubilize phosphorus. They release organic acids and enzymes that dissolve bound phosphate compounds, transforming them into plant-accessible forms.

Without these microbes, large quantities of phosphorus in the soil would remain locked away — useless to crops despite its abundance. Their work ensures that existing soil nutrients are used efficiently, which is crucial for sustainable farming and environmental conservation.

Mycorrhizal Networks: The Underground Internet

Perhaps one of the most fascinating relationships in soil biology is the one between plant roots and mycorrhizal fungi. These fungi attach themselves to plant roots and grow extensive thread-like structures called hyphae, which spread far into the surrounding soil. This network, often referred to as the "wood wide web," acts as an underground communication and nutrient distribution system.

Through this symbiotic partnership, mycorrhizae extend the effective root zone of plants by many times, dramatically improving the plant's ability to absorb water and minerals, particularly phosphorus. But that's not all — these networks can also transfer nutrients and chemical signals between plants, allowing them to share resources or warn each other about threats like insect attacks or diseases. In essence, mycorrhizal fungi amplify the plant's capacity to survive and thrive, especially in nutrient-poor or drought-prone soils.



Decomposition and Soil Formation: Turning Death into Life

Every year, plants shed leaves, roots die off, and crop residues are left behind after harvest. Without microbes, this organic matter would simply pile up, slowly decaying and choking the land. Instead, decomposer microbes — including bacteria, actinomycetes, and fungi — step in to break down dead material into simpler compounds. This process creates humus, the dark, spongy material that gives fertile soil its rich texture and earthy smell. Humus acts like a sponge, holding moisture, buffering pH, and storing nutrients for future plant use. It also sequesters carbon, helping mitigate climate change by trapping it underground instead of releasing it as carbon dioxide. Their work recycles nutrients back into the soil, sustaining the continuous loop of growth, decay, and renewal.

Microbes and Climate Change:

Soil isn't just where plants grow — it's a vital piece of the global climate puzzle. After the oceans, soil is the second-largest carbon sink on the planet, storing more carbon than all the world's vegetation and the atmosphere combined. But soil can only play this role with the help of microbes, the microscopic organisms that manage the fate of carbon and other greenhouse gases below the surface. These tiny creatures act as gatekeepers of the Earth's carbon cycle — deciding whether carbon is released into the air as a gas or safely stored in the ground as organic matter.

Carbon Storage: Locking Carbon Beneath Our Feet

When plants die or shed leaves and roots, that organic material becomes food for microbes. Some of these microbes break it down into stable forms of soil organic carbon, which can remain locked in the soil for decades or even centuries. This long-term storage helps reduce the concentration of carbon dioxide (CO_2) in the atmosphere, slowing the pace of global warming.

However, if soil conditions are poor — degraded, over-tilled, or chemically imbalanced — microbial communities may decompose organic matter too quickly, releasing CO_2 instead of storing it. That's why how we treat our soil determines whether it becomes a carbon sink or a carbon source.

Greenhouse Gas Regulation: Natural Emissions Control

Soil microbes also influence the cycling of other powerful greenhouse gases — namely methane (CH_4) and nitrous oxide (N_2O), both of which have far greater warming potential than CO_2. In rice paddies, for example, anaerobic conditions (low oxygen) encourage methane-producing microbes known as methanogens. But certain bacteria can consume methane before it escapes into the atmosphere, acting as natural filters.

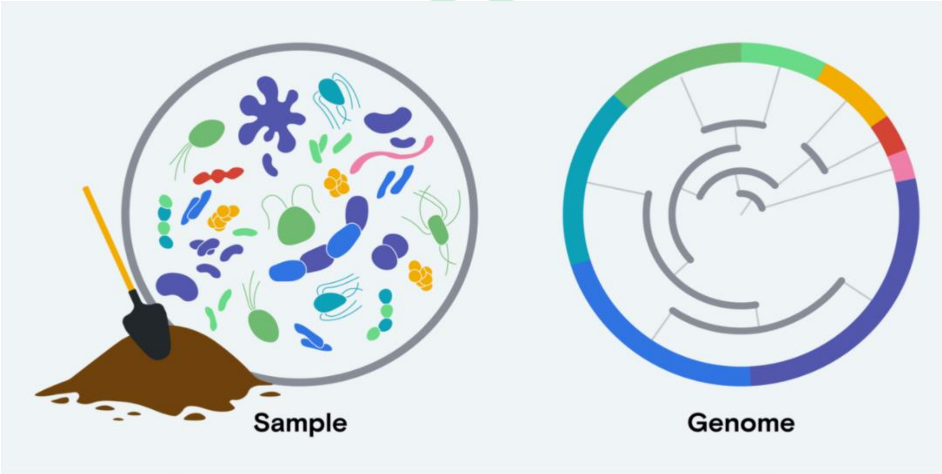
Similarly, microbes in fertilized fields can release nitrous oxide during the nitrogen cycle. But the use of nitrification inhibitors — either synthetic or microbial — can reduce these emissions by slowing down the conversion of nitrogen compounds in the soil. These microbial processes mean that soil management is also climate management.

A New Scientific Frontier: Harnessing the Invisible Intelligence of Soil

We are entering an exciting new chapter in agriculture — one where farmers, scientists, and technology converge to unlock the full potential of the soil microbiome. For centuries, the microbial world beneath our feet remained a mystery, invisible and poorly understood. But today, with breakthroughs in metagenomics, artificial intelligence (AI), and microbiome analytics, we are beginning to see the soil not just as a growing medium — but as a living, dynamic ecosystem ripe for innovation. This new frontier promises to transform how we grow food, manage land, and sustain ecosystems. It brings precision, predictability, and possibility to the ancient relationship between people and the land.

Metagenomics: Reading the Microbial Script of Soil

Metagenomics — the study of genetic material recovered directly from environmental samples — is revolutionizing our understanding of soil microbes. By extracting and sequencing DNA from a handful of soil, scientists can now, identify thousands of microbial species without needing to culture them in the lab, determine the roles and metabolic pathways of microbes — such as nitrogen fixation, phosphorus cycling, or hormone production and monitor changes in microbial communities in response to different crops, fertilizers, or land-use practices.



AI and Microbiome Analytics: Predicting Soil Behaviour

With so much microbial data generated, artificial intelligence is stepping in to help make sense of complex biological interactions. AI-powered models can now analyze patterns in soil microbiomes and predict soil fertility, disease risk, and plant performance based on microbial indicators, suggest customized soil management strategies for individual fields, help breeders select plant varieties that best interact with beneficial microbes. This means that in the near future, farmers might rely on soil microbiome dashboards just as they use weather forecasts or satellite maps — allowing them to make data-driven decisions that enhance productivity and sustainability.

From Lab to Land: Microbial Products in Action

Biotech companies around the world are now racing to bring these innovations to the field. Notable examples include: Bioprime Agrisolutions (India) – developing biostimulants based on endophytic microbes that improve plant stress tolerance, especially under Indian climatic conditions. Pivot Bio (USA) – producing microbial products that replace synthetic nitrogen fertilizers by fixing nitrogen directly at the root zone. Indigo Agriculture – using naturally occurring microbes to boost yields and climate resilience in crops like wheat, cotton, and corn.

These products are not just experimental — they are already being used by thousands of farmers across continents. And as research advances, such solutions are becoming more cost-effective, scalable, and crop-specific.

The Next Evolution in Farming

The idea of cultivating microbial life alongside crops marks a profound shift in how we approach agriculture. Instead of dominating nature, we're learning to work with the invisible ecosystems beneath our feet — harnessing their intelligence to restore balance and boost productivity. In the coming years, soil management may become as much about biology as it is about machinery or chemicals. Farmers will need not just fertilizers and tractors, but microbial allies and genome maps.

One promising approach is regenerative agriculture, which emphasizes practices that build soil health rather than deplete it. Techniques like cover cropping, composting, crop rotation, and reduced tillage help create a favourable environment for beneficial microbes to thrive. These practices restore organic matter, improve soil structure, and foster the biological activity that drives natural nutrient cycles. New tools are also emerging, such as microbial soil testing, which allows farmers to assess the diversity and functionality of soil organisms. With this data, they can make smarter, more targeted decisions — such as choosing specific microbial inoculants or adjusting management practices to support native microbial populations.

Replacing synthetic inputs with biofertilizers and biopesticides is another key strategy. These living products harness beneficial bacteria, fungi, and other microbes to supply nutrients, protect plants from pests and diseases, and stimulate growth — all without the environmental costs of traditional agrochemicals. For this shift to succeed at scale, farmer training and policy support are essential. Subsidies, education campaigns, field demonstrations, and easy access to microbial products can help farmers confidently adopt these new techniques. In India, the movement toward nature-friendly farming is already underway. Zero Budget Natural Farming (ZBNF) promotes low-cost microbial formulations like Jeevamrit — a fermented blend of cow dung, cow urine, jaggery, pulse flour, and soil — to restore microbial life in degraded fields. This approach has shown remarkable results in improving yields, reducing input costs, and regenerating soil health for thousands of smallholders.

By embracing the power of microbes, we can transform agriculture from an extractive system into a living, regenerative cycle — one that nourishes both people and the planet. The way forward lies not beneath steel and sprays, but beneath our feet, in the vibrant, invisible world of soil microbes.

Conclusion: A New Vision Rooted in the Soil

Soil microbes are the invisible architects of life, tirelessly working below ground to sustain the systems we depend on. They unlock essential nutrients, protect plants from disease, build soil structure, and regulate the global carbon cycle. Though microscopic in size, their collective impact is monumental — shaping the health of our crops, our ecosystems, and even our climate.

The answers we seek may not lie in more chemicals, more machines, or more extraction. Instead, they may lie in learning how to work with the ancient intelligence of nature itself — starting with the teeming, unseen world beneath our feet. By embracing microbial science, regenerative practices, and a more holistic view of farming, we can rebuild the fertility of our soils, restore balance to our ecosystems, and cultivate resilience in the face of a changing world.

This century, the real revolution in agriculture may not be found in how high our technologies can reach, but in how deeply we can see into the living soil below and how wisely we choose to nurture the microscopic life that makes all other life possible. The future of farming is not only in our hands it's in our soil.

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Climate-Resilient Crop Breeding: Innovative Strategies for Sustainable Agriculture under Changing Environments

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1. Introduction

The escalating impacts of climate change, characterized by increased frequency and intensity of extreme weather events, altered precipitation regimes, and rising global temperatures, are profoundly affecting agricultural ecosystems worldwide. These changes threaten crop yields, compromise nutritional quality, and exacerbate food insecurity, particularly in vulnerable regions. Traditional agricultural practices, often reliant on stable climatic conditions, are proving inadequate in the face of these rapid and unpredictable shifts. Consequently, there is an urgent need for innovative and proactive strategies to develop crops that can thrive under these new environmental pressures.

Climate-resilient crop breeding emerges as a cornerstone of sustainable agriculture in this changing environment. It involves the systematic development of crop varieties with enhanced tolerance or resistance to climate-induced stresses, thereby ensuring stable yields and improved food security. This article aims to provide a comprehensive overview of the current state and future directions of climate-resilient crop breeding, examining various breeding approaches, technological advancements, and the broader socio-economic and policy contexts that influence its success.

2. The Imperative for Climate-Resilient Crops

The consequences of climate change on agriculture are multifaceted and far-reaching. Rising temperatures lead to heat stress, affecting critical physiological processes such as photosynthesis, flowering, and grain filling. Altered rainfall patterns result in prolonged droughts or excessive floods, both detrimental to crop growth and productivity. Increased incidence of pests and diseases, often exacerbated by warmer temperatures, further compounds these challenges.

Table 2. Impact of Climate Change on Crop Physiology

Climate Factor	Impact on Crop Physiology	Consequence
Elevated CO_2	Enhanced photosynthesis (initially)	Increased biomass, but potential for reduced nutritional quality; C3 crops benefit more than C4.
Increased Temperature	Accelerated phenological development	Reduced time for grain filling, leading to smaller grains and lower yields; heat stress damages pollen, reducing fertility.
Drought	Stomatal closure, reduced water uptake	Decreased photosynthesis, wilting, leaf senescence, reduced growth, and yield; affects nutrient transport.
Flooding	Anaerobiosis, root damage	Oxygen deprivation to roots, accumulation of toxic compounds, stunted growth, chlorosis, and eventual plant death.
Extreme Weather Events	Physical damage to crops	Lodging, defoliation, and direct yield losses from hail, wind, and heavy rainfall.
Pests & Diseases	Altered life cycles, geographical shifts	Increased incidence and severity of pest outbreaks and disease epidemics; emergence of new strains or vectors.
Salinity	Ion toxicity, osmotic stress	Reduced water uptake, impaired nutrient balance, and oxidative stress, leading to stunted growth and yield reduction.

These impacts underscore the urgency of breeding crops that possess intrinsic mechanisms to cope with these stresses. Climate-resilient crops are not merely tolerant to a single stressor but ideally exhibit broad-spectrum resilience, enabling them to thrive under a combination of adverse conditions.

3. Strategies for Climate-Resilient Crop Breeding

Developing climate-resilient crops involves a multi-pronged approach, integrating traditional breeding methods with cutting-edge molecular and biotechnological tools.

3.1. Conventional Breeding

Conventional breeding, based on Mendelian genetics and phenotypic selection, has been instrumental in developing improved crop varieties for centuries. It involves identifying desirable traits in existing germplasm, cross-pollinating selected parents, and selecting superior offspring over generations.

a. **Germplasm Collection and Characterization:** A vast and diverse germplasm collection is the bedrock of any successful breeding program. This includes landraces, wild relatives, and advanced breeding lines, which harbour a wealth of genetic variation for stress tolerance. Characterizing these genetic resources for their response to various abiotic and biotic stresses is crucial.

b. **Phenotyping for Stress Tolerance:** Accurate and efficient phenotyping, the measurement of an organism's observable characteristics, is paramount. This involves evaluating germplasm under controlled stress conditions (e.g., drought chambers, heat tents, saline soils) or in multi-location field trials that represent diverse environmental challenges. High-throughput phenotyping techniques, utilizing sensors, drones, and imaging technologies, are revolutionizing this process, allowing for rapid and precise data collection on large populations.

c. **Selection and Hybridization:** Breeders select individuals exhibiting superior stress tolerance and cross them to combine desirable traits. Repeated cycles of selection and hybridization lead to the accumulation of favourable alleles, ultimately resulting in new, resilient varieties.

3.2. Molecular Breeding

Molecular breeding integrates molecular biology techniques into conventional breeding to enhance efficiency and precision.

a. **Marker-Assisted Selection (MAS):** MAS utilizes DNA markers (e.g., SNPs, SSRs) linked to genes or quantitative trait loci (QTLs) associated with stress tolerance. By genotyping plants at early growth stages, breeders can select individuals carrying desirable alleles without waiting for phenotypic expression, significantly accelerating the breeding cycle.

b. **Genomic Selection (GS):** GS uses genome-wide DNA markers to predict the breeding value of individuals for complex traits, even in the absence of known major genes. It involves training a statistical model using a reference population with both genotypic and phenotypic data, which is then used to predict the performance of unphenotyped individuals. GS is particularly powerful for traits controlled by many small-effect genes, like most stress tolerance traits.

c. **Association Mapping:** This approach leverages linkage disequilibrium (non-random association of alleles at different loci) in diverse germplasm collections to identify marker-trait associations. It can pinpoint novel genes or QTLs underlying stress tolerance, offering new targets for breeding.

3.3. Biotechnological Approaches

Biotechnology offers advanced tools to introduce or modify genes for enhanced stress resilience.

a. **Genetic Engineering (GE):** GE involves the direct transfer of specific genes from one organism to another, or within the same organism, to confer new traits. For climate resilience, GE can introduce genes that enhance drought tolerance (e.g., water-use efficiency genes), salt tolerance (e.g., ion transporters), or heat tolerance (e.g., heat shock proteins). While promising, public acceptance and regulatory hurdles remain significant considerations for GE crops.

b. Genome Editing (CRISPR/Cas9): Genome editing technologies, particularly CRISPR/Cas9, allow for precise, targeted modifications to a plant's genome without introducing foreign DNA in many cases. This enables the creation of new alleles of existing genes, the knock-out of undesirable genes, or the insertion of new genetic material at specific locations. CRISPR offers unprecedented precision and speed, with the potential to rapidly develop crop varieties with enhanced resilience. Examples include editing genes to improve root architecture for better water uptake or modifying stomatal development for reduced water loss.

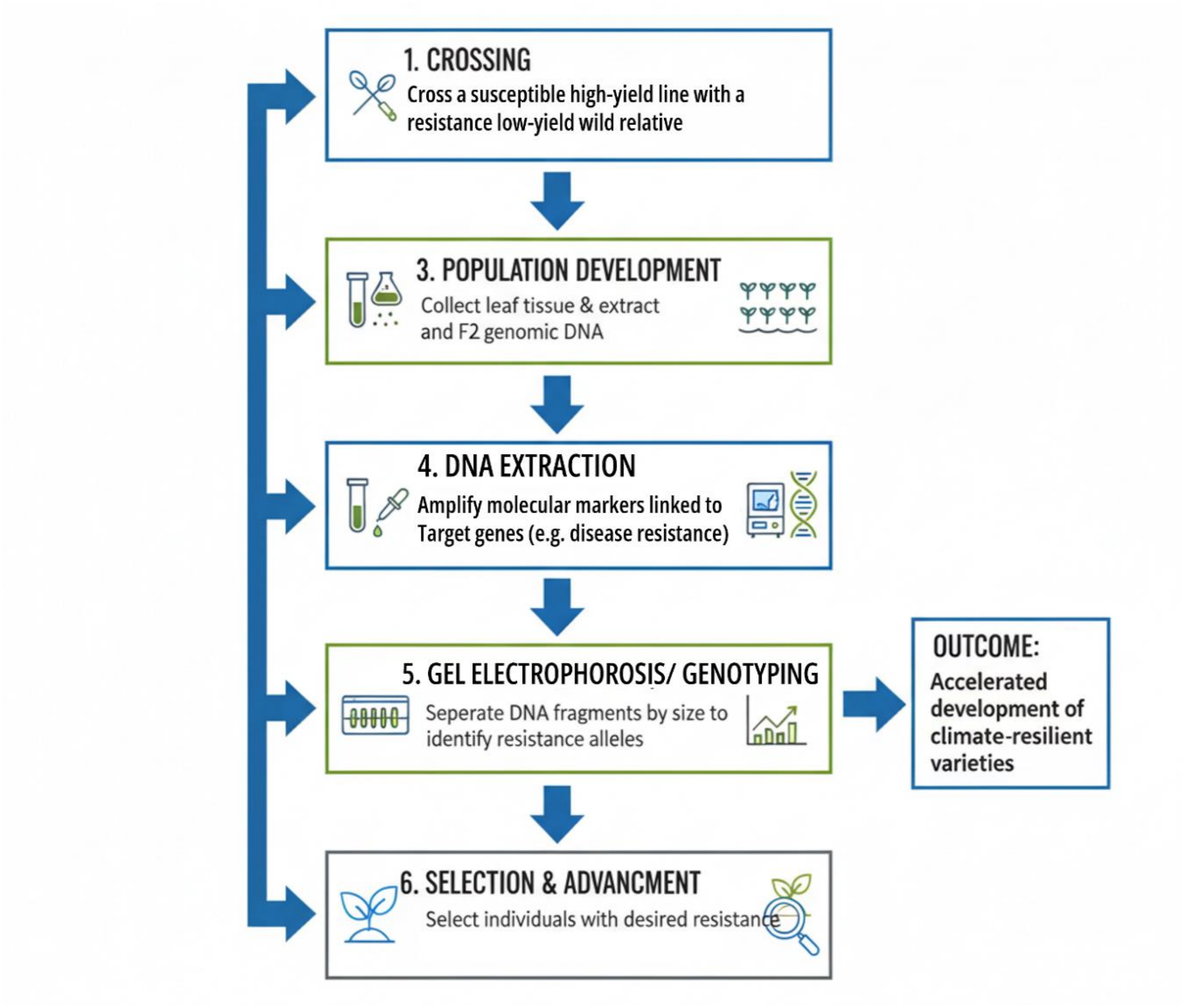

Figure 1. Workflow of Marker-Assisted Selection (MAS)

4. Key Traits for Climate Resilience

Developing climate-resilient crops requires focusing on a suite of interconnected traits that contribute to overall plant performance under stress.

a. Drought Tolerance:

- **Improved Root System Architecture:** Deeper and more extensive root systems enhance water uptake from deeper soil layers.
- **Water Use Efficiency (WUE):** Efficient use of available water, often involving stomatal regulation and reduced transpiration.
- **Osmotic Adjustment:** Accumulation of compatible solutes to maintain turgor pressure under low water potential.
- **Early Vigor and Rapid Growth:** Enables plants to establish quickly and complete critical developmental stages before severe stress sets in.

b. Heat Tolerance:

- **Thermostability of Photosynthetic Apparatus:** Maintenance of photosynthetic efficiency at elevated temperatures.
- **Heat Shock Protein (HSP) Production:** HSPs protect cellular proteins from denaturation under heat stress.
- **Membrane Stability:** Maintaining membrane integrity to prevent cellular damage.
- **Altered Flowering Time:** Adjusting flowering to avoid peak heat periods.

c. Salinity Tolerance:

- **Ion Exclusion/Sequestration:** Preventing the uptake of toxic ions (Na^+, Cl^-) or sequestering them in vacuoles.
- **Osmotic Adjustment:** Similar to drought tolerance, maintaining cell turgor.
- **Antioxidant Systems:** Scavenging reactive oxygen species (ROS) produced under salt stress.

d. Flood Tolerance:

- **Adventitious Root Formation:** Ability to develop new roots that can access oxygen closer to the water surface.
- **Aerenchyma Formation:** Development of air channels in roots and stems to facilitate oxygen transport.
- **Submergence Tolerance:** Ability to survive prolonged periods of complete or partial submergence (e.g., *SUB1A* gene in rice).

e. Nutrient Use Efficiency (NUE):

- **Enhanced Nutrient Uptake:** Efficient scavenging of nutrients from the soil.
- **Internal Nutrient Cycling:** Efficient re-mobilization and utilization of nutrients within the plant, especially under suboptimal soil conditions.
- **Symbiotic Relationships:** Leveraging beneficial microbial associations (e.g., mycorrhizae) for nutrient acquisition.

f. Resistance to Abiotic/Biotic Stresses:

- Developing broad-spectrum resistance to new and emerging pests and diseases whose ranges are expanding due to climate change.

5. Advanced Technologies and Tools

The acceleration of climate-resilient crop breeding is heavily reliant on the integration of advanced technologies.

a. **High-Throughput Phenotyping (HTP):** HTP platforms utilize a combination of sensors (RGB, NIR, thermal, hyperspectral), robotics, drones, and ground-based vehicles to rapidly and non-destructively measure various plant traits (e.g., canopy temperature, plant height, biomass, chlorophyll content) in field or controlled environments. This generates massive datasets that are critical for identifying resilient genotypes.

b. **Genomic Technologies:** Next-generation sequencing (NGS) technologies have dramatically reduced the cost and increased the speed of DNA sequencing, enabling whole-genome sequencing, resequencing of diverse germplasm, and high-density SNP genotyping. This provides an unprecedented level of genomic information for marker discovery, gene identification, and genomic selection.

c. **Bioinformatics and Data Science:** The sheer volume of data generated from genomic and phenomics platforms necessitates sophisticated bioinformatics and data science tools. Machine learning algorithms, artificial intelligence (AI), and advanced statistical models are essential for integrating diverse datasets, identifying complex trait-gene associations, predicting breeding values, and optimizing breeding strategies.

d. **Controlled Environment Agriculture (CEA):** Facilities like growth chambers and greenhouses with precise control over temperature, humidity, light, and CO2 levels enable researchers to simulate future climate scenarios and rapidly screen germplasm for specific stress tolerances without the variability of field conditions.

e. **Modeling and Simulation:** Crop growth models, climate models, and genetic simulation tools are used to predict the impact of climate change on crop production, evaluate the effectiveness of different breeding strategies, and forecast the performance of new varieties under future climate scenarios.

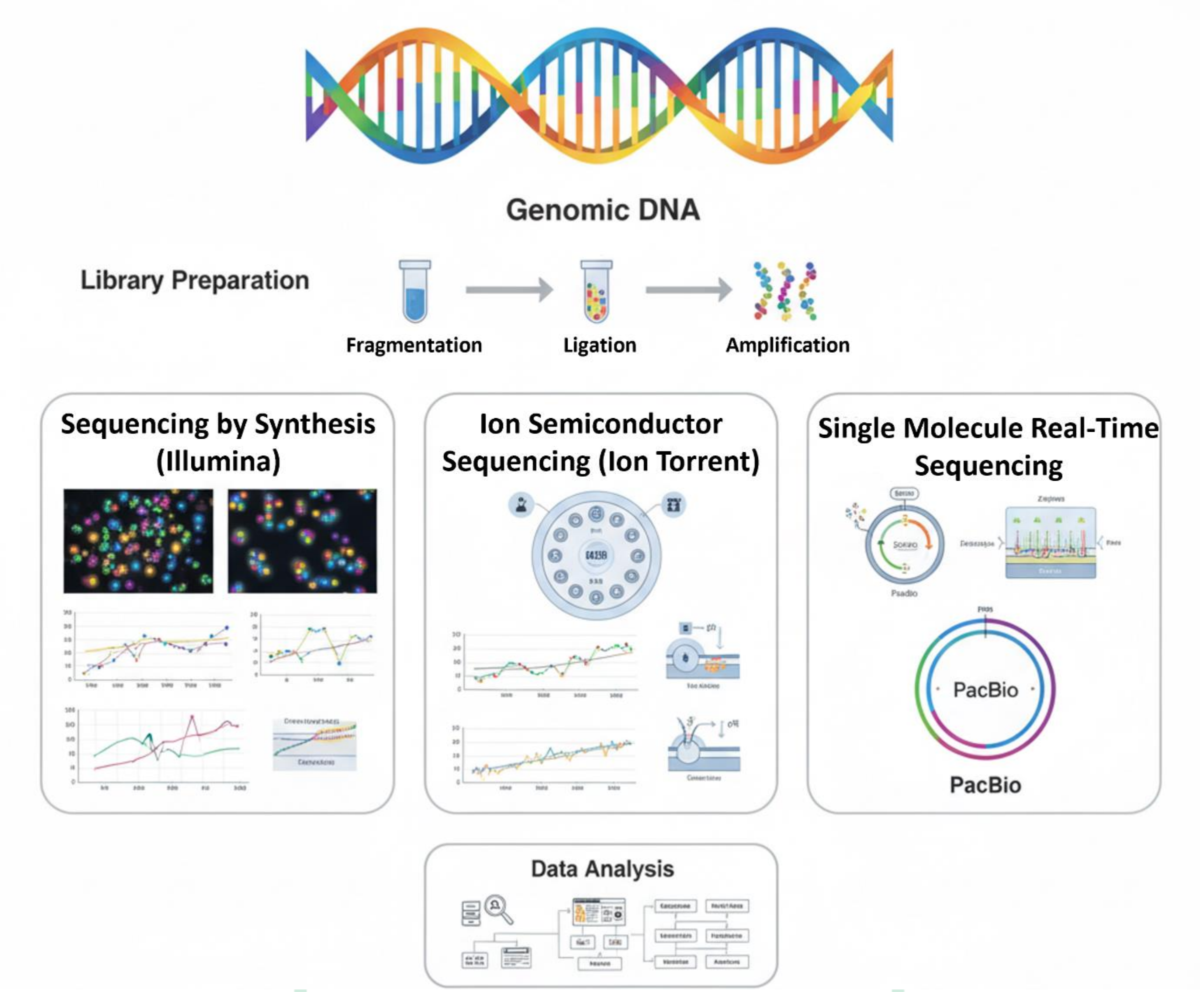

Figure 2. Overview of Next-Generation Sequencing (NGS) Technologies

6. Case Studies and Success Stories

Several crops have seen significant progress in climate-resilient breeding:

- **a. Rice (Oryza sativa):** Development of submergence-tolerant rice varieties carrying the *SUB1A* gene has saved millions of dollars in flood-prone regions of Asia. Additionally, efforts are underway to breed for drought-tolerant and salt-tolerant rice, leveraging genes from wild relatives.
- **b. Maize (Zea mays):** Significant strides have been made in breeding drought-tolerant maize hybrids, particularly in Africa, through both conventional breeding and MAS. These varieties exhibit improved stay-green characteristics and maintain yield under water-limited conditions.
- **c. Wheat (Triticum aestivum):** Breeding programs focus on developing heat-tolerant wheat varieties, especially for South Asia, where terminal heat stress severely impacts yields. This involves selecting for traits like delayed senescence and efficient grain filling under high temperatures.
- **d. Sorghum (Sorghum bicolor):** Naturally a highly drought-tolerant crop, sorghum breeding continues to enhance its resilience to even more extreme drought conditions and heat, making it a crucial crop for arid and semi-arid regions.
- **e. Legumes (e.g., Common Bean, Chickpea):** Efforts are concentrated on developing drought- and heat-tolerant varieties of these vital protein sources, often utilizing wild relatives for genetic diversity.

7. Challenges and Future Perspectives

Despite significant advancements, several challenges remain in climate-resilient crop breeding.

a. **Complexity of Stress Tolerance:** Most stress tolerance traits are quantitative, controlled by multiple genes, and heavily influenced by environmental interactions, making their breeding challenging.
b. **Genetic Erosion:** Loss of genetic diversity in traditional landraces and wild relatives due to habitat destruction and displacement by modern varieties threatens the raw material for future breeding.
c. **Deployment and Adoption:** Even with successful breeding, the widespread adoption of new climate-resilient varieties is hindered by factors such as lack of access to quality seeds, inadequate extension services, and socio-economic barriers for farmers.
d. **Funding and Policy Support:** Sustained investment in research and development, along with supportive agricultural policies, is crucial for accelerating breeding efforts and facilitating technology transfer.
e. **Transgenic Crop Acceptance:** Regulatory hurdles and public perception issues continue to limit the widespread adoption of genetically engineered crops, despite their potential for rapid trait introduction.

Future Perspectives:

a. **Integrated Breeding Systems:** Moving towards holistic breeding systems that combine conventional, molecular, and biotechnological approaches in an integrated manner for maximum efficiency.
b. **Omics Integration:** Deeper integration of genomics, transcriptomics, proteomics, and metabolomics to unravel the complex molecular mechanisms of stress tolerance and identify novel genes and pathways.
c. **Precision Agriculture:** Leveraging precision agriculture technologies (e.g., IoT sensors, variable rate application) in conjunction with climate-resilient varieties to optimize resource use and maximize benefits.
d. **Participatory Breeding:** Engaging farmers in the breeding process to ensure that new varieties meet their specific needs and local environmental conditions, thereby enhancing adoption rates.
e. **Gene Stacking:** Combining multiple stress-tolerance genes into a single variety to confer broad-spectrum resilience.
f. **Digitalization and AI:** Increased use of AI and machine learning for predictive breeding, rapid data analysis, and decision-making in breeding programs.

8. Socio-Economic and Policy Considerations

The success of climate-resilient crop breeding extends beyond scientific and technical advancements; it requires robust socio-economic and policy frameworks.

a. **Capacity Building:** Investing in human capital development, including training scientists, breeders, and extension workers, is essential for implementing advanced breeding strategies and disseminating knowledge to farmers.
b. **Seed Systems:** Strengthening formal and informal seed systems is crucial to ensure that improved varieties reach farmers efficiently and affordably.
c. **Policy Support:** Governments need to implement policies that incentivize research and development in climate-resilient agriculture, facilitate the registration and release of new varieties, and provide support mechanisms for farmers adopting these crops (e.g., subsidies, crop insurance).
d. **Public-Private Partnerships:** Fostering collaboration between public research institutions, private seed companies, and international agricultural research centres (e.g., CGIAR) can accelerate the development and deployment of climate-resilient varieties.
e. **Intellectual Property Rights:** Balancing intellectual property protection with equitable access to genetic resources and new technologies is critical for promoting innovation while ensuring benefits reach smallholder farmers.
f. **Communication and Awareness:** Effectively communicating the benefits of climate-resilient crops to farmers, policymakers, and the public is vital for overcoming resistance to change and promoting widespread adoption.

9. Conclusion

Climate-resilient crop breeding is not merely an option but an urgent necessity for safeguarding global food security in the face of a rapidly changing climate. By integrating conventional breeding with cutting-edge molecular and biotechnological tools, supported by advanced phenotyping, genomics, and data science, breeders can develop crops that are robust, productive, and sustainable under adverse environmental conditions. However, the journey towards a climate-resilient agricultural future demands more than scientific breakthroughs. It requires a concerted global effort, encompassing sustained investment, supportive policies, effective knowledge transfer, and strong collaborations across all stakeholders. By embracing these innovative strategies and fostering a collaborative environment, we can build agricultural systems that are resilient, equitable, and capable of nourishing a growing global population for generations to come.

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Impact of Climate Change on the Epidemiology and Dynamics of Plant Diseases

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1. Introduction

Plant diseases represent a significant and escalating threat to global food security, causing substantial yield losses and economic damage annually, often estimated to be between 10% and 40% of global crop production, depending on the crop and region. The loss of such a vital resource is compounded by a rapidly growing global population, making the effective management of phytosanitary risks paramount. Simultaneously, the global climate is undergoing unprecedented changes, characterized by rising average temperatures, altered precipitation regimes, increased frequency and intensity of extreme weather events, and elevated atmospheric CO_2 concentrations.

These climatic shifts are not only impacting crop physiology and productivity directly but are also profoundly influencing the intricate relationships between plants, pathogens, and their environment, the well-known disease triangle (host, pathogen, and environment). Consequently, the epidemiology and dynamics of plant diseases are being reconfigured, leading to:

- **Emergent disease threats:** Pathogens spreading to new geographical areas.
- **Altered virulence:** Changes in the aggressiveness and lifecycle of existing pathogens.
- **Challenges to conventional disease management strategies:** Reduced efficacy of historical control measures.

Understanding these complex ecological and epidemiological shifts is essential for developing resilient agricultural systems. Furthermore, integrating advanced techniques, such as remote sensing and soil spectroscopy, is becoming increasingly critical for proactive disease management. While these tools are often employed for monitoring soil health parameters (like organic carbon, EC, and pH, which directly influence host vigor), their utility is expanding to include large-scale, non-destructive monitoring of early disease stress and environmental conditions conducive to outbreaks. This article aims to synthesize current knowledge on how the various facets of climate change are affecting the key components of the disease triangle and the overall trajectory of plant disease epidemics, laying the groundwork for adaptive and data-driven management strategies.

2. Components of Climate Change and Their Influence on Plant Diseases

Climate change manifests through several interacting factors, each with distinct and often synergistic effects on plant disease systems.

2.1. Elevated Temperatures

Temperature is a primary environmental factor dictating the growth, development, and reproduction of both plants and pathogens. Rising global temperatures have several direct and indirect implications for plant disease epidemiology:

a. **Accelerated Pathogen Life Cycles:** Many pathogens, particularly fungi, bacteria, and oomycetes, exhibit optimal growth and sporulation within specific temperature ranges. Increased temperatures can shorten the pathogen's latent period (time from infection to sporulation) and incubation period (time from infection to symptom expression), leading to more disease cycles within a growing season and a faster rate of epidemic development.

b. **Geographical Range Expansion:** Warmer temperatures can enable pathogens to survive and establish in regions previously too cold for their proliferation. This facilitates the northward or poleward migration of diseases, exposing new host populations to novel pathogens for which they lack resistance. For instance, diseases typically confined to tropical or subtropical zones may extend their range into temperate regions.

c. **Altered Host Susceptibility:** Temperature extremes can induce stress in plants, compromising their immune systems and making them more susceptible to infection. Conversely, some pathogens may become less virulent at higher temperatures if these exceed their optimal range. The balance between these effects determines the overall impact on host-pathogen interactions.

d. **Vector Dynamics:** Temperature directly influences the reproduction rates, survival, and feeding activity of insect vectors that transmit viral and some bacterial diseases. Warmer conditions can lead to increased vector populations and extended periods of vector activity, thereby enhancing disease spread.

2.2. Altered Precipitation Patterns

Changes in rainfall distribution, intensity, and frequency are critical drivers of plant disease dynamics.

a. **Increased Moisture and Humidity:** More frequent or intense rainfall, coupled with higher temperatures, can create prolonged periods of leaf wetness and high humidity. These conditions are highly conducive to the germination of fungal spores, bacterial multiplication, and the dissemination of many water-borne pathogens. Diseases like late blight of potato (*Phytophthora infestans*) and various downy mildews thrive under such humid environments.

b. **Drought Stress:** Conversely, prolonged drought periods can stress plants, reducing their physiological Vigor and making them more vulnerable to opportunistic pathogens, particularly those causing vascular wilts or root rots. Drought can also influence soil microbial communities, potentially favouring certain soil-borne pathogens.

c. **Spore Dispersal:** Rain splash is a primary mechanism for the dispersal of many fungal and bacterial spores. Changes in rainfall intensity can therefore directly impact the rate and distance of disease spread within a field.

d. **Irrigation Practices:** In response to altered precipitation, increased reliance on irrigation can inadvertently create microclimates favourable for disease development, especially if overhead irrigation systems are used.

2.3. Elevated Atmospheric CO_2 Concentrations

Rising atmospheric CO_2 levels, a direct consequence of anthropogenic activities, affect plant physiology and can indirectly influence disease dynamics.

a. **Host Physiology Alterations:** Elevated CO_2 generally stimulates photosynthesis and biomass production in C3 plants (the majority of crop species). This CO_2 fertilization effect can lead to thicker leaves or altered nutrient composition, which may either increase or decrease host susceptibility depending on the specific host-pathogen system.

b. **Impact on Pathogen Fitness:** Some studies suggest that pathogens might exhibit altered growth or sporulation in plants grown under elevated CO_2, although the effects are highly variable. For instance, some fungal pathogens have been observed to produce more spores on CO_2-enriched hosts.

c. **Altered Plant Defences:** Changes in plant carbon assimilation and secondary metabolite production under elevated CO_2 can modify host defence responses, potentially making plants more or less resistant to certain pathogens.

2.4. Extreme Weather Events

The increased frequency and intensity of extreme weather events, such as heatwaves, cold snaps, severe storms, and floods, represent acute challenges to plant health.

a. **Physical Damage and Wounding:** Hailstorms and strong winds can cause physical damage to plants, creating entry points for pathogens and facilitating rapid infection. Such events can also dislodge and disperse pathogen inoculum over long distances.

b. **Stress-Induced Susceptibility:** Heatwaves and floods can impose severe stress on crops, weakening their defences and making them highly vulnerable to a range of diseases. For example, waterlogging can lead to root anoxia and increased susceptibility to root rot pathogens.

c. **Disruption of Management Practices:** Extreme weather can disrupt farming operations, preventing the timely application of fungicides or other disease management interventions, leading to uncontrolled disease outbreaks.

3. Disease Epidemiology and Dynamics under Climate Change

The interplay of the aforementioned climatic factors significantly reconfigures the epidemiology of plant diseases, influencing disease incidence, severity, and geographical distribution.

3.1. Shifting Disease Incidence and Severity

a. **Increased Epidemic Potential:** For many pathosystems, warmer temperatures and altered moisture regimes create conditions more favourable for pathogen reproduction and dissemination, leading to more severe and frequent epidemics.

b. **Emergence of New Diseases:** As pathogens expand their geographical ranges, they may encounter new host populations lacking adequate resistance, leading to the emergence of novel disease problems in previously unaffected regions.

c. **Changes in Dominant Pathogens:** Climate change can shift the competitive balance among different pathogen species, leading to a change in the dominant disease threats in a particular cropping system. For example, a pathogen previously considered minor might become a major threat.

3.2. Geographical Redistribution of Diseases

One of the most observable impacts of climate change is the alteration of disease distribution.

- **Poleward and Higher-Altitude Migration:** Diseases historically limited to warmer latitudes or lower altitudes are now being observed in cooler regions and at higher elevations as isotherms shift. This phenomenon is particularly evident for vector-borne diseases.

Table 3. Potential Impacts of Climate Change Components on Plant Disease Epidemiology

Climate Change Component	Impact on Pathogen	Impact on Host	Impact on Environment	Epidemiological Outcome
Elevated Temperature	• Faster growth/reproduction • Range expansion • Increased virulence (some)	• Stress-induced susceptibility • Altered defence responses	• Extended growing seasons • Reduced frost barriers	• Increased disease cycles • New disease outbreaks • Shifting disease ranges
Altered Precipitation	• Enhanced dispersal (rain splash) • Favourable humidity for sporulation (wet) • Stress on soil microbes (dry)	• Stress-induced susceptibility (drought/waterlogging) • Altered stomatal function	• Prolonged leaf wetness • Soil moisture extremes	• Increased incidence (wet) • Root diseases (dry/wet) • Disrupted disease forecasting
Elevated CO_2	Varied, some increased fitness	• Increased biomass • Altered nutrient content • Modified defence responses	• No direct environmental impact, but affects plant physiology	• Variable disease outcomes, often with increased severity
Extreme Weather	• Dispersal by wind/hail • Entry points via wounding	• Physical damage • Severe physiological stress	• Direct physical disruption	• Acute disease outbreaks • Rapid spread

3.3. Modified Host-Pathogen Interactions

Climate change can perturb the delicate balance of host-pathogen interactions at the molecular and physiological levels.

a. **Compromised Host Resistance:** Stress from abiotic factors (heat, drought, flooding) can suppress plant immune responses, rendering previously resistant cultivars susceptible.
b. **Pathogen Adaptation:** Pathogens may adapt to new climatic conditions, developing resistance to formerly effective control measures or evolving new virulence factors to overcome host defences. This evolutionary pressure is intensified by accelerated pathogen life cycles.
c. **Mycotoxin Production:** Environmental stress on crops can enhance the production of mycotoxins by fungal pathogens (e.g., aflatoxins by *Aspergillus* species), posing food safety risks.

4. Vectors of Plant Diseases and Climate Change

Insect vectors play a pivotal role in the transmission of many devastating plant viruses, phytoplasmas, and bacteria. Climate change impacts vector dynamics in several ways:

a. **Increased Vector Populations:** Warmer temperatures generally accelerate insect metabolism, leading to faster development, increased reproductive rates, and shorter generation times. This can result in larger vector populations.
b. **Extended Vector Activity:** Milder winters and extended growing seasons allow vectors to survive for longer periods and extend their active transmission seasons, increasing the window for disease spread.
c. **Geographical Expansion of Vectors:** Like pathogens, insect vectors are expanding their geographical ranges into previously unsuitable areas, introducing new vector-borne diseases to naive host populations.
d. **Altered Vector-Pathogen Interactions:** Temperature can influence the acquisition, retention, and inoculation efficiency of pathogens by their vectors, potentially enhancing or diminishing transmission rates.

5. Challenges for Disease Management in a Changing Climate

The dynamic nature of plant diseases under climate change presents significant challenges for conventional disease management strategies.

a. **Efficacy of Host Resistance:** Current disease-resistant cultivars may lose their effectiveness as pathogen populations adapt or as plant stress compromises resistance mechanisms. Breeding for durable resistance under future climate scenarios is paramount.
b. **Predicting Disease Outbreaks:** Traditional disease forecasting models rely on historical climate data and established thresholds. These models need to be recalibrated and refined to account for the altered environmental conditions and pathogen dynamics.
c. **Chemical Control Efficacy:** Altered temperature and humidity can influence the persistence and efficacy of fungicides and bactericides. Increased disease pressure may also lead to greater reliance on chemical inputs, potentially accelerating the development of pathogen resistance.
d. **Quarantine and Biosecurity:** The expansion of pathogen and vector ranges necessitates strengthened quarantine measures and biosecurity protocols to prevent the introduction and establishment of new disease threats.

6. Adaptation and Mitigation Strategies

Addressing the impact of climate change on plant diseases requires a multi-pronged approach encompassing both adaptation and mitigation strategies.

a. **Integrated Disease Management (IDM):** Emphasizing diverse approaches including cultural practices (crop rotation, sanitation, optimal planting dates), biological control, and judicious chemical application. IDM strategies must be flexible and adaptive to changing climatic conditions.
b. **Climate-Resilient Crop Varieties:** Breeding for cultivars with broad-spectrum and durable resistance to multiple diseases, as well as enhanced tolerance to abiotic stresses (heat, drought, flood), is critical. This includes leveraging genetic diversity from wild relatives and implementing advanced genomic breeding techniques.
c. **Enhanced Surveillance and Early Warning Systems:** Robust disease surveillance networks, coupled with real-time climate monitoring and predictive modeling, are essential for early detection of new disease outbreaks and for informing timely interventions.

d. **Conservation Agriculture:** Practices such as no-till farming, cover cropping, and diversified cropping systems can improve soil health, enhance plant resilience to stress, and potentially alter microclimates to be less favourable for certain pathogens.

e. **Agroforestry and Landscape Diversity:** Integrating trees into agricultural landscapes can create more stable ecosystems, support beneficial insects (including natural enemies of vectors), and provide microclimatic buffering.

f. **Policy and International Cooperation:** Coordinated international efforts are needed to monitor disease movement, share genetic resources, and develop harmonized quarantine regulations. Policies that support sustainable agricultural practices and reduce greenhouse gas emissions are also crucial.

7. Conclusion

Climate change is undeniably reshaping the landscape of plant disease epidemiology and dynamics, presenting unprecedented challenges to global agriculture. The complex interactions between rising temperatures, altered precipitation, elevated CO_2, and extreme weather events are accelerating pathogen life cycles, expanding their geographical ranges, modifying host susceptibility, and influencing vector activity. Consequently, farmers and agricultural systems globally face new disease threats, intensified disease pressure, and reduced efficacy of traditional management practices.

Moving forward, a paradigm shift towards proactive, adaptive, and integrated disease management (IDM) strategies is imperative. This requires significant investment in climate-resilient crop breeding, focusing on durable, broad-spectrum resistance that performs well under multiple abiotic stresses (heat, drought, flood). Furthermore, establishing advanced surveillance and forecasting systems, coupled with real-time climate data and robust predictive modeling, is essential for early detection and timely intervention. Beyond the farm gate, systemic changes that promote sustainable agricultural practices and foster international collaboration are crucial for mitigating disease risks on a global scale. Food security in the 21st century will depend not just on optimizing current practices, but on our ability to understand, anticipate, and adapt to these profound, ongoing changes in the ecology of plant diseases.

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Blockchain Applications in Agri-Food Systems: Ensuring Data Integrity and Consumer Confidence

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1. Introduction

The global agri-food system is a multi-trillion-dollar industry characterized by its extensive reach, intricate network of stakeholders, and inherent vulnerabilities. From agricultural production to processing, distribution, and retail, numerous points exist where information can become distorted, lost, or intentionally altered. This lack of transparency contributes to significant challenges, including food fraud, product recalls, unsustainable practices, and inefficient resource allocation. Consumers, increasingly aware of the origins and production methods of their food, demand greater assurance regarding the safety, quality, and ethical sourcing of their food.

Traditional record-keeping and data management systems, often centralized and siloed, are ill-equipped to meet these demands. They typically rely on paper-based records or disparate digital databases, making it difficult to establish a comprehensive and verifiable chain of custody for food products. The emergence of blockchain technology offers a promising solution to these systemic issues. Originally conceived as the underlying technology for cryptocurrencies, blockchain's core attributes, decentralization, immutability, transparency, and cryptographic security are highly relevant to the agri-food sector.

2. Understanding Blockchain Technology

The core principles of blockchain technology are instrumental to its application in the agri-food sector, addressing the inherent limitations of traditional, centralized data systems. A blockchain is essentially a type of Distributed Ledger Technology (DLT) that records transactions across many computers, ensuring data integrity and transparency without relying on a single, centralized authority.

2.1 The Foundational Mechanism: Blocks, Chains, and Hashing

The term blockchain directly describes its structure: a growing list of records, called blocks, which are securely linked together using cryptography.

A. The Block Structure

Each block functions as a digital container for data. In the context of the agri-food supply chain, this data represents transactions, such as a farmer logging a harvest, a processor recording a quality control check, or a distributor noting a temperature reading. A typical block contains three essential elements:

a. **Transaction Data:** The actual records of events (e.g., date, product ID, GPS coordinates, handler signature).
b. **Timestamp:** The precise time the block was created and added to the chain.
c. **Hash of the Previous Block:** A unique cryptographic fingerprint of the block immediately preceding it. This is the mechanism that links the blocks together, forming the chain.

B. Cryptographic Hashing and Immutability

A cryptographic hash is a fixed-length string of characters (e.g., a 256-bit number) generated from the data within a block.

a. **Uniqueness:** Even a minor change in the block's data results in a completely different hash.
b. **Immutability:** Since each new block contains the hash of its predecessor, altering any data in an older block would change that block's hash. This, in turn, would invalidate the hash stored in the *next* block, breaking the entire chain and immediately alerting the network to the attempted tampering. This cryptographic linkage is the fundamental guarantee of data integrity.

2.2 Decentralization and Consensus Mechanisms

Unlike traditional databases managed by a single entity (e.g., a company or government), a blockchain is decentralized, meaning the ledger is distributed and replicated across numerous independent computers, or **nodes**, in the network.

A. Decentralization Benefits

This distribution eliminates the single point of failure inherent in centralized systems. If one node fails or attempts a malicious action, the ledger remains intact and valid across all other nodes. This architecture significantly enhances resilience and security against cyberattacks or data manipulation.

B. Consensus Mechanisms

For a new block of transactions to be accepted and added to the chain, the decentralized network must agree that the block is valid. This agreement is achieved through a consensus mechanism. While the original Bitcoin blockchain uses Proof-of-Work (PoW), many enterprises and private agri-food blockchains use more energy-efficient and scalable mechanisms:

a. **Proof-of-Stake (PoS):** Nodes are selected to validate blocks based on the amount of cryptocurrency (or 'stake') they hold.
b. **Proof-of-Authority (PoA):** Consensus is reached by pre-approved, authorized participants (nodes), often specific, identifiable organizations within the supply chain (e.g., major retailers, food safety regulators). This is common in permissioned blockchains used in the industry, as it balances security and speed, allowing only vetted parties to validate transactions.

2.3 Smart Contracts: Automation and Trustless Execution

Smart contracts are one of the most powerful features of modern blockchain platforms (like Ethereum or Hyperledger Fabric). They are self-executing agreements with the terms of the agreement directly written into lines of code.

A. Automation

A smart contract automatically executes the predefined actions once certain conditions are met and verified by the blockchain. For example, in an agri-food context:

a. **Payment Release:** A contract could automatically release payment to a farmer if and only if the sensor data recorded on the blockchain verifies the shipment arrived at the warehouse within the specified temperature range.
b. **Compliance Triggers:** A contract could flag a product batch for re-inspection or quarantine if the recorded pesticide application data exceeds regulatory limits.

B. Trustless Execution

The execution of a smart contract is transparent, immutable, and fully automated, eliminating the need for a legal intermediary, reducing manual error, and accelerating transactions. This creates a trustless environment where the participants rely on the code, rather than on the goodwill or solvency of a counterparty.

2.4 Permissioned vs. Permissionless Blockchains

For the agri-food sector, permissioned blockchains are typically preferred because they provide the necessary balance of data integrity, high transaction throughput, and regulatory compliance by ensuring all participants are known and accountable.

Table 4. The choice of blockchain type is critical for agri-food applications

Feature	Permissionless (Public) Blockchain	Permissioned (Private/Consortium) Blockchain
Access	Open to anyone to join, read, and write	Restricted to pre-selected, authorized participants
Identity	Anonymous/Pseudonymous	Known (KYC/KYB verified)
Consensus	PoW, PoS (Focus on security against all actors)	PoA (Focus on efficiency and identity-based trust)
Scalability	Lower transaction speed, high energy use	High transaction speed, lower operating cost
Use Case in Agri-Food	Less common, perhaps for consumer-facing transparency	**Predominant:** Used by IBM Food Trust, TracetoGo, where identities must be verified for liability and regulation.

3. Blockchain Applications in Agri-Food Systems

The application of blockchain technology in agri-food systems spans various critical areas, from upstream production to downstream consumption.

3.1 Enhanced Traceability and Supply Chain Visibility

One of the most compelling applications of blockchain in agri-food is its ability to provide unprecedented levels of traceability. In complex global supply chains, tracking a product from its origin to the consumer is notoriously difficult. Blockchain creates a digital, immutable record of every step a product takes, allowing for precise tracking and verification.

Table 5. Comparison of Traditional vs. Blockchain Traceability

Feature	Traditional Traceability Systems	Blockchain-based Traceability Systems
Data Storage	Centralized, fragmented databases, paper records	Decentralized, distributed ledger
Data Integrity	Susceptible to manipulation, errors, and data loss	Immutable, cryptographically secured
Visibility	Limited to direct upstream/downstream partners	End-to-end visibility for authorized participants
Speed of Access	Can be slow, manual reconciliation	Near real-time data access
Trust Mechanism	Relies on trust between individual parties	Cryptographic proof, network consensus
Interoperability	Often poor between different systems	Designed for interoperability (with standards)

Mechanism: Each participant in the supply chain (e.g., farmer, processor, distributor, retailer) can record relevant data points on the blockchain. This might include:

a. **Farm Level:** Planting dates, fertilizer application, pesticide use, harvest dates, geographical origin (GPS coordinates), animal welfare records.
b. **Processing Level:** Processing dates, ingredients used, batch numbers, quality control results.
c. **Logistics Level:** Transportation routes, temperature data, and delivery times.
d. **Retail Level:** Shelf-life information, store location.

Each piece of information is recorded as a transaction, timestamped, and linked to previous blocks, forming an unbroken chain. This allows for rapid identification of the origin of contaminants in case of a food safety incident or verification of sustainability claims.

3.2. Improved Food Safety and Quality Assurance

Food safety is paramount in the agri-food sector. Contamination incidents can have devastating consequences for public health and significant economic repercussions for businesses. Blockchain can significantly enhance food safety protocols by providing a verifiable and transparent record of product attributes and handling practices.

a. **Rapid Recall Management:** In the event of contamination, traditional systems can take weeks to identify the source, leading to widespread recalls and consumer panic. With blockchain, the precise origin of a contaminated product can be identified within minutes, allowing for targeted recalls, minimizing waste, and protecting public health.
b. **Verification of Quality Standards:** Data related to quality checks, certifications (e.g., organic, GMO-free), and compliance with regulatory standards can be recorded on the blockchain. This provides an unalterable audit trail, assuring consumers and regulators of product quality.
c. **Temperature Monitoring:** IoT sensors can automatically record temperature data for perishable goods and write it to the blockchain. If temperature thresholds are violated, smart contracts can trigger alerts or automatically adjust payment terms, ensuring optimal storage conditions throughout the cold chain.

3.3. Sustainable Sourcing and Ethical Practices Verification

Consumers are increasingly concerned about the environmental and social impact of their food choices. Blockchain offers a robust mechanism to verify claims related to sustainable sourcing, fair trade, and ethical labour practices.

a. **Certification Verification:** Certifications such as organic, fair trade, or dolphin-safe often involve complex audits. By digitizing these certifications and linking them to specific product batches on the blockchain, their authenticity can be easily verified.

b. **Carbon Footprint Tracking:** Data on energy consumption, water usage, and greenhouse gas emissions at various stages of production can be recorded on the blockchain, providing a transparent basis for calculating and verifying a product's carbon footprint.

c. **Labor Practice Monitoring:** Information related to fair wages, working conditions, and absence of child labour can be submitted by certified auditors or even directly by workers through secure mechanisms, enhancing accountability in the supply chain.

3.4. Optimized Financial Transactions and Supply Chain Finance

Beyond data integrity, blockchain can revolutionize financial processes within the agri-food supply chain.

a. **Automated Payments with Smart Contracts:** Smart contracts can automate payments to farmers or suppliers upon verified delivery of goods or achievement of quality milestones. This reduces administrative overhead, accelerates payment cycles, and improves cash flow for producers, particularly smallholder farmers who often face delayed payments.

b. **Reduced Intermediaries and Costs:** By streamlining processes and automating agreements, blockchain can reduce the reliance on costly intermediaries in financial transactions, leading to lower transaction fees and improved margins for participants.

c. **Enhanced Access to Finance:** A verifiable and immutable record of a farmer's production history, yield, and quality can serve as robust collateral for obtaining loans or insurance, potentially unlocking new financing opportunities.

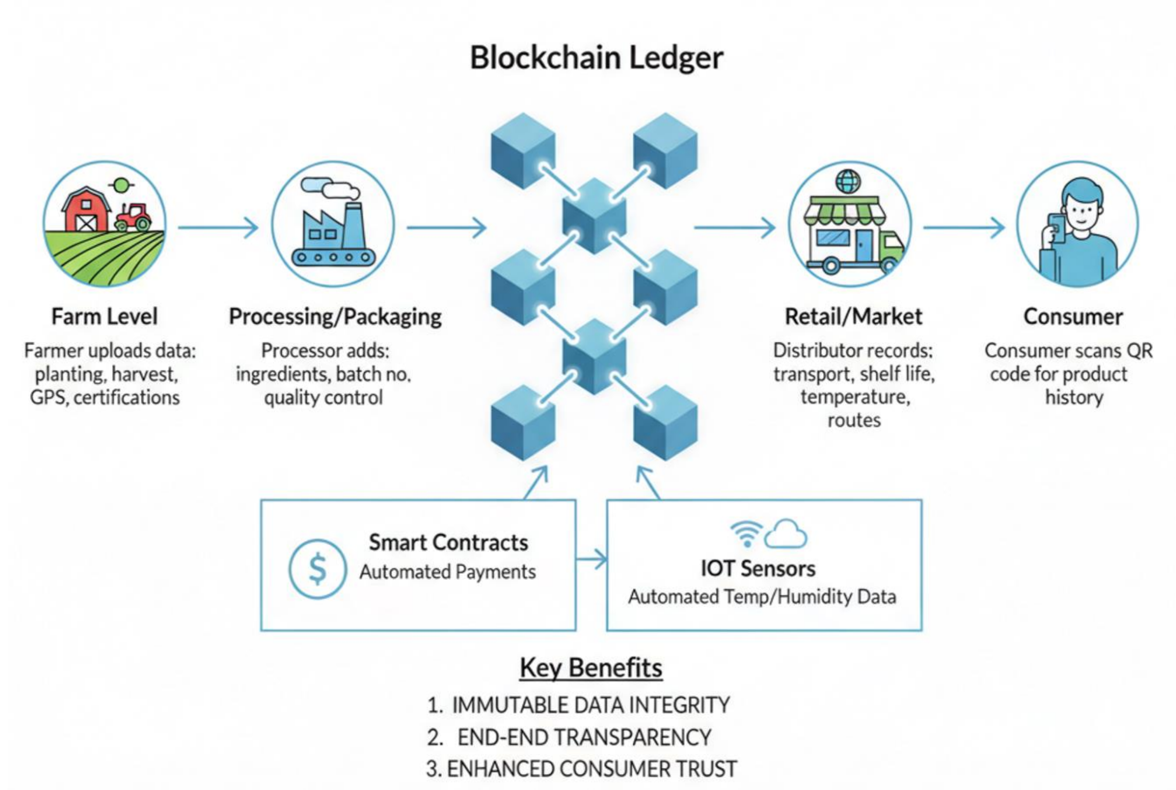

Figure 3. Simplified Blockchain-enabled Agri-Food Supply Chain

4. Benefits for Stakeholders

The adoption of blockchain in agri-food systems offers distinct advantages for various stakeholders:

a. **Farmers/Producers:** Improved access to finance, faster payments, better market access, enhanced reputation for quality and sustainability.

b. **Processors/Manufacturers:** Reduced food fraud, optimized inventory management, streamlined compliance, and faster recall management.

c. **Retailers:** Enhanced brand reputation, increased consumer trust, reduced waste from recalls, and better supply chain management.
d. **Consumers:** Greater transparency about food origin and production, assured food safety, confidence in ethical and sustainable claims, ability to make informed purchasing decisions.
e. **Regulators:** Easier enforcement of food safety standards, better oversight of supply chains, access to reliable data for policy making.

5. Challenges and Considerations for Adoption

Despite its immense potential, the widespread adoption of blockchain in agri-food systems faces several challenges:

a. **Scalability and Interoperability:** Large-scale implementation across diverse agri-food sectors requires robust, scalable blockchain platforms that can handle vast amounts of data and interoperate with existing legacy systems.
b. **Cost of Implementation:** The initial investment in blockchain infrastructure, software development, and training can be substantial, particularly for smaller businesses.
c. **Data Input Integrity (Garbage In, Garbage Out):** Blockchain guarantees the integrity of data *once it's on the chain*, but it doesn't inherently ensure the accuracy of the initial data input. Robust methods for data capture (e.g., IoT sensors, verified human input) are crucial.
d. **Lack of Standardization:** The absence of universally accepted standards for data formats, protocols, and governance models across different blockchain solutions can hinder widespread adoption and create silos.
e. **Regulatory Uncertainty:** The legal and regulatory frameworks surrounding blockchain and smart contracts are still evolving, leading to uncertainty for businesses.
f. **Education and Training:** Stakeholders across the supply chain, especially farmers and small businesses, require education and training to understand and effectively utilize blockchain technology.
g. **Consortium Building:** Successful blockchain implementation often requires collaboration and agreement among multiple, sometimes competing, entities within a supply chain. Building these consortia can be challenging.

6. Case Studies and Pilot Projects

Several pilot projects and initiatives are demonstrating the viability of blockchain in agri-food:

a. **IBM Food Trust:** A prominent example, IBM Food Trust is a blockchain-enabled network designed for global food supply chains. Retailers like Walmart have used it to significantly reduce the time taken to trace the origin of food products, from days to seconds.
b. **Provenance in Seafood:** Projects utilizing blockchain to track seafood from catch to plate, combating illegal fishing and verifying sustainability claims.
c. **Coffee Bean Traceability:** Initiatives allowing consumers to scan QR codes on coffee bags to see the journey of their beans, including farm origin, processing, and fair-trade certifications.
d. **Wine and Spirits Verification:** Blockchain is being used to combat counterfeiting in high-value products like wine and spirits, ensuring authenticity for consumers.

These early successes highlight the practical benefits and pave the way for broader adoption.

7. Conclusion

Blockchain technology presents a paradigm shift for the agri-food sector, offering robust solutions to long-standing challenges of transparency, data integrity, and consumer trust. By providing an immutable, decentralized, and cryptographically secure ledger, it enables end-to-end traceability, enhances food safety, verifies sustainable practices, and optimizes financial transactions across complex supply chains.

While significant challenges remain, particularly concerning scalability, standardization, and initial investment, the benefits of blockchain, from rapid recall management to assured ethical sourcing and increased consumer confidence, are compelling. As the technology matures and collaborative efforts among stakeholders intensify, blockchain is poised to revolutionize the agri-food landscape, fostering a more efficient, transparent, and trustworthy global food system for generations to come. Future research should focus on developing open-source, interoperable blockchain solutions tailored for the agri-food sector, alongside advocating for supportive regulatory frameworks and industry-wide standardization.

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How the Body Moves Electrons from Food to Energy

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This article traces the major steps in the breakdown of sugars and shows how ATP, NADH, and other activated carriers are produced along the way. It concentrates on the breakdown of glucose because it generates most of the energy produced in the majority of animal cells. The chapter explains how cells use many of the molecules generated from the breakdown of sugars and fats as starting points to make other organic molecules. It examines how cells regulate their metabolism and how they store food molecules for their future metabolic needs. After digestion, the small organic molecules derived from food enter the cytosol of a cell, where their gradual oxidative breakdown begins. For most animal and plant cells, glycolysis is only a prelude to the third and final stage of the breakdown of food molecules, in which large amounts of ATP are generated in mitochondria by oxidative phosphorylation, a process that requires the consumption of oxygen.

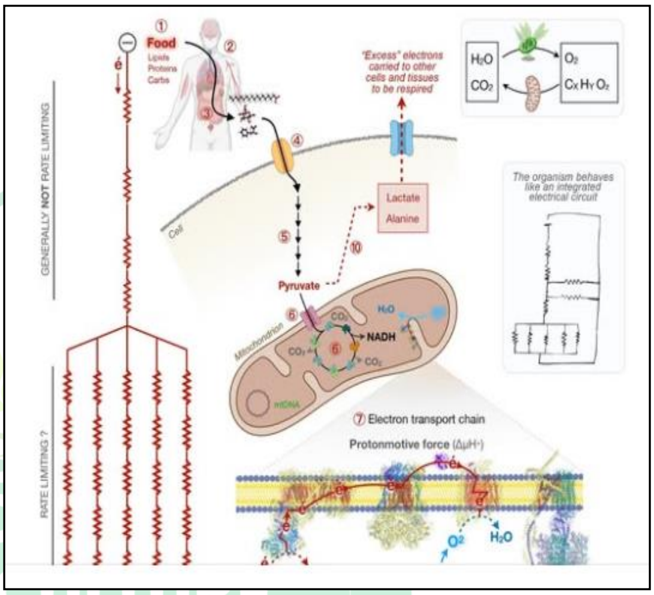

Figure 1. Electron cascade from food to oxygen, encountering sequential source of resistance

This figure explains how the human body acts like an electrical circuit—moving electrons extracted from food all the way to oxygen to generate energy. Every meal you eat feeds an invisible current that powers your cells through a continuous flow of electrons inside the mitochondria.

Food as an electron source

Carbohydrates, fats, and proteins are broken down into molecules like glucose and fatty acids that release electrons during oxidation. These electrons are captured by carrier molecules such as NAD^+ and FAD.

Example: One molecule of glucose donates enough electrons through NADH and $FADH_2$ to drive the production of about 30 ATP molecules.

Electron delivery to mitochondria

Nutrients are converted into acetyl-CoA, which enters the TCA cycle in mitochondria. Each turn of the cycle generates high-energy electron carriers that feed into the electron transport chain.

Example: When oxygen is limited, cells divert pyruvate to lactate to keep glycolysis running and prevent a bottleneck in electron flow.

The electron transport chain

Electrons move through a series of protein complexes embedded in the inner mitochondrial membrane. As they flow, energy is released to pump protons across the membrane, creating an electrochemical gradient.

Example: This “proton motive force” is the voltage that powers ATP synthase, the enzyme that produces ATP from ADP and phosphate.

Oxygen as the final electron acceptor

At the end of the chain, oxygen captures electrons and forms water, completing the circuit. Continuous oxygen flow keeps the system balanced and prevents electron buildup.

Example: When oxygen supply drops, excess electrons can leak, generating reactive oxygen species that damage cells.

ATP as usable energy

The proton gradient drives ATP synthase to generate ATP, the chemical energy currency used for everything from muscle contraction to DNA repair.

Example: Tissues with high energy demand, such as the brain and heart, contain dense mitochondrial networks to maximize electron throughput.

In essence, metabolism is electricity at the molecular level. Food provides the electrons, mitochondria manage their flow, and oxygen completes the circuit—turning chemical energy into the electrical current that sustains life.

The "William Wallace electron food theory" is not a recognized scientific theory in the field of nutrition, biology, or chemistry. The concept appears to be a fringe or pseudoscientific idea promoted by a specific individual named Dr. William Wallace, likely a self-proclaimed expert or "nutritionist," rather than a widely accepted scientific principle.

Here are the key facts regarding the concept:

No Scientific recognition: Scientific literature, university curricula, and established nutritional guidelines do not refer to an "electron food theory" as a valid framework for understanding diet or energy.

Actual energy in Food: In established science, the energy in food comes primarily from the chemical bonds within macronutrients (carbohydrates, fats, and proteins). This stored chemical energy is released through metabolic processes like the Krebs cycle and the electron transport chain to produce ATP, the body's main energy currency. These processes involve the transfer of electrons, but "electron food" is not a scientific term for the food itself.

Likely Pseudoscience: The use of scientific term like "electron" combined with an unconventional, proprietary-sounding "theory" is characteristic of some pseudoscientific health and diet claims designed to sound legitimate to the layperson.

Individual Promoter: The name "Dr. William Wallace" is associated with a podcast and website that discusses the role of micronutrients and plant compounds, but the "electron food theory" itself is likely a personal, non-consensus-based concept rather than a peer-reviewed scientific theory.

In summary, the "electron food theory" is not a credible scientific theory and has no basis in mainstream nutritional science.

When you eat food-especially carbohydrates, fats, and proteins—your body breaks them down into smaller molecules like glucose, fatty acids, and amino acids. These molecules contain high-energy electrons in their chemical bonds. The body's job is to extract those electrons and use their energy to make ATP (adenosine triphosphate), the main energy currency of cells.

1. Glycolysis – The First Step

Location: Cytoplasm

Glucose (a 6-carbon sugar) is broken down into two molecules of pyruvate.

During this process, electrons are transferred to the carrier NAD^+, forming NADH.

A small amount of ATP is made directly.

2. Pyruvate Oxidation & the Citric Acid Cycle (Krebs Cycle)

Location: Mitochondrial matrix

Pyruvate is converted to acetyl-CoA, releasing CO_2 and producing more NADH.

The Citric Acid Cycle (or TCA cycle) further breaks down acetyl-CoA.

Each turn of the cycle produces:

NADH and $FADH_2$ (electron carriers)

A bit more ATP

CO_2 (waste)

At this stage, most energy from food is stored in NADH and $FADH_2$—molecules carrying high-energy electrons.

3. Electron Transport Chain (ETC)

Location: Inner mitochondrial membrane

NADH and $FADH_2$ donate their electrons to the electron transport chain, a series of protein complexes (I–IV).

As electrons flow through these complexes, they release energy that pumps *protons (H^+)* across the membrane, creating an *electrochemical gradient.

4. ATP Synthase & Oxidative Phosphorylation

The proton gradient drives *ATP synthase*, a molecular turbine.

As protons flow back through ATP synthase, *ADP + P_i → ATP*.

Oxygen acts as the final electron acceptor, combining with electrons and protons to form water (H_2O).

The proteins, lipids, and polysaccharides that make up most of the food we eat must be broken down into smaller molecules before our cells can use them-either as a source of energy or as building blocks for other molecules. The breakdown processes must act on food taken in from outside, but not on the macromolecules inside our own cells. Stage 1 in the enzymatic breakdown of food molecules is therefore *digestion*, which occurs either in our intestine outside cells, or in a specialized organelle within cells, the lysosome. (A membrane that surrounds the lysosome keeps its digestive enzymes separated from the cytosol, as described in Chapter 13.) In either case, the large polymeric molecules in food are broken down during digestion into their monomer subunits—proteins into amino acids, polysaccharides into sugars, and fats into fatty acids and glycerol—through the action of enzymes. After digestion, the small organic molecules derived from food enter the cytosol of the cell, where their gradual oxidation begins. As illustrated in Figure 2, oxidation occurs in two further stages of cellular catabolism: stage 2 starts in the cytosol and ends in the major energy-converting organelle, the mitochondrion; stage 3 is entirely confined to the mitochondrion.

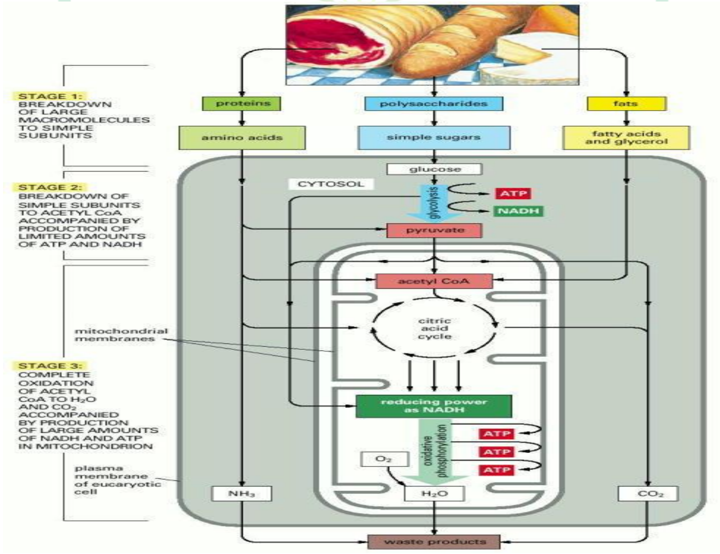

Figure 2. Simplified diagram of the three stages of cellular metabolism that lead from food to waste products in animal cells

In Summary:

Food → Electrons → NADH/$FADH_2$ → Electron Transport Chain → Proton Gradient → ATP.

This entire process efficiently converts the chemical energy in food into the usable energy molecule ATP, which powers everything your cells do—from muscle contraction to nerve signaling.

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ROLE OF NUTRACEUTICAL AND ITS APPLICATIONS IN POULTRY

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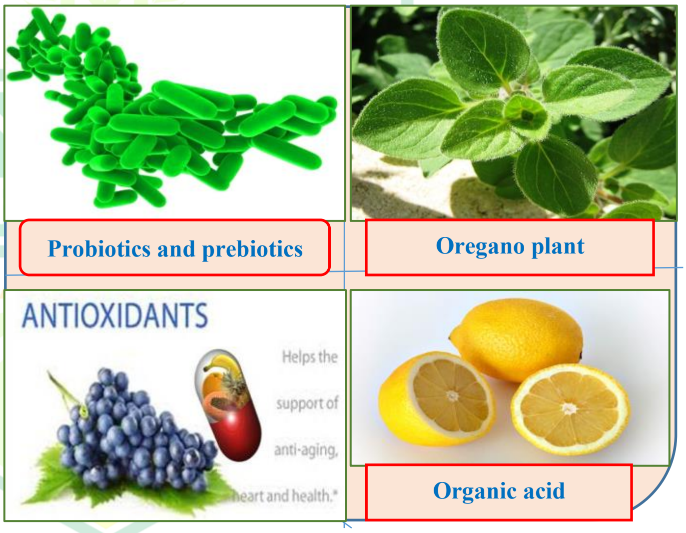
Introduction

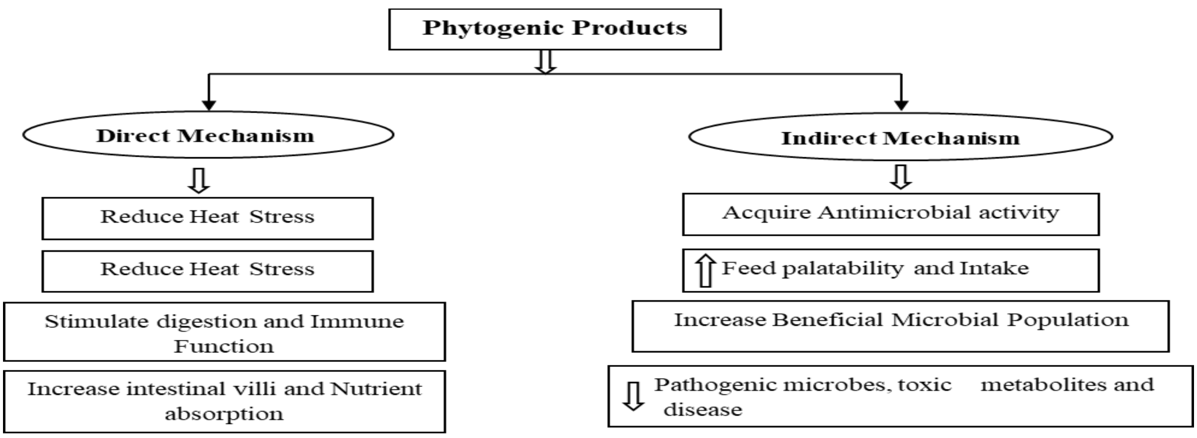
In poultry usage of antibiotics is major health issues to the peoples, so have to develop the alternative to antibiotics used in poultry production, for this there are number of food or food components that provide the beneficial effect on growth and animal health. Food or food components that have the role in modifying and maintaining the normal physiological function and animal health and protecting against infectious diseases, this food based components is called as nutraceuticals. (Das *et al*..2012). Nutraceuticals in poultry nutrition is substances like plant extracts, vitamins, minerals, and probiotics that are added to feed to improve bird health and performance, replacing the need for antibiotic growth promoters. These additives provide antioxidant, anti-inflammatory, anti -microbial activity and Immuno modulatory property (Mehdi *et al*.,2018), Which helps better growth, egg production, and meat quality while supporting gut health and the immune system.

List of nutraceutical components

Source	Components
Isolated nutrients	❖ Vitamin ❖ Mineral ❖ Amino acids ❖ Fatty acids
Herbal products	❖ Polyphenols ❖ Herbes ❖ Spices
Dietary supplements	❖ Probiotcs ❖ Prebiotics ❖ Synbiotics ❖ Organic acids ❖ Antioxidants ❖ Enzymes



Phytogenics have direct and indirect benefits on the chicken's health



Nutraceutical functions

- In human it is used for alternative therapies for cancer, diabetes, osteoporosis and depression.
- In chicken modulating the gut microbial population and immune system of the host.
- Enteric infection prevention or treatment it can be used.
- Intestinal morphology improvement and enhancing growth.
- To promote the growth performance of birds.

Probiotics

It is live bacteria or yeast that beneficially affect the gut microorganism, it can improve the growth performance of the birds and it is have different immunomodulatory effect due to ability of probiotic to induce cytokine production, which leads to modulation of innate and adaptive immune responses (Brisbin *et al* 2010).Probiotic containing *L.acidophilus*, *B,bifidum,* which lowered number of *Coliforms* and *Caphylobacto*r in the gut and increased production of antibodies at systemic and local levels, also induced T-helper-1-cytokinines,anti-inflammatory responses and transforming growth factor in caecal tonsil cells. In chicken enhanced intestinal mucosal immunity and increased spleen and bursa weight.

Prebiotics

Prebiotics are non-digestible feed ingredients that beneficially affect the host by selectively altering the composition and metabolism of the gut microbiota. Prebiotics may provide energy for the growth of endogenous favourable bacteria in the gut such as *bifidobacteria* and *lactobacilli*, thus improving the host microbial balance. Prebiotics enhanced the host defence and reduced the birds mortality, the mechanism of addition of prebiotic enhance the lactic acid bacteria production in gut may aid competitive exclusion of pathogens and short chain fatty acids which can increased the intestinal acidity acidity may contribute the suppression of pathogens in the gut of chicken. Some of the commonly used prebiotics are fructo- oligosaccharide (FOS),mananoligosaccharide(MOS), galactooligosaccharides (GOS), soya-oligosaccharides(SOS), xylo-oligosaccharides(XOS), pyrodextrins, isomaltooligosaccharides (IMO) and lactulose (Alloui *et al*., 2013).

Functions :

- Reduced the intestinal clonozation by salmonella and decreased population of *Cl.perfriengens* and *E .Coli* in gut.
- Provide the nutrients for growth of beneficial bacteria in the gut.
- Increased the population of *bifidobacterium* and *lactobacilli.*
- Increase the serum concentration of IgA, IgG, IgM and enhanced systemic immune capacity in chicken.
- Increased spleen weight.

Synbiotics

Combination of probiotics and prebiotics are commonly referred as synbiotics. This combination could improve the survival and persistence of the health-promoting organism in the gut of birds because its specific substrate is available for fermentation. Using synbiotic can help the improvement of intestinal morphology and nutrient absorption; it seems to contribute to enhance the birds growth performance.

Function

- Increased lactic the acid bacteria and reduced *E.coli* and total coliform count in intestine.
- Increased antibody production and stimulated the expression interleukin-6 and IF N-γ.
- Improved the antibody response to NDV and infectious bronchitis virus (IBV) vaccine.

Phytobiotic

Phytobiotics are plant-derived natural bioactive compounds represent a wide range of bioactive compounds that can be extracted from various plant sources, such as herbs and spices,it can be added to the feed to improve the performance and well-being of birds. The essential oils helps to improve flavour and palatability of feed and may thus improve the feed intake and performance of the chickens. Bioactive compounds to stimulate the proliferation and growth of absorptive cells in the gastrointestinal tract (greater villus height and deeper crypt) and to influence the production and/or activity of the digestive enzymes, e.g., increasing the activities of amylase and protease .There are several kinds of phytobiotics used such as Oregano, Acacia extract, Essential oils, Garlic, Neem, Black cumin, Polysaccharide extracts from mushrooms and turmeric *etc*. Phytobiotics have antimicrobial activity and immune system enhancement through the mechanism was explained as follows.

Mechanism:

- Modulating the cellular membrane of microbes leading to membrane disruption of the pathogens.
- Increasing the hydrophobicity of the microbial species which may influence the surface characteristics of microbial cells and thereby affect the virulence properties of the microbes.
- Stimulating the growth of favourable bacteria such as *lactobacilli* and *bifidobacteria* in the gut.
- Acting as an immune stimulatory substance
- Protecting the intestinal tissue from microbial attack

Phytobiotic	Biological activities
Acacia extract and renga renga lily extract	Increased the number of lactobacilli in the ileum of broiler chicken Caused reduction in coliform counts in the ileal and caecal digesta of chicken
Oregano	Antimicrobial and bactericidal actions
Garlic	Favoured the growth of LAB and reduced the growth of *Clostridium spp.*
Neem	Favourable influences on immune responses of broiler chicken
Essential oil of Oreganum aetheroleum	Enhanced cell mediated and humoral immune responses of chicken against *E. coli* infections(El-Ghany and Ismail (2013).
Black cumin	Enhanced immune responsiveness in broiler chickens against NDV vaccine

Organic acid

Organic acids, such as lactic, acetic, tannic, fumaric, propionic, caprylic acids, etc., have been shown to exhibit beneficial effects on the intestinal health and performance of broilers.

Function

- Increased Lactic acid bacteria counts in the ileum and caecum of broiler chicken. This had the effect of significantly decreased Enterobacteriaceae and Salmonella counts in the intestine of birds
- Improved body weight gains and feed conversion ratio
- Antimicrobial property of acids has been suggested to play a crucial role in controlling the population of pathogenic bacteria in the gut.

Conclusion

The potentials of nutraceuticals improving the gut ecosystem and immune functions of chicken may reasonably translate the potential of these compounds as the nutritional tools for growth promotion as well as for the prevention or treatment of enteric infections in poultry and also manipulation of these types of diet can reduce the condition of antibiotics residues in the products, so it can produce the better and safe food production.

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Innovative Nutritional Strategies to Control Milk-Fever in High-Yielding Dairy Animals

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Introduction

High-yielding dairy animals (cows and buffaloes) undergo profound metabolic, endocrine and nutritional changes in the transition from late gestation to early lactation. The sudden onset of copious colostrum and milk production immediately post parturition places a major demand on calcium (Ca) mobilisation, absorption and redistribution. If the calcium homeostatic mechanisms cannot meet the demand, the cow/buffalo develops hypocalcaemia, clinically manifesting as the syndrome commonly known as milk fever or parturient paresis. According to previous studies, the incidence of clinical milk fever ranges from a few percent to more than 10 % in high-risk herds, while subclinical hypocalcaemia is far more prevalent and carries significant production, welfare and fertility costs.

Historically, prevention of milk fever has relied on two main nutritional strategies: (1) feeding a low-calcium diet during the dry (close-up) period to stimulate the cow's calcium regulatory system; and (2) feeding anionic salts to create a negative dietary cation-anion difference (DCAD) in the close-up diet to promote calcium mobilisation and gastrointestinal absorption.

Nevertheless, despite these measures, milk fever remains a significant problem in modern, high-producing dairy operations. Recent work using systems biology and transition cow nutrition has shown that the pathogenesis of milk fever is more complex than a simple static calcium shortage; it involves endocrine (parathyroid hormone, vitamin D_3), immune/inflammatory mediators, metabolic stress, and nutritional imbalances of other minerals such as magnesium (Mg), potassium (K), phosphorus (P) and sodium (Na).

In this context, innovative nutritional approaches are warranted not only refining the classic low-Ca/negative-DCAD paradigm, but also targeting enhanced magnesium provision, optimising trace minerals (e.g., zinc, manganese), using rumen-protected feed additives, balancing energy and protein in the dry cow diet, and leveraging emerging feed technologies (e.g., zeolites, phytic acid feeds) to improve calcium homeostasis.

This paper aims to present a comprehensive overview of the nutritional aspects of milk fever control in high-yielding dairy animals, covering causes, symptoms, pathophysiology and mechanisms of action of interventions, diagnosis, treatment and nutritional management. Particular emphasis is placed on innovative and evidence-based approaches that dairy nutritionists and veterinarians can integrate into herd health programmes to reduce incidence, improve welfare, and enhance productivity.

Causes

The primary cause of milk fever is an abrupt rise in calcium demand at the onset of lactation that outpaces skeletal mobilisation, intestinal absorption and renal conservation of Ca. Contributory nutritional factors include feeding high-potassium (K) forages (which impair acid–base balance and reduce Ca mobilisation) and diets with high sodium (Na) or high cation load, which blunt the cow's ability to mobilise Ca. Inadequate magnesium status reduces responsiveness to parathyroid hormone (PTH) and thus impedes skeletal Ca release. Moreover, failure to pre-activate the homeostatic mechanisms (for example through dietary Ca restriction in the dry period) means the cow enters lactation with un-primed calcium absorption and mobilisation capacity. Genetic, metabolic stress and management factors (e.g., over-conditioned cows, low dry-matter intake) further predispose to the disorder.

Symptoms

Clinical milk fever typically appears within 24 hours of calving (though may occur up to 48 hours later) and is characterised by hypocalcaemia. Affected cows show weakness, ataxia, inability to rise (recumbency), cold extremities, decreased rumen motility, reduced feed intake and a typical sternal or lateral recumbent posture.

Some cows may show hypersensitivity of skin, head drawn back, dilated pupils, and decreased body temperature. If untreated, they may suffer cardiac arrhythmias, convulsions and death. Subclinical cases although lacking obvious recumbency present with reduced muscle tone, slower first standing time, decreased appetite, lower colostrum/milk yield, increased risk of retained placenta, metritis, and displaced abomasum. Early recognition is vital for prompt intervention.

Milk fever continues to be a major metabolic disorder in high-yielding dairy cows, despite long-standing preventive strategies. The financial cost is substantial beyond treatment costs, there is production loss, fertility impairment, increased risk of other transition-diseases (ketosis, metritis, retained placenta, displaced abomasum) and culling.

One of the first breakthroughs was the demonstration that feeding a low calcium diet (less than 20 g Ca/day) in the dry period activates the cow's calcium regulatory mechanisms (parathyroid hormone responsiveness, bone resorption, increased intestinal absorption) such that when lactation begins, the cow is physiologically primed. Controlled studies show that cows on low-Ca diets had a relative risk of milk fever reduced to 0–0.20 compared to higher Ca diets. However, practical implementation of extremely low Ca diets is challenging, especially with forages that naturally contain moderate to high Ca, and compliance may reduce dry cow intake.

A second major strategy is manipulation of the dietary cation-anion difference (DCAD). The DCAD concept calculates the difference between major cations (Na + K) and anions (Cl + S). A negative DCAD (e.g., –50 to –150 mEq/kg DM) induces a mild systemic metabolic acidosis in the close-up period, which enhances tissue responsiveness to PTH, increases bone resorption and intestinal Ca absorption, and reduces urinary Ca loss. Studies report relative risk of milk fever of ~0.19–0.35 for negative versus positive DCAD. Practical steps include using anionic salts (ammonium chloride, magnesium sulphate, calcium chloride) and monitoring urine pH (target ~6.0-6.5) to ensure sufficient acidity.

More recently, novel nutritional tools and feed-additives have emerged. For example, rumen-protected rice bran high in phytic acid has been investigated as a strategy to reduce calcium availability pre-partum, stimulating regulatory mechanisms without reducing feed intake. Zeolites, which bind calcium in the gut, have shown promise though DMI depression was a concern.

Enhancing magnesium intake in the close-up period is critical, since Mg is required for PTH release, target tissue PTH response and bone mobilisation of Ca. Some guidelines suggest 40-50 g Mg (0.30-0.45 % of DM) in the dry cow diet.

Beyond mineral manipulations, nutritional management of energy and protein intake is increasingly recognised. A sudden drop in feed intake around calving reduces Ca and other mineral absorption and impedes adaptation of homeostatic mechanisms. Ensuring good dry matter intake (DMI) close to calving, moderate body condition score (BCS) at dry-off (not over-fat), and balanced forage: concentrate transitions contribute to improved outcomes.

Implementation of nutritional programmes must be tailored to the herd: factors such as parity, prior history of milk fever, breed (Holstein vs Jersey), forage potassium levels (especially if legumes or grass silages high in K), and management (housing, comfort, calving environment) all influence risk. Economic modelling in India showed that feeding an anionic mineral mixture in the pre-partum period reduced milk fever incidence from 21 % to 2 % and increased milk yield by about 12 % and net income by about 38 %.

Milk fever is best viewed not as a simple deficiency but as a failure of the calcium regulatory network to respond to the abrupt onset of lactation demands. Nutritional approaches must therefore go beyond single-nutrient correction and incorporate system-based strategies that prime and support the cow's physiology.

Patho-physiology

In order to comprehend the emergence and control of milk fever, one must understand calcium homeostasis in dairy cows around calving. During late gestation, the cow's calcium requirements are moderate (for maintenance, foetal growth, bone deposition). The intestinal absorption is largely passive paracellular, and skeletal mobilisation is minimal. Thus, the calcium regulatory system (parathyroid hormone; PTH release, vitamin D_3 activation, bone resorption and enhanced intestinal absorption) remains in a relatively quiescent state.

At calving and immediately after, the demand for calcium to produce colostrum and milk may exceed 30–50 g/day of Ca (depending on breed and yield). Intestinal passive absorption alone is insufficient; the cow must rapidly up-regulate active intestinal absorption (via 1,25-dihydroxyvitamin D_3) and mobilise skeletal reserves (bone resorption via PTH/1,25-D_3 mechanisms) and reduce urinary losses. If this activation is slow or impaired, plasma Ca falls (typically less than 2.0 mmol /L) this is hypocalcaemia.

When plasma Ca falls, PTH is secreted from the parathyroid glands, binds to receptors in bone and kidney, stimulates conversion of 25-hydroxyvitamin D to 1,25-dihydroxyvitamin D_3 in the kidney, increases Ca reabsorption in the kidney, enhances bone resorption, and increases intestinal absorption. However, in the high-yield cow just after calving, several factors may impair this response: high dietary potassium and sodium may reduce target tissue responsiveness and increase urinary excretion of Ca; low magnesium impairs PTH release and tissue sensitivity; metabolic stress, inflammation and endotoxaemia (e.g., from retained placenta or subclinical infection) may depress PTH release or receptor responsiveness.

In effect, there is a mismatch: Ca demand (for milk) more Ca supply (absorption + mobilisation) → plasma Ca declines → muscle contraction (skeletal and smooth) and nerve excitability become depressed → symptoms of weakness, ruminal atony, recumbency. In addition, low Ca impairs smooth muscle contraction in rumen/abomasum, contributing to displaced abomasum risk, and impairs immune cell function, raising risk of metritis and mastitis. Sub-clinical hypocalcaemia (plasma Ca 2.0-2.2 mmol/L) may not produce obvious signs but still predisposes to production and health issues.

Thus the key pathophysiological features are inadequate adaptation of Ca homeostasis pre-partum, triggered by transition stresses, high mineral loads (K, Na), low magnesium status, and systemic inflammation. From a nutritional viewpoint, the challenge is to prime the cow's mechanisms so that when demand rises they respond promptly, thereby maintaining normocalcaemia and avoiding the cascade of downstream disorders.

Mechanism of Action (of key nutritional interventions)

Understanding how specific nutritional approaches act helps explain why they are effective in preventing milk fever.

Low-calcium pre-partum diet: By restricting dietary Ca to < 20 g/day (≈ 0.4 % of DM) in the close-up dry period for 2-3 weeks, the cow's homeostatic mechanisms (PTH secretion, vitamin D activation, bone resorption, enhanced intestinal absorption) are up-regulated prior to the major post-partum Ca demand. This pre-activation means that when lactation begins, the system is ready to mobilise Ca rapidly, reducing the risk of hypocalcaemia.

Negative DCAD (anionic salts): Reducing the dietary cation (Na + K) minus anion (Cl + S) difference to negative values (e.g., –50 to –150 mEq/kg DM) leads to a mild systemic metabolic acidosis (decreased blood pH) which in turn increases tissue responsiveness to PTH, enhances bone resorption, increases intestinal Ca absorption and reduces renal Ca loss. The effect is to improve calcium fluxes at calving and reduce incidence of hypocalcaemia.

Magnesium optimisation: Adequate Mg (about 0.30-0.45 % of DM) supports the release of PTH from the parathyroid gland and the responsiveness of target tissues to PTH, enabling effective calcium mobilisation. Without sufficient Mg, PTH release may be blunted and skeletal mobilisation reduced.

Feed-additive strategies (zeolites, phytic acid, rumen-protected rice bran): These approaches reduce effective dietary Ca availability pre-partum (even when total Ca intake is not extremely low), thereby stimulating the calcium regulatory mechanisms without compromising palatability or intake. For instance, rumen-protected rice bran reduces Ca absorption pre-partum thus promoting adaptation.

Dietary K and forage management: High forage K (especially from legumes or K-rich grass silage) increases the positive cation load, which raises DCAD and causes metabolic alkalosis, reducing PTH response and Ca mobilisation. Lowering K intake (e.g., via forage selection, K-binder additives) improves the cow's capacity to cope with calcium demands.

Collectively, these nutritional mechanisms act to shift calcium homeostasis into a primed state before the calving-induced demand spike, thus ensuring adequate absorption, mobilisation and retention of Ca when needed.

Diagnosis

Diagnosis of milk fever is based on clinical and laboratory findings. Clinically, cows at or shortly after calving (typically within 24 hours) showing weakness, ataxia, sternal or lateral recumbency, extended neck, cold extremities, dry muzzle, decreased rumen motility and feed intake suggest the condition. Differentiation from hypomagnesaemia, downer cow syndrome from dystocia, or traumatic injury is necessary.

Laboratory diagnosis includes measuring total plasma/serum calcium (ionised Ca is best if available). A plasma total Ca below 2.0 mmol/L or about 8 mg /dL) is indicative of hypocalcaemia; values between 2.0-2.2 mmol/L may indicate subclinical hypocalcaemia. Some farms monitor urine pH (especially for pre-partum negative DCAD programmes) and pre-partum urinary Ca: creatinine or blood PTH levels (in research settings).

In herd-level screening, measuring incidence of subclinical hypocalcaemia (via postpartum blood Ca/ionised Ca) is increasingly recommended because these cases, though not obviously ill, predispose to production losses and health disorders. Pre-partum forage K, urine pH in close-up cows, and DCAD of diet are useful risk-assessment tools.

Accurate diagnosis helps not only treatment of the individual cow, but also herd-level monitoring of control programmes and early detection of risk factors (e.g., high-K forages, high DCAD, low Mg intake).

Treatment

Once a cow develops clinical milk fever, immediate treatment is required. The primary therapeutic intervention is the administration of calcium salts, either intravenously or orally (or both). Typically, a slow intravenous infusion of 500 mL of 23 % calcium gluconate (about 11 g Ca) over 5–10 minutes is given, monitoring for cardiac arrhythmias. After clinical recovery, oral calcium boluses or drenches (e.g., calcium chloride/ calcium propionate) may be administered to stabilise plasma Ca and prevent relapse.

Alongside calcium therapy, other supportive measures include: ensuring cow is kept in sternal recumbency with head elevated to avoid aspiration; providing heat/ventilation, slip-free footing; monitoring for secondary complications (e.g., retained placenta, displaced abomasums and metritis); correcting electrolyte or acid–base imbalances; and ensuring prompt rise and feed intake. Some practitioners use intravenous magnesium if hypomagnesaemia suspected. Prevention of further drops relies on ensuring adequate feed intake and mineral supplementation (Mg, P, trace elements) and transitioning to lactation diet smoothly.

From the nutritional viewpoint, after treatment the cow's diet should support high calcium availability: increasing dietary Ca intake, ensuring adequate vitamin D status, supplying enough magnesium and phosphorus, and progressively adapting to lactation demands. In herds with recurrent cases, prophylactic programmes (low-Ca/negative-DCAD pre-partum) must be implemented. It is also good practice to monitor for subclinical hypocalcaemia, as untreated mild cases predispose to other health problems.

The goal of treatment is rapid restoration of normocalcaemia, recovery of muscle tone, rumen motility and rumination, and prevention of relapse. With early and effective intervention, most cows recover within a few hours; however, cows remaining recumbent more than 24 hours have poorer prognosis due to secondary muscle/blood flow damage.

Nutritional strategies

The cornerstone of controlling milk fever in high-yielding dairy cows is effective nutritional strategies during the close-up dry period (3 weeks pre-partum) and early lactation. Given the complexity of calcium homeostatic mechanisms, a multi-pronged nutritional programme is preferred rather than a single-nutrient focus. Below are key elements and innovative considerations:

1. Close-up dry period diet formulation

Low dietary calcium: Reducing Ca intake to approximately less than 20–30 g per cow per day (about 0.4 % DM or less) for about 10-21 days pre-partum stimulates the cow's calcium-mobilising systems. Controlled studies show substantial risk reduction.

Negative DCAD: Target DCAD (of about –50 to –150 mEq /kg DM) by adding anionic salts (such as ammonium chloride, calcium chloride, magnesium sulphate and ammonium sulfate) for about 3 weeks pre-partum, monitor urinary pH (target about 6.0–6.5 in Holsteins cows) to verify efficacy.

Potassium and sodium control: Use forages low in K (ideally < 1.8 % K in DM) and avoid high-K fertilised legume forage; reduce Na load where feasible. High K and Na raise DCAD and blunt adaptation.

Magnesium adequacy: Ensure Mg intake of ~40–50 g/day (~0.30-0.45 % DM) in the close-up diet to support PTH responsiveness; magnesium-rich mineral supplements or Mg-oxide/Mg-sulphate inclusion are common.

Phosphorus: Though less critical than Ca/Mg/K/Na, ensure P intake is adequate (≈ 20–25 g/day) and the Ca:P ratio remains around 1.5-2.0:1 to avoid P-induced inhibition of vitamin D activation.

Energy and protein balance: Maintain moderate energy intake so body condition score (BCS) at calving remains ~3.0–3.5 (on 5-point scale). Avoid over-fat cows, as greater mobilisation stress may hamper calf response. Feed sufficient ADF/forage to maintain good rumen fill and DMI; maximize DMI pre-partum (≥10–12 kg DM) to support Ca absorption and reduce risk.

Forage management: Choose forages with moderate K, moderate Ca, and good dry matter intake potential. Consider low K forages, avoid oversupply of alfalfa or high K grass silage. Where forages are high K, consider corrective measures (e.g., gypsum, sulphate binder).

Feed-additive innovations: Consider including rumen-protected rice bran (high phytic acid) or zeolite to reduce effective Ca availability, thus stimulating the adaptation of Ca regulation pre-partum. Early trials show promise although intake effects must be monitored.

Trace minerals and vitamins: While Ca/Mg/K/Na dominate, ensure the diet meets recommended levels of vitamins D (pre-partum and postpartum), A and E, as well as trace elements such as zinc, manganese and copper given their role in bone metabolism and immune function. Some studies suggest vitamin D metabolites may help, though risk of toxicity exists.

2. Monitoring and adjustments

1. Urinary pH measurement in close-up cows (ideally about 1–2 weeks pre-partum) provides a simple on-farm check of DCAD effectiveness. If pH remains more than 7.0, adjustments to anionic salt inclusion are needed.
2. Forage K, Na and Cl analyses should be done pre-partum to compute DCAD and anticipate dietary adjustments.
3. Blood/plasma total Ca (or ionised Ca) measurement postpartum (e.g., 12–24 hours after calving) in a sample of cows allows evaluation of subclinical hypocalcaemia prevalence and the success of the programme.
4. Herd-level records of milk fever incidence, retained placenta, metritis, displaced abomasum and milk yield drop serve as indirect indicators of calcium-homeostasis adequacy.

3. Early lactation diet and management

After calving, supply high-quality forages and concentrates to support dry matter intake along with adequate Ca supply (such as 60–80 g Ca/day or as per local recommendations) to meet the high milk-Ca demand. Continue to supply supplements of Mg, P, vitamin D and trace elements and consider oral Ca boluses for high-risk cows (e.g., multiparous, previous milk fever history) within 12 hours of calving. Ensure comfortable calving environment, early standing and feeding, monitoring for appetite drop or retention of placenta (which may drive endotoxaemia and liquid shifts compromising Ca regulation). Where necessary, individual cow risk assessment may lead to targeted prophylactic calcium drenching or bolusing for cows at very high risk.

4. Herd health integration

Nutritional management must be integrated with overall transition-cow management: Comfortable housing, minimal social stress, early feed access, cow grouping (close-up group separate from dry and fresh cows), calving supervision and post-partum monitoring are critical. The nutrition alone cannot fully eliminate milk fever if management fails. Training of farm staff in monitoring close-up cows (DMI drop, urine pH, condition score) and rapid intervention for early signs of hypocalcaemia (weakness, recumbency, DMI drop) is essential.

5. Economic considerations

Economic studies indicate that prevention pays: One Indian field study found reduction of milk fever from 21 % to 2 % and net income increase by about 38 % by feeding an anionic mineral mixture. Cost-benefit of feeding specialised feeds/additives must be assessed in each herd setting, considering forage composition, previous milk fever history, and labour input. In short, nutritional management of milk fever must go beyond simple Ca supplementation and instead adopt pre-partum adaptation strategies (low-Ca diet, negative DCAD, Mg adequacy, K/Na control), innovation via feed-additives, effective monitoring, and integration with whole-herd transition-management. When well-implemented, such programmes minimize clinical and subclinical hypocalcaemia, improve cow health, fertility, milk yield and farm profitability.

Conclusion

Milk fever in high-yielding dairy cows remains a challenge, but modern nutritional and management strategies offer powerful tools to prevent this debilitating condition. By viewing milk fever as a failure of the calcium regulatory network, rather than simply a Ca deficiency, herd health programmes can more effectively target adaptation of absorption, mobilisation and retention mechanisms. Key innovations such as low-calcium pre-partum diets, negative DCAD rations, adequate magnesium and potassium control, feed-additives reducing intestinal Ca availability, and careful monitoring permit proactive prevention rather than reactive treatment. When integrated with effective transition cow management, these approaches enhance welfare, reduce production losses and improve profitability. The dairy industry stands to gain significantly by embracing these evidence-based, innovative nutritional strategies to control milk fever.

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Growing Smarter: The Science Behind Sustainable Vegetable Farming

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Abstract

The modern agricultural landscape is witnessing a paradigm shift from high-input, yield-centric farming systems to ecologically balanced, resource-efficient and socially responsible approaches. Sustainable vegetable farming represents this transformative movement. Rooted in scientific principles, it seeks to balance productivity, profitability and environmental conservation. This article explores the scientific foundations, innovations and real-world practices that underpin sustainable vegetable farming. From soil microbiology and precision irrigation to integrated pest management, renewable energy integration and climate-smart adaptation, it unpacks how technology and ecological understanding are redefining the future of vegetable cultivation. Moreover, it delves into socio-economic dimensions and the policy frameworks essential for large-scale adoption. The discussion concludes that the science behind growing smarter lies not only in adopting advanced tools but also in restoring harmony between nature and agriculture, ensuring food and nutritional security for generations to come.

Keywords: sustainable agriculture, vegetable production, soil health, precision farming, climate resilience, IPM, biodiversity conservation.

1. Introduction

Vegetable crops hold a unique position in the global agricultural system. They are rich in essential vitamins, minerals and dietary fiber and contribute directly to human health and economic welfare. According to the **FAO (2023)**, global vegetable production has surpassed 1.2 billion tonnes, yet nearly one-third of the world's population still experiences micronutrient deficiencies. To address this nutritional gap sustainably, agriculture must evolve beyond conventional production systems that rely heavily on chemical inputs and water-intensive practices.

Traditional farming models, while successful in increasing yields during the Green Revolution, have often led to **soil degradation, water scarcity, biodiversity loss and greenhouse gas emissions**. The emerging scientific consensus emphasizes that future food production must be sustainable - meaning it must **meet present needs without compromising the ability of future generations** to meet theirs.

Figure 1. The Three Pillars of Sustainability in Vegetable Farming

Sustainable vegetable farming integrates **ecological science, environmental ethics and modern technologies** such as precision irrigation, renewable energy and biological pest management. It promotes productivity while conserving resources and maintaining environmental quality. This holistic approach ensures the long-term resilience of the food system.

2. The Science of Sustainability in Vegetable Production

2.1 Defining Sustainability in Agriculture

The sustainability concept extends beyond environmental conservation - it includes **economic viability and social equity**. A sustainable vegetable farm should generate consistent income, minimize ecological footprints and empower local communities.

Dimension	Objective	Example Practice
Environmental	Conserve soil, water and biodiversity	Use of cover crops, crop rotation, organic inputs
Economic	Maintain profitability	Market linkages, value addition, efficient input use
Social	Support rural livelihoods	Inclusive farmer cooperatives, equitable access to resources

2.2 Ecological and Biological Foundations

Vegetable farming ecosystems are complex living systems. Soil microorganisms, beneficial insects and natural predators form symbiotic relationships that support plant health. For instance:

- *Rhizobacteria* promote root growth and nitrogen fixation.
- *Mycorrhizal fungi* enhance phosphorus uptake.
- Pollinators and parasitoids contribute to yield and pest regulation.

Understanding and preserving these relationships allows farmers to reduce dependence on synthetic fertilizers and pesticides.

Scientific Note: Research by Sharma *et al*. (2021) found that integrating organic amendments and microbial biofertilizers improved tomato yield by 18% compared to conventional systems.

3. Soil Health: The Cornerstone of Sustainability

3.1 Importance of Soil Organic Matter

Soil is the living skin of the earth. Its fertility depends on organic matter content and microbial diversity. Continuous monocropping and chemical overuse have depleted soil carbon, leading to compaction and poor water infiltration. Adding **organic compost, farmyard manure and vermicompost** rejuvenates soil structure, enhances microbial activity and releases nutrients slowly, mimicking natural cycles.

Organic Amendment	Nutrient Function	Scientific Benefit
Compost	Improves structure and CEC	Increases root penetration and water retention
Green manure	Adds nitrogen biologically	Reduces fertilizer dependency
Biochar	Carbon sequestration	Enhances soil aeration and pH stability

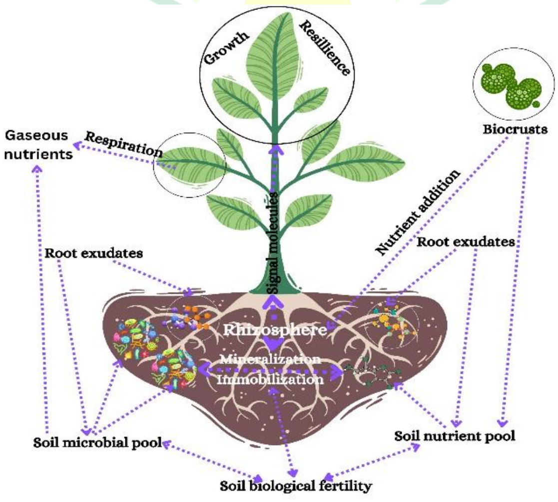

Figure 2. The Soil–Plant–Microbe Interaction Model

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3.2 Precision Nutrient Management

Soil testing and nutrient mapping are scientific tools that ensure site-specific nutrient application. Using **leaf tissue analysis** and **fertigation through drip systems**, farmers can deliver precise quantities of NPK, reducing wastage and preventing nutrient leaching.

Case Study: In Karnataka, India, integrating soil testing with fertigation in capsicum cultivation improved yield by 25% and reduced fertilizer cost by 18% (ICAR, 2022).

3.3 Conservation Tillage

Reduced tillage helps preserve soil structure, reduce erosion and maintain carbon sequestration. In vegetable systems, raised-bed planting with minimal soil disturbance supports aeration and improves microbial activity.

4. Water Management: Every Drop Counts

4.1 Efficient Irrigation Systems

Vegetables require frequent watering due to shallow root systems. Traditional flood irrigation causes excessive water loss. Modern **micro-irrigation** techniques, including drip and sprinkler systems, deliver water uniformly with remarkable efficiency.

Irrigation System	Water Saving (%)	Suitable Crops
Drip irrigation	50–70	Tomato, cucumber, brinjal
Sprinkler	30–40	Leafy greens
Subsurface irrigation	60–80	Greenhouse crops

Irrigation Method	Water Efficiency	Energy Efficiency
Surface Irrigation	50–65%	Low
Level Basin	60–80%	Low
Sub irrigation	50–75%	Low to Medium
Overhead irrigation	60–80%	Medium
Sprinkler irrigation	60–85%	Medium
Drip irrigation	80–90%	Medium to High

Figure 3. Comparative Efficiency of Irrigation Methods

4.2 Water Harvesting and Recycling

Rainwater harvesting, check dams, and farm ponds can store water for dry periods. In peri-urban areas, treated greywater can be reused safely in vegetable farming after proper filtration.

4.3 Mulching and Moisture Conservation

Mulches - both organic (straw, compost) and plastic - minimize evaporation losses and suppress weeds. Mulching also stabilizes soil temperature, creating a favourable microclimate for root growth.

5. Pest and Disease Management: Working with Nature

5.1 Integrated Pest Management (IPM)

IPM is based on the principle of managing pests, not eradicating them. It combines ecological understanding with careful monitoring and selective interventions.

IPM Component	Example Application
Cultural	Crop rotation and resistant varieties
Biological	Natural enemies such as *Trichogramma* spp.
Mechanical	Light and sticky traps
Botanical	Neem oil and bio-pesticides

5.2 Role of Biological Control

Biological control harnesses natural enemies - predators, parasitoids and pathogens - to suppress pests. For example, *Beauveria bassiana* effectively controls whiteflies and aphids in greenhouse crops.

Figure 4. IPM Cycle

6. Smart Technologies Transforming Vegetable Farming

6.1 Precision Agriculture and IoT

Precision agriculture applies **data-driven decision-making**. Sensors, drones and GPS-based monitoring systems provide real-time information about soil moisture, temperature and nutrient levels. This information enables farmers to optimize inputs and reduce losses.

Example: A drone-based NDVI (Normalized Difference Vegetation Index) scan can detect nutrient stress before visible symptoms appear, allowing timely correction.

6.2 Protected Cultivation and Hydroponics

Controlled-environment agriculture, including **greenhouses, net houses and hydroponics**, is revolutionizing vegetable farming. Hydroponics - growing plants without soil - uses nutrient-enriched water, saving up to 90% of water and ensuring year-round production.

System	**Water Saving (%)**	**Yield Increase (%)**
Hydroponics	90	30–40
Polyhouse cultivation	60	25–35
Open field (traditional)	—	—

Figure 5. Vertical Hydroponic System Model

6.3 Renewable Energy in Farming

Solar pumps and wind-driven ventilation in polyhouses lower energy costs and carbon emissions. In India, the **KUSUM scheme** promotes solar irrigation pumps, making sustainable energy accessible to smallholders.

7. Crop Diversification and Biodiversity

7.1 Intercropping and Rotation

Intercropping vegetables with legumes or herbs enhance resource use and suppresses pests. Rotating solanaceous crops with legumes restores soil nitrogen and reduces nematode infestation.

Cropping System	Benefits
Tomato + Onion	Reduced whitefly attack
Okra + Cowpea	Nitrogen fixation
Cabbage + Garlic	Pest repellence

7.2 Conservation of Indigenous Varieties

Local vegetable landraces are genetically resilient and adapted to regional climates. Conserving these through **community seed banks** and participatory breeding enhances climate resilience and genetic diversity.

8. Socio-Economic Dimensions

Sustainability involves equitable growth. Vegetable farming supports **smallholders, women farmers and urban growers**. Empowering them through cooperatives, training and credit access ensures inclusive development.

Aspect	Social Impact
Women's participation	Income and empowerment
Local markets	Reduced food miles
Farmer groups	Collective marketing power

9. Climate-Smart Vegetable Farming

Climate change impacts vegetables through temperature stress, drought and unpredictable rainfall. Climate-smart practices include:

- Drought-resistant hybrids (e.g., heat-tolerant tomato varieties)
- Microclimate modification via shade nets
- Weather forecasting tools for planting schedules

Research by **Rana and Yadav (2020)** showed that introducing climate-smart practices in North Indian vegetable farms increased yield stability by 15–20%.

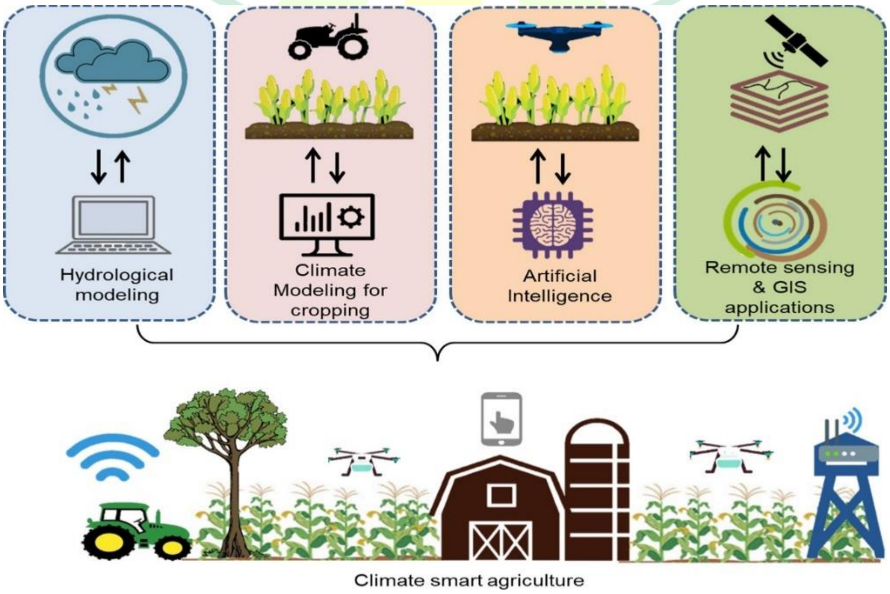

Figure . Climate-Smart agriculture

10. The Road Ahead

The integration of scientific research with traditional wisdom will shape the next era of vegetable farming. Policies promoting **carbon credits, water-saving incentives and digital extension platforms** will encourage sustainability. Education and capacity-building are essential to empower farmers to "grow smarter."

Conclusion

The journey toward sustainable vegetable farming reflects humanity's broader quest for balance between productivity and ecological responsibility. The science behind "growing smarter" lies in integrating soil biology, precision technology, biodiversity and social awareness into one coherent system. By shifting from extractive agriculture to regenerative models, we can ensure resilient food systems, improved livelihoods and planetary health. Sustainable vegetable farming is not merely a method - it is the foundation for a sustainable future.

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Organic Farming Practices, Challenges and Policy Recommendation in India

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Overview

According to FIBL survey 2031, India holds a prominent place as one of the top countries practicing organic agriculture. Thirty percent of the world's total organic producers call India home, and with 2.3 million hectares of organic cultivated area and totals of 27,59660 farmers, 1703 processors, and 745 traders. Just recently, we have seen a significant growth of major organic agriculture land across the country.

India's organic farming is still in its infancy. As of March 2019, about 2.8 million hectares of farmland is used for organic cultivation. With a total net sown area across the country of 140.1 million hectares, there are a few states which have taken a lead in promoting organic farming. Over 25% of the total organic cultivated area is in those states such as Madhya Pradesh, Maharashtra etc. The major states involved in organic farming are Madhya Pradesh (26%), Maharashtra (22%), Gujarat (15%), Rajasthan (13%) etc.

India has ranked second in global organic land area and first in the number of organic producers based on FiBL report in 2022. According to the projected figures for 2024, organic agricultural area under the National Program for Organic Production in India is pegged at 4.5 million hectares, 2.5% of the total agricultural land in the country. However, the percentage of total area organic farming area relative to net sown area of each state , Sikkim holds first place with 98% of its net sown area in organic cultivation, followed closely by Uttarakhand at 89%. Four states from the Northeastern region occupy a place in the top 10 states for area under organic agriculture nationally. CAGR of organic farming in India in FY 2020-2024 is about 7%. If cotton is taken out of the equation, the CAGR (Compound Annual Growth Rate) of production overall fell by 5.8%.

Challenges

Sustainability in the global economy means balancing organic principles with commercial imperatives. It is necessary to ensure that organic standards and certification processes are flexible to address the present challenges regarding nature conservation and restoration . Equitable, affordable, and adaptable access to certification services is necessary for organic production which is a problem prevailing the society . Responsible labor relations and land ownership arrangements is also a challenge in organic production.

The introduction of new inputs like 'natural' biocides, soil enhancers, and GMOs; and an unscientific, or incomplete, basis for the inclusion or exclusion of materials from organic standards is difficult . The pursuit of international standardization in matters of certification and regulations is important and need monitoring . of importance is the creation of locally relevant agronomic solutions to production challenges, including weeds, animal health, and soil fertility.

The need exists to extend research efforts across a wide range of areas and to improve knowledge integration. Improvement of productivity must be accompanied by preservation of quality in foods. Education and training at all levels are crucial for capacity building, infrastructure development, and network establishment. Regulatory and marketing structures have deficiencies, such as labeling, High prices for consumers, along with inconsistent quality and availability, create challenges. One should establish and uphold credibility and professionalism, local agronomic needs may exert pressure to adapt standards. The question of whether organic food is healthier for humans than conventionally produced food is the key issue for organic consumers.

Timing is he one of the major problems in organic farming. Getting organic foods and meats to market faster often, but not in all cases, requires an efficient supply chain. The main difference between conventional and organic farming is the use of fewer chemicals in the production process. Although apparently healthier, organic produce tends to spoil easier for several reasons. Because organic produce is commonly more sensitive to temperature fluctuations during transportation and also has shorter expiration dates, it should be consumed sooner to maintain safety and appeal.

Infestations of pests, which are as ancient as agriculture itself, are some of the major barriers that stand in the way of organic farming, enabling rodents, insects, and other pests to destroy crops. Because of this fact, pesticides have been utilized by humankind for a long time to eliminate pests efficiently. However, since many of these substances are synthetic and detrimental to the environment, organic farming is not allowed to make use of them.Organic farms, therefore, need to plan pest management strategically and effectively. Even though pesticides are banned in organic farming, there are some natural insecticides which are allowed under the system of organic farming.

Marketing organic products is more difficult, organic farming relies on timely delivery to the market as a method of maintaining products' nutritional value and freshness. However, organic products are at a disadvantage in today's culture of long commutes and online purchasing. Because of this, organic farmers need to find regional markets for their products, which isn't always easy. Farmers may instead spend their dollars on reliable

Existing policies for organic farming in India:

- National Programme for Organic Production (NPOP):
- Launched in 2000, this standard regulates organic farming, sets standards of production, and accredits the certification bodies.
- Paramparagat Krishi Vikas Yojana (PKVY): Initiated in 2015 with the aim of promoting traditional organic farming on a cluster basis with financial support to farmers.
- Rashtriya Krishi Vikas Yojana (RKVY): Initiated in 2007 to fund adoption of organic practices, input units and organic market development.
- Mission Organic Value Chain Development for North Eastern Region (MOVCDNER): Promotes organic farming in the Northeast by way of training, certification, value addition, and marketing.
- National Project on Organic Farming (NPOF): Supports the production of organic inputs such as biofertilizers and biopesticides and finances input units.
- National Mission on Oilseeds and Oil Palm: Provides subsidies for biofertilizers and vermicomposting to promote organic oilseed and oil palm farming.
- CISS – Capital Investment Subsidy Scheme: Promotes the use of biofertilizers and biopesticides to reduce dependency on chemicals and foster soil health.
- National Horticulture Mission (NHM): Trains farmers; land allocation for organic horticulture and sustainable crop production.
- One District One Product (ODOP): Promotes unique district products, enhances local economies, and supports organic product marketing.
- Zero Budget Natural Farming (ZBNF) Promotes chemical-free, low-cost farming pioneered by Subhash Palekar for sustainable livelihoods.
- Agri Export Policy (AEP): Launched in 2018 to promote organic exports, increase farmers' incomes, and gain greater access to more export markets.
- National Centre for Organic Farming (NCOF): Apex body for research, training, and promotion of organic farming to improve the health and sustainability of soil.
- Government has also set up some standard quality certifications for the organic products .
- Two types of organic certification systems have been developed to ensure quality control of organic produce as given below:
- Third Party Certification by Accredited Certification Agency under National Programme for Organic Production (NPOP) scheme under Ministry of Commerce and Industry for development of export market. Under NPOP certification scheme the production and handling of activities at all stages such as production, processing, trading and export requirements for organic products is covered.
- Participatory Guarantee System- (PGS-India) under Ministry of Agriculture and farmers Welfare in which stakeholders including farmers/ producers are involved in the decision making about the operation of the PGS-India certification itself by assessing, inspecting and verifying the production practices of each other

and collectively declaring the produce as organic. The PGS - India certification is to meet the demand of domestic market.

Policy Recommendations:

Some states, such as Kerala, have piloted organic procurement in select districts. Under its Organic Farming Policy, the state facilitated direct procurement from certified farmer groups to school-feeding programs, reducing chemical intake among children while giving farmers assured markets. In the same vein, in Madhya Pradesh, certain tribal hostels have started incorporating organic millets into their menus in partnership with local Self-Help Groups and Farmer Producer Organisations. This can be followed in entire National to improve the states of organic farming and farmers.

Subsidies for organic farming in India have historically been input-focused rather than outcome-oriented.In contrast, the European Union's Common Agricultural Policy provides area-based subsidies and compensatory payments for yield losses during the conversion period, recognising that ecosystem services offered by organic farms benefit entire communities.

Sikkim's successful organic transition was partly due to strong government incentives, including free organic input distribution, assured market linkages, and capacity building programmes. Farmers were assured that despite possible initial yield reductions, long-term soil health improvement and premium market pricing would offset risks. However, such comprehensive incentive models remain rare across India.Transition support must go beyond subsidies because Farmers require handholding through certification processes, market linkage facilitation, and risk mitigation tools such as organic-specific crop insurance.

Globally, the Zero Hunger Programme of Brazil stipulates that at least 30% of the food bought for school meals must be sourced from small-scale organic or agroecological farmers. This model not only raised nutrition levels but also rejuvenated local economies and reduced rural poverty. If adapted effectively, such policies could transform India's public food systems into engines of health and environmental sustainability.

Globally, South Korea's Organic Farming Promotion Act offers a model worth emulating. It combines transition subsidies with direct marketing support, research funding, and consumer awareness campaigns under a single policy umbrella, creating an ecosystem conducive for organic growth.

Japan's Teikei movement – farmer-consumer co-operatives where members commit to buying directly from farmers for a season – shows how local market structures rooted in trust can sustain organic economies without heavy government subsidies. India could adapt such models to strengthen its own local organic mandis, ensuring organic remains affordable and farmers remain profitable.

These successful models around the world can be adopted and followed to increase the organic products production in India.

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From Farm to Pharmacy: Vegetables as Functional Foods

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1. Introduction: Where Nutrition Meets Medicine

Vegetables are far more than colorful additions to our plates they are nature's original medicine. From ancient times, civilizations have recognized the healing power of vegetables in maintaining health, curing ailments, and promoting longevity. Today, with rising cases of non-communicable diseases such as obesity, diabetes, cardiovascular disorders, and cancers, there is renewed global interest in "functional foods" foods that provide physiological benefits beyond basic nutrition. Vegetables, rich in vitamins, minerals, fibers, and bioactive compounds, are at the forefront of this movement. They not only nourish but also prevent, manage, and sometimes reverse chronic diseases. This new understanding of vegetables as "functional foods from the farm to the pharmacy" marks a paradigm shift toward sustainable, preventive healthcare through everyday diets.

2. What Are Functional Foods

The concept of *functional foods* originated in Japan in the 1980s, where foods with specific health-promoting properties were classified as Foods for Specified Health Uses (FOSHU). Functional foods are defined as foods that exert beneficial effects on one or more target functions in the body, beyond adequate nutrition, improving health and reducing disease risk. Vegetables perfectly fit this definition. They contain a complex matrix of nutrients and bioactives that work synergistically to enhance well-being. The transition from *"food as sustenance"* to *"food as medicine"* places vegetables at the heart of modern nutritional science and preventive medicine.

3. Bioactive Compounds: The Healing Chemistry of Vegetables

Vegetables are biological treasure houses of secondary metabolites and phytochemicals which play protective roles in both plants and humans. These compounds include:

Phytochemical Class	Examples in Vegetables	Health Function
Carotenoids	β-carotene (carrot), lycopene (tomato), lutein (spinach)	Antioxidant, eye and heart health
Flavonoids	Quercetin (onion), kaempferol (broccoli), anthocyanins (red cabbage)	Anti-inflammatory, anti-cancer
Phenolic acids	Caffeic, ferulic acids (beetroot, tomato)	Antioxidant, antimicrobial
Glucosinolates	Broccoli, cabbage, radish	Detoxification, anti-cancer
Organosulfur compounds	Garlic, onion	Cardioprotective, antimicrobial
Saponins and Alkaloids	Bitter gourd, spinach	Antidiabetic, immune-boosting

These phytochemicals act at molecular and cellular levels to protect against oxidative stress, regulate metabolism, strengthen immunity, and support tissue repair.

4. The Health-Protective Power of Vegetables

a. Antioxidant and Anti-Aging Properties

Reactive oxygen species (ROS) contribute to aging and degenerative diseases. Antioxidants in vegetables such as vitamin C, E, polyphenols, and carotenoids neutralize ROS, preventing cellular damage.

- Carrot and spinach pigments protect skin and vision.
- Tomato lycopene scavenges free radicals, lowering cancer risk.
- Beetroot betalains exhibit strong antioxidant activity.

b. Anti-Inflammatory and Immunomodulatory Effects

Flavonoids and phenolic compounds in onion, cabbage, and amaranth regulate inflammatory pathways and cytokines, reducing chronic inflammation and strengthening immune response.

c. Cardioprotective Benefits

Garlic's allicin and onion's sulfur compounds lower cholesterol and prevent platelet aggregation. Green leafy vegetables rich in nitrates enhance **nitric oxide** production, improving vascular health and lowering blood pressure.

d. Antidiabetic and Metabolic Regulation

Bitter gourd (*Momordica charantia*) contains **charantin and polypeptide-P**, known for insulin-like activity. Fenugreek and drumstick leaves also modulate blood glucose and lipid levels.

e. Cancer Prevention

Cruciferous vegetables such as broccoli, cauliflower, and radish are rich in **glucosinolates**, which form **isothiocyanates** potent agents that activate detoxifying enzymes and inhibit carcinogenesis.

5. From Soil to Cell: The Nutritional Pathway of Health

The health-promoting power of vegetables begins in the soil. Sustainable and organic cultivation practices rich in compost, biofertilizers, and microbial activity enhance phytochemical synthesis.

For example:

- Organic spinach and lettuce show higher phenolic and flavonoid content than conventionally grown ones.
- Integrated nutrient management (INM) systems improve both yield and nutraceutical value.

Thus, the *farm stage* determines the *pharmacy value* of vegetables reinforcing the link between agroecology, nutrition, and health.

6. Functional Foods and the Modern Diet

Functional vegetables have become central to modern food systems:

- Tomato lycopene capsules are used for heart and prostate health.
- Garlic extracts serve as natural cholesterol regulators.
- Beetroot juice is marketed as an energy enhancer.
- Drumstick powder and amaranth leaves are incorporated in nutraceutical beverages.

This intersection of agriculture and pharmacology is transforming vegetable farming into a bio-health industry, where the focus is not just on yield but on health-enhancing compounds.

7. Scientific Evidence Supporting Vegetable Functional Foods

- Tomato lycopene reduces prostate cancer risk by 30% (Harvard Health, 2022).
- Garlic supplementation lowers total cholesterol by 10-12%.
- Beetroot juice improves oxygen utilization and athletic endurance.
- Spinach folate reduces neural tube defects during pregnancy.
- Bitter gourd and drumstick improve glycemic control in diabetic patients.

Such evidence underscores that vegetables are not mere dietary components but potent natural therapeutics.

8. Value Addition and Nutraceutical Development

Value addition enhances both shelf life and medicinal potential.

- Dehydrated powders of beetroot, drumstick, and spinach retain antioxidants.
- Encapsulation of phytochemicals ensures controlled release.
- Cold-pressed vegetable oils and extracts preserve bioactive stability.
- Functional soups, juices, and snacks merge convenience with health.

Promoting vegetable-based nutraceutical industries offers dual benefits: improving public health and creating income opportunities for farmers.

9. Future Prospects: Precision Nutrition and Green Healthcare

The future of vegetable functional foods lies in precision nutrition tailoring diets to individual genetic and metabolic profiles. Emerging technologies such as metabolomics, biofortification, and nanodelivery systems will enhance the bioavailability of phytochemicals. Integration of urban farming, hydroponics, and protected cultivation ensures year-round supply of nutrient-dense vegetables, linking sustainable horticulture with preventive healthcare.

10. Conclusion

Vegetables represent the perfect marriage of agriculture and medicine *"From farm to pharmacy."* They nourish, protect, and heal naturally. In a world increasingly dependent on synthetic drugs, vegetables provide a sustainable, side-effect-free path to wellness. Encouraging diversified vegetable cultivation, promoting research on phytochemicals, and strengthening public awareness on the medicinal value of vegetables are key to achieving nutrition-sensitive and health-driven agriculture.

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Fodder potential and innovation in Maize (*Zea mays* L.)

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Abstract

Maize (*Zea mays* L.) is one of the most versatile and high-yielding cereal crops grown worldwide. It is a globally vital cereal, valued for both grain and green biomass production. The crop has tremendous potential as a forage source. Traditionally grown for grain, maize is increasingly recognized for its value in fodder systems due to high biomass, energy-rich content, and adaptability. Its swift adoption for forage is driven by high yield, nutritional quality, and adaptability across environments. Although traditionally cultivated for grain, maize has emerged as an important forage crop due to its high biomass productivity, excellent nutritive value, and adaptability across diverse agro-climatic zones. This review consolidates recent findings on the nutritional composition, agronomic management, varietal development, and breeding advances aimed at improving maize as a fodder resource. Emphasis is placed on dual-purpose hybrids, digestibility-enhancing traits such as the brown midrib (bmr) gene and the role of maize in integrated crop–livestock systems. The integration of genomic tools, biofortification, and climate-resilient breeding is expected to enhance the sustainability and productivity of maize-based forage systems.

Keywords: Maize fodder; dual-purpose hybrids; digestibility; stay-green; silage; forage quality; *Zea mays*; livestock integration

Introduction

Maize is the third most important cereal crop globally, following rice and wheat, and is widely cultivated for food, feed, and industrial uses (FAO, 2023). In India, maize occupies a central position owing to its high yield potential, short growth duration, and adaptability to diverse environments. The adoption of single-cross hybrids and improved agronomic management has led to substantial gains in productivity in recent decades (Kumar *et al*., 2024). Apart from its significance as a grain crop, maize is increasingly valued as a fodder source, particularly for silage preparation. With green fodder yields ranging from 25–50 t/ha, maize is among the most efficient forage crops, characterized by high digestibility, palatability, and ensiling properties. It requires relatively low labor and machinery inputs compared to other forage crops (Sharma & Singh, 2022). Moreover, maize residues, including stover and husk, provide an additional resource for livestock feeding, especially in mixed farming systems. Maize's superiority as a non-leguminous fodder lies in its high energy value, absence of anti-nutritional factors such as hydrocyanic acid (HCN) and oxalates, and excellent fermentability during silage formation. These attributes make it a cornerstone of forage-based dairy and livestock systems in Asia, Africa, and Latin America (Patel *et al*., 2025).

Nutritional Value and Comparative Performance

Maize is recognized for its balanced nutritional profile and energy-dense fodder. The crude protein (CP) content of green maize ranges between 7.2–8.5%, crude fiber (CF) between 32–34%, and fat content between 1–2.5%, making it ideal for ruminant feed (Roth *et al*., 1995; Dahmardeh, 2011). Unlike sorghum and pearl millet, maize lacks anti-nutritional compounds such as HCN and oxalate, ensuring safety and palatability.

Table 1. Comparison of nutritional quality of maize with other non-leguminous fodders

Fodder Crop	Physiological Stage	Harvest Stage (DAS)	Crude Protein (%)	IVDMD (%)
Maize	Silk to milk stage	55–65	11–8	68–52
Bajra	Boot stage	45–55	10–7	62–55
Sorghum	Initiation of flowering	70–80	8–7	60–57
Teosinte	Pre-flowering	80–85	9–7	62–58
Sudax	After 30 days of cut	65–70	11–7	60–55
Napier bajra hybrid	1 m height, 30-day cut	55–60	11–7	60–55
Guinea grass	1 m height, 25–30-day cut	55–60	10–8	60–57

Source: Gupta *et al*. (2005)

The stage of harvest strongly influences the nutritional composition. Optimum fodder quality is obtained when harvested at the silk to milk stage, balancing dry matter yield and digestibility.

Table 2. Forage performance of maize compared with other potential forages

Crop	Green Forage Yield (t/ha)	Dry Forage Yield (t/ha)	Crude Protein (%)
Sorghum	32.7	7.7	6.0
Pearl Millet	37.6	8.5	8.7
Maize	30.9	6.5	5.5
Pigeonpea	40.6	12.6	23.7

Source: Rao *et al*. (2002); AICRP Forage Trials (ICAR, India)

Table 3. Changes in nutritive value of maize with stage of maturity

Stage of Maturity	Dry Matter (%)	Crude Protein (%)	Net Energy of Lactation (Mcal/lb)
Pre-silk	10	12.4	0.62
Silk	15	11.3	0.64
Milk	21	7.0	0.67
Over-ripe	45	9.1	0.62
Drought-stressed	25	9.9	0.62
Non-pollinated	27	7.6	0.70

Optimal ensiling quality is achieved at 30–35% dry matter content, usually at the milk–dough stage.

Agronomic and Management Practices

Standard agronomic recommendations for forage maize include:

Sowing time : June–July (*kharif*) and February–March (*rabi*)
Seed rate : 50–60 kg/ha
Spacing : 30 × 10 cm
Fertilization : 120:60:40 NPK kg/ha + micronutrients (Zn, B)
Harvest stage : 50% flowering to milk–dough stage

Intercropping maize with legumes such as cowpea enhances forage protein content and improves soil fertility through biological nitrogen fixation (Kumar & Patel, 2023). Conservation agriculture practices and precision irrigation have also been shown to enhance biomass and water-use efficiency in maize fodder systems (Singh *et al*., 2025).

Fodder Varieties and Dual-Purpose Hybrids

Maize breeding programs in India and abroad have focused on developing dual-purpose hybrids capable of delivering both grain and stover yield. The progress of major released varieties is summarized below.

Table 4. Major maize fodder varieties and hybrids released in India

Year	Variety/Hybrid	Zone/Region	Type
1982	African Tall	All India	Tall fodder variety
1992	J-1006	Punjab	Composite
1997	APFM-8	South Zone	Composite
2008	Pratap Makka Chari-6	Punjab, Haryana, Rajasthan, UP	Dual-purpose
2022	HQPM 5 (ICAR-IIMR)	North & Central India	Quality Protein Maize (QPM)
2023	DHM 117	Telangana, Andhra Pradesh	Dual-purpose (grain + stover)
2024	COH(M) 6	Tamil Nadu	High fodder, bmr hybrid
2024	Bio-9525	Pan India	Stay-green dual-purpose

Recent advances have led to the release of stay-green and brown midrib (bmr) hybrids such as COH(M) 6 and Bio-9525, offering improved digestibility and stover quality (Rani *et al*., 2024).

Advances in Breeding for Fodder Traits

Breeding for forage maize emphasizes traits like high biomass yield, stay-green, digestibility, and resilience. Key breeding objectives include

- High Green Forage Yield: Selection for tall, vigorous plants with high leaf-to-stem ratios.
- Improved Nutritional Quality: Enhanced CP%, IVDMD, and TDN values; incorporation of bmr mutants for lower lignin content.
- Quality Protein Maize (QPM): Increased lysine and tryptophan contents for enhanced feed value.
- Silage Suitability: Optimal dry matter (30–35%), high water-soluble carbohydrates (WSCs), and good fermentation stability.
- Abiotic and Biotic Stress Resistance: Tolerance to drought, heat, and salinity; resistance to leaf blight, rusts, and stem borers.
- Modern breeding approaches using genomic selection, marker-assisted introgression, and CRISPR-based gene editing have accelerated the improvement of digestibility and stress tolerance traits (Banerjee *et al*., 2023; Tiwari *et al*., 2025).

Integration in Livestock and Farming Systems:

Maize plays a critical role in integrated crop–livestock systems, providing high-quality green fodder during lean periods. Dual-purpose hybrids enhance feed security and ensure sustainable dairy production. The stay-green trait maintains stover quality post-physiological maturity, beneficial for silage and stover feeding (Shinde *et al*., 2024). When ensiled properly, maize provides high-energy feed that supports higher milk yields and feed conversion efficiency compared with sorghum or pearl millet silage (Patel & Kumar, 2023). Adoption of silage-making technologies and mini-silage units under ICAR and state programs has further improved fodder conservation and smallholder income.

Future Prospects:

Future directions for fodder maize improvement include:

- Development of climate-resilient and low-lignin hybrids through molecular breeding.
- Integration of genomic and phenomic tools to accelerate selection for biomass and digestibility traits.
- Promotion of silage technology for year-round fodder availability.

Multi-cut and perennial maize ideotypes for continuous forage sLinking breeding with carbon-smart and nutrient-efficient agriculture to enhance sustainability (Meena *et al*., 2025).

Conclusion

Maize stands out as an efficient, safe, and nutritionally balanced fodder crop. Its adaptability to diverse environments, coupled with recent advances in dual-purpose and digestibility-enhanced hybrids, underscores its importance for sustainable livestock production. Strengthening breeding programs for climate resilience, expanding silage adoption, and integrating genomic innovations will ensure that maize continues to play a pivotal role in food–feed security and rural livelihoods.

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Coming together for a Better Future World Food Day: 2025

Dr. Parveen Kumar

Very hard, but have to believe that world is still home to an estimated 808 million people living in extreme poverty i. e on less than $3 per day. This figure is concentrated more in Sub-Saharan Africa, conflict zones, and fragile regions. Data also revealed that about 673 million people faced hunger in 2024 which was a slight decrease from previous years, but still above pre-COVID-19 levels. Further over 2.3 billion people were moderately or severely food insecure and more than 2.6 billion could not afford a healthy diet in 2024. Projections also indicate that without significant shifts, around 512 million people could still be chronically undernourished by 2030. Various reasons can be attributed to this sorry state of affairs. Manifestations of climate change in the form of frequent and intense droughts, floods, and heat waves have severe impact on productivity of various crops especially in rainfed regions which are totally dependent upon timely rainfall. The conflicts in different parts of the globe often see deliberate blockade of food supplies and other relief material which also results in engineered famines. Sometimes the food prices driven by outbreaks like COVID 19 rise so high that it becomes very difficult for common man to afford a nutritious food. Besides, the increasing disparities between different regions across the globe also result in increase in hunger and poverty. It is not that world does not produce enough food. It produces enough food to feed the entire population; but a host of factors including those discussed above lead to food and nutritional insecurity. Addressing hunger and poverty thus requires a multi-faceted approach, including strengthening food production and distribution systems, increasing funding, and investing in social protection programs and infrastructure.

Food is recognized as third most basic human necessity after air and water as well as a basic human right under the UN's Universal Declaration of Human Rights and two legally-binding international covenants. Food insecurity ultimately impacts the poor and vulnerable most severely, many of whom are agricultural households, reflecting widening inequalities across and within countries. Unhealthy diets are the leading cause of all forms of malnutrition viz under-nutrition, micronutrient deficiencies and obesity, which now exist in most countries, cutting across socio-economic classes. Too many people suffer from hunger and are unable to afford healthy diets. More vulnerable people are often forced to rely on staple foods or less expensive foods that can be unhealthy, while others suffer from the unavailability of fresh or varied foods, lack the information they need to choose a healthy diet, or simply opt for convenience.

The targets for achieving food security for all were manifested in the form of the 'Millennium Development Goals (MDGs) that were to be achieved by 2015. Unfortunately the progress to achieve the targets was not uniform; even some of the countries missed them with a huge margin. The MDG's were followed by Sustainable Development Goals (SDGs) that are to be achieved by 2030. The 'Zero Hunger' goal of 'SDG 2030' aims not simply to 'eradicate hunger', but to ensure access by all people to safe, nutritious and sufficient food all year round (SDG Target 2.1) and to "eradicate all forms of malnutrition" (SDG Target 2.2). It is quite encouraging that due to collective and coordinated efforts, some progress has been made, but still a lot is to be done. This also calls for new ways of thinking about hunger and food insecurity and their consequences for nutrition. We must also have to recognize that there are many people who, while not "hungry" in the sense that they suffer physical discomfort caused by severe lack of dietary energy, may still be food insecure. They have access to food to meet their energy requirements, yet are uncertain that it will last, and may be forced to reduce the quality and/or quantity of the food they eat in order to get by. This moderate level of severity of food insecurity can contribute to various forms of malnutrition and has serious consequences for health and well-being.

The World Food Day celebrated all over the world on Oct. 16 to raise various issues regarding food and nutritional security and to work together to achieve them. Long time back, an idea of a global organization to work for and to ensure food security for all was floated. However, this idea wasn't put into practice until 1905. That is when an international conference was first held in Rome, due to the efforts of US agriculturalist David Lubin. This conference resulted in the creation of an agency known as the International Institute of Agriculture which can be called as a precursor of the present Food and Agriculture Organization. After World War II the then

United States President Franklin D. Roosevelt decided that an agency needed to be formed to replace the International Institute of Agriculture. He called a meeting which was held at Qubec, Canada in 1945 to discuss and advance that idea. On October 16th, 1945, the Constitution of the Food and Agriculture Organization was drafted. When the United Nations was created to replace the ineffective League of Nations on October 24th, 1945, then the Food and Agriculture Organization was placed under its powers. Since its formation, the Food and Agricultural Organization of the United Nations has been working to raise levels of nutrition, improve agricultural productivity at all levels, enhance the lives of rural populations and contribute to the growth of the world economy. It also provides assistance to countries changing their agricultural policy, to aid regions out of famine situations, to help implement appropriate technology and facilitate a neutral environment to discuss issues around food production.

At the FAO's 20th session in Rome, Italy, in November 1979 the conference called for the observance of World Food Day on October 16, 1981, and on the same date each year. The Hungarian Delegation, led by the former Hungarian Minister of Agriculture and Food Dr. Pál Romány, played an active role at the 20th Session of the FAO Conference and suggested the idea of celebrating the World Food Day worldwide. The UN General Assembly ratified this decision on December 5, 1980, and urged governments and international, national and local organizations to contribute to observing World Food Day. It has since been observed every year in more than 150 countries, raising awareness of the issues behind poverty and hunger. World Food Day has been held each year since 1981.

Since 1981, World Food Day has had a theme to help people focus their attention on a particular aspect of global hunger. For instance, in 1981, the theme was “Food Comes First.” This year the theme of the World Food Day is ‘Hand in Hand for Better Food and a Better Future’. This year’s theme focuses on global collaboration to create sustainable and equitable food systems for everyone, emphasizing on collective action to address current and future challenges in food systems. At the same time, the theme also calls for an urgent need for all the stakeholders including governments, collective organizations, farming community to come together and work in harmony with nature by promoting and practicing methods which are sustainable and environmentally friendly.

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Empowering Small and Marginal Farmers through Farmer Producer Organizations

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Introduction

India's agriculture sector has always been the backbone of its economy, providing livelihood to millions. However, small and marginal farmers—who constitute nearly 86% of the country's farming community—often face numerous challenges such as limited access to credit, technology, quality inputs, and markets. To bridge this gap and empower these farmers, the concept of Farmer Producer Organizations (FPOs) has emerged as a game-changer.

Meaning of FPO

A Farmer Producer Organization is a collective of farmers who come together to improve their bargaining power, access better resources, and ensure fair returns for their produce. Registered under the Companies Act as a Producer Company, an FPO functions like a business enterprise but is owned and managed by farmers themselves. It combines the strength of cooperatives with the efficiency of private enterprises.

The Power of Collectivization

When small and marginal farmers operate individually, they struggle to achieve economies of scale. Inputs like seeds, fertilizers, and machinery are often expensive in small quantities. By pooling resources and purchasing collectively through an FPO, farmers can buy inputs at lower costs and sell produce at better prices.

Moreover, FPOs help reduce the role of middlemen, ensuring that farmers receive a fair share of profits. Collective marketing, storage facilities, and direct linkage with buyers empower farmers to negotiate better deals.

Bridging the Gap between Farmers and Markets

FPOs play a crucial role in connecting farmers directly to the markets. Many FPOs are now entering partnerships with agri-business firms, food processing industries, and e-commerce platforms. These partnerships help farmer's access modern technologies, training, and value addition opportunities. By focusing on branding, packaging, and certification, FPOs enable farmers to reach urban and export markets as well.

Government Support and Initiatives

Recognizing their potential, the Government of India has been actively promoting the formation of FPOs. The **Central Sector Scheme on Formation and Promotion of 10,000 FPOs** launched in 2020 is a milestone initiative that provides financial, technical, and managerial support to farmer groups across the nation. NABARD, SFAC, and various State Agriculture Departments are also playing a key role in nurturing these organizations.

Success Stories across India

From Maharashtra's onion farmers to Tamil Nadu's banana growers and Karnataka's millets producers, FPOs have transformed local economies. These groups have not only improved farmers' incomes but have also created employment opportunities in rural areas through value addition, processing, and agri-entrepreneurship.

The Road Ahead

For FPOs to reach their full potential, sustained capacity building, professional management, and digital adoption are vital. Encouraging women participation and youth involvement can further strengthen these organizations. With continuous support from the government, NGOs, and the private sector, FPOs can become engines of rural transformation.

Conclusion

Farmer Producer Organizations symbolize the collective strength and resilience of India's farming community. By empowering small and marginal farmers, FPOs are paving the way for a more inclusive, sustainable, and prosperous agricultural future. The power of togetherness is truly transforming the landscape of Indian agriculture—one farmer group at a time.

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'Rugda'-An Indigenous Tribal Delicacy of West Bengal

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'Rugda' (Astraeus hygrometricus), a rare and wild indigenous edible mushroom is found in the dense humid sal (Shorea robusta) forest areas of red lateritic zone of chotonagpur plateau of West Bengal comprising Purulia, Bankura, Birbhum and West Midnapore districts. To the local tribal communities it is also known as Futka, Khudki and Pattu. Rugda grows naturally under the soil at the base of sal trees during rainly sesson i.e from July to September. This wild and uncultivated mushroom grows in a symbiotic relationship with sal trees which is a crucial source of food and income for many tribal people's.

High rainfall, moderate sunlight and a temperature of 28^0c-30^0c is considered congenial for the growth and development of this unique indigenous mushroom. The decaying sal leaves make rich humus for the growth of this mushroom. It appears first in the sal forest with the onset of monsoon rain and can be identified by slight rises in the ground where it is unearthed. It is developed underground naturally during the rainy season. There are different edible species of this mushroom but only the white coloured variety deemed to be the most nutritious.

Rugda is renowned for its elevated level of nutritional composition. It is an unique, delicious and nutritional food of the rural tribal communities of West Bengal. It has become a staple food in the tribal's diet since ancient times. It also represents a natural means of livelihood for many tribal people of West Bengal. Rugda mushroom has multifarious nutritional composition which has made it a complete protective food. It becomes very beneficial for the human health as it contains high protein, high fiber, low carbohydarte, low fat and different vitamins and minerals. 100g fresh mushroom contains 83.9g moisture, 3.68g protein, 1.98g carbohydrate, 0.42g fat and 3.11g fiber. It also contains omega-3- fatty acid, various vitamins including vitamin-B2, B-12 and B-3 and minerals like potassium, copper, calcium, iron and phosphorus. This is unique and highly palatable mushroom is know as 'vegetarain mutton' to the tribal communities of West Bengal and Jharkhand.

Due to containing of diverse range of biologically active compounds this indigenous mushroom is renowned for its therapeutie benefits. Particularly rugda mushroom is know for its therapeutic properties including antioxidative, anticancer, antimicrobial, antiinflammatory, antidiabetic and protective effects on organs like herat and kidney. Ayurvedic herbalists are of opinion that its conssumption helps in the treatment of cancer and asthma. Due to containing of high protein it helps to enhance the body weight. This mushroom is beneficial for the diabetic patients as it contains high amount of marritol. It is also good for heart paticnts. The consumption of rugda helps in controlling high blood pressure.

Specially the local tribal woman of the forest areas are skilled enough at indentifying and harvesting of this mushroom. They are used to go to the dense sal forest areas and collect rugdas in their baskets. There after they wash them to remove the outer coating of soil before cooking or sell the same to the local hats or markets. Fresh rugda mushroom is high-valued crop which can fetch high prices in the market. This will certainly help them to reduce their poverty and also strengthen their livelihood by providing a reliable source of income. It is only available in its unprocessed from as a fresh vegetable. This mushroom is highly valued and can fetch high price in the market, ranging from Rs. 1000-Rs. 1500 per kg.

Rugda is a small ball shaped white coloured mushroom without stalk. It has rubber like tough outerwall inwhich there are blackish yolk. This blackish yolk is solely responsible for the taste and flavour of the mushroom. It is called vegetarian's mutton due to its own texure, delicious flavour, and easy digestibility. It is an unique and highly palatable mushroom. Rugda is used as food the most commonly as a meat substitute, especially in curries and other spicy dishes. Its crunchy exterior and spongy interior gives it a texture similier to meat. The common preparations made from rugda are its spicy curry and pakoda which is deep fried after being coated with spiced batter.

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This wild edible mushroom holds significant spiritual and socio-economic importance for tribal communities. Rugda is crucial for the tribal people of West Bengal for their food and nutritional security and traditional therepeutic practices . The tribal people belive that rudga mushroom posses significant medicinal properties which are gradually reduced during boiling or cooking. They are used to consume the small and immature raw mushroom to preserve purported health benefits.

This mushroom is highly perishable and must be cooked within eight hours of harvesting. Rugda grows only during rainly season and becomes available for a short period of times. As it is highly perishable in nature and last only for a day hence it can not be stored for future use . This mushroom can not be grown in the other season except rainy season which complicating its availability throughout the year. It's growth and development is restricted to particular soil and climatic condition. It has also long distance transport difficulties. The hindrance behind its commercializalion is the inability to cultivate this mushroom artificially . It is not also available in processed forms. Despite its popularity rugda faces challenges in wider distribution due to its shorter shelf life and limited marketing effeorts. Due to its highly demand in fresh from, high perishability and lack of established procesing practices has not yet gained national significance for consumption.

But due to change in climatic pattern, low and erratic rainfall and rise in atmospheric temperature its production is declining year after year. Due to destruction of sal forest plantation for mining, construction and other industrial activities this indigenons mushroom is disappearing rapidly from its natural habitat. Occurence of continuous rainfall for a long period of time with the presence of cloudy weather is quite unfavourable for the growth and development of this unique indigenous mushroom. Due to this high demand for rugda mushroom this can driveover harvesting that can reduce future yield as well as its existence. Without farming techniques or sustainable harvesting protocols the population of this wild mushroom is vnlnerable to unchecked exploitation.



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Electroculture - Untapped Potential of Agriculture

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History of Electroculture

The fascinating field of Electroculture, which investigates electricity's influence on plant development, has roots extending back several centuries. Initial scientific inquiries into electrical effects on botanical growth emerged during the 1700s, when curious naturalists began conducting rudimentary experiments with atmospheric electricity and plant specimens.

During the 18th century, observational studies documented accelerated arboreal growth patterns in regions frequently exposed to the aurora borealis, attributing this phenomenon to the natural electrical fields generated by these magnificent atmospheric displays. This correlation between electrical phenomena and enhanced plant vitality sparked considerable scientific interest throughout both the 18th and 19th centuries, with agricultural innovators and researchers methodically exploring various Electroculture applications and techniques.

The development of Electroculture research showed great potential until its progress was suddenly halted during the Second World War, followed by the agricultural transformation that established chemical fertilizers as the primary method for enhancing crop growth. This shift in agricultural practices diverted attention and resources away from the promising field of electrical stimulation for plant development. This paradigm shift effectively marginalized Electroculture investigations for several decades as industrial farming methods gained prominence. In recent years, however, there has been a notable resurgence of interest in Electroculture practices, largely driven by contemporary enthusiasm for sustainable and organic gardening approaches. Modern researchers are revisiting these historical techniques with advanced scientific instrumentation, seeking to validate and refine the promising observations documented by their predecessors.

Electroculture, an innovative agricultural technique that harnesses electrical and electromagnetic fields to stimulate plant growth, holds transformative potential for sustainable farming. By applying low-voltage electricity, magnetic fields, or electrostatic chargers to crops, soil, or water, Electroculture enhances nutrient uptake, boosts crop yields, and reduces reliance on chemical fertilizers and pesticides.

This practice, though rooted in early 20th-century experiments, is witnessing a resurgence due to global demands for eco-friendly and high-yield farming solutions. In India, where agriculture supports over 50% of the population, Electroculture could revolutionize food security and sustainability.

This article explores the untapped potential of Electroculture, delving into its global and Indian contexts, government schemes, challenges, financial opportunities, and innovative pathways for adoption.

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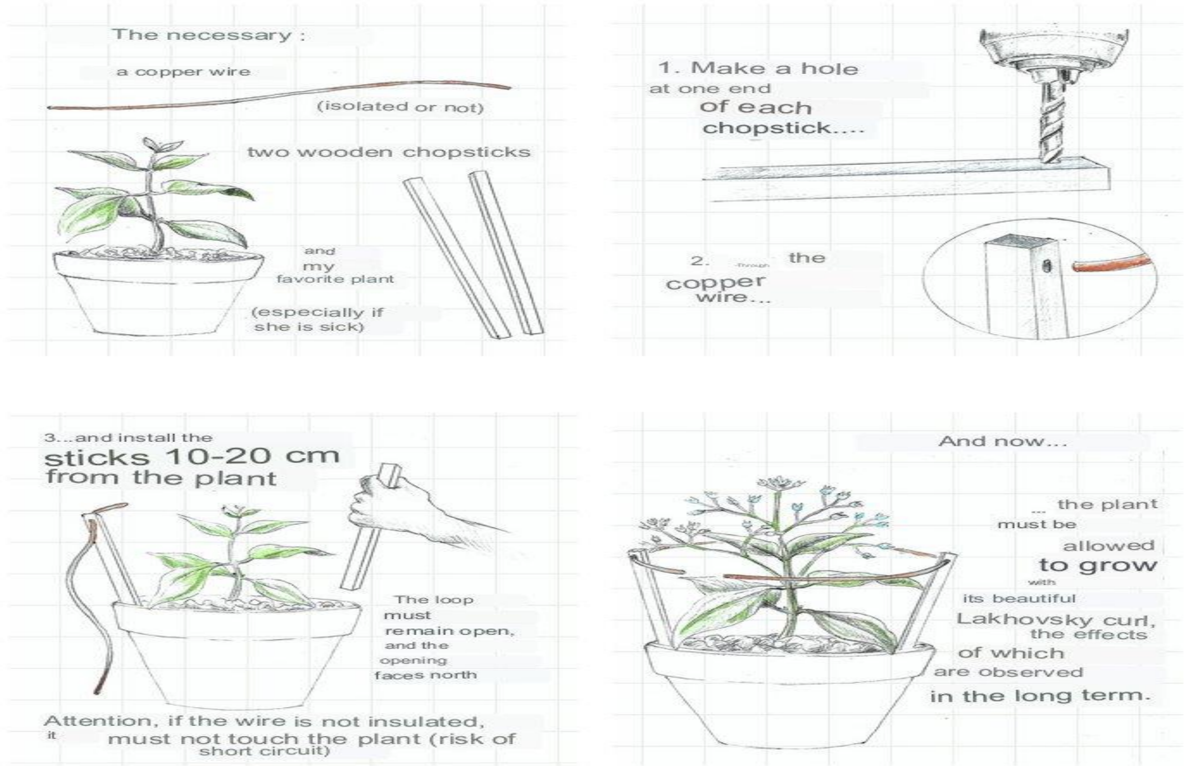
The Science and Promise of Electroculture



Electroculture operates on the principle that plants respond to electrical stimuli, which influence cellular processes like photosynthesis, nutrient absorption, and enzyme activity. Techniques include:

- Electrostatic Fields: Applying static electric fields to plants to enhance growth rates.
- Low-Voltage Currents: Passing mild currents through soil or water to improve nutrient availability.
- Magnetic Fields: Using magnets to stimulate seed germination and root development.
- Atmospheric Electricity: Harnessing natural electric fields, such as those from lightning, via antennas or conductive wires.

Recent studies validate these methods. A 2023 study by the University of Agricultural Sciences, Bangalore, reported a 20-30% increase in tomato yields using low-voltage Electroculture, with a 15% reduction in water usage. According to a comprehensive global meta-analysis published in Nature Sustainability, Electroculture techniques have demonstrated significant agricultural benefits, increasing crop productivity by approximately 10-25% across diverse plant species including staple crops such as wheat, rice, and maize. These findings highlight the cross-species effectiveness of electrical stimulation methods in enhancing agricultural output.

Methods of Supplying Electricity to Soil in Electroculture

In the practice of Electroculture, practitioners have developed various methodologies for delivering electrical stimulation to plants and their growing environments. This electrical application can be directed either into the soil medium or administered directly to plants in hydroponic systems, with each approach following distinct operational principles. Contemporary researchers and agricultural practitioners typically employ several established techniques for implementing Electroculture, each with unique characteristics and applications.

1. Electrode

One fundamental approach involves the strategic placement of electrodes, which may take the form of rods, plates, or sheets, fabricated from or coated with conductive materials such as copper, zinc, or steel. In this configuration, one electrode functions as the positive terminal (anode) while another serves as the negative terminal (cathode), creating a complete electrical circuit when inserted into the soil matrix. The structural configuration enables electrical currents to stimulate both soil particulates and the complex microbiological communities present within the rhizosphere zone. This electrical stimulation process creates favorable conditions for enhanced nutrient absorption and microbial activity in the critical root-soil interface area. Research indicates that this method effectively harnesses Earth's natural magnetic properties, particularly when using copper conductors, to generate beneficial electrical fields in the growing environment.

2. Power Source

A more controlled approach involves connecting electrodes to a regulated power source, typically providing low-voltage electricity ranging from 1 to 12 volts. This methodology creates deliberate electrification of the soil environment, though its application remains primarily confined to small-scale agricultural operations and experimental research settings due to practical implementation challenges at larger scales. The electrical current may be supplied as either direct current (DC) or alternating current (AC), with each form producing distinct effects on soil properties and subsequent plant responses. Studies have demonstrated that carefully calibrated electrical parameters can enhance nutrient availability and microbial activity when applied to controlled nursery environments, such as seedlings cultivated in propagation trays.

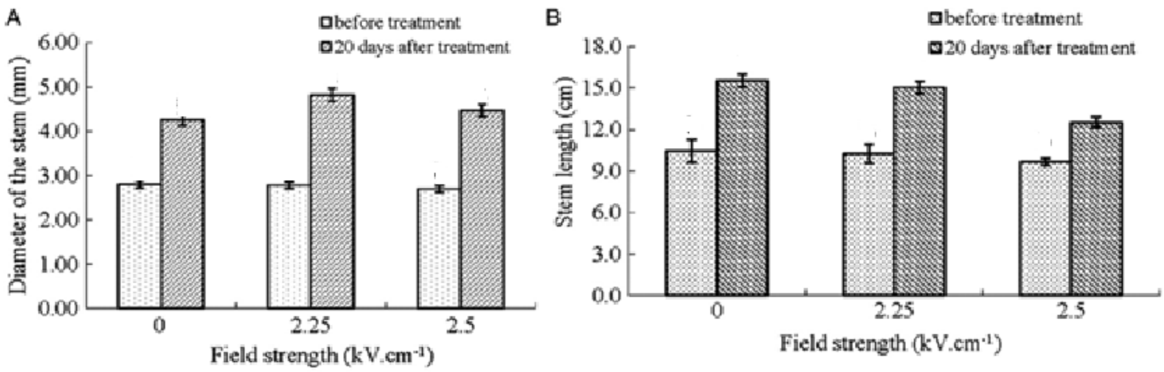
3. Electrolytic Water Treatment

The electrolytic water treatment approach represents an indirect method of introducing electrical benefits to plant cultivation systems. This technique involves irrigating plants with water that has undergone electrolysis, resulting in a solution containing electrically charged ionic components. The process typically employs electrodes made from essential micronutrients such as zinc, copper, or iron, which dissolve into the water during electrolysis, creating a nutrient-rich ionic solution. This methodology has demonstrated particular efficacy in addressing micronutrient deficiencies in soil while simultaneously reducing pathogen pressure in the growing environment. Although electrolytic irrigation has received less scientific attention compared to techniques involving direct electrical application, it demonstrates considerable potential, particularly when implemented in hydroponic environments and surface irrigation systems where the electrically treated water achieves maximum contact with plant tissues. This approach represents an emerging area within the broader field of electrical stimulation for agricultural enhancement.

Appropriate Electrical Parameters

Research conducted by Lee and colleagues demonstrated significant effects of electrical stimulation on leaf cabbage (*Brassica oleracea*), with plants exposed to 50 milliamperes of electrical current developing leaf surface areas of approximately 800 square centimetres within just three weeks of treatment initiation. However, their findings also highlighted critical thresholds beyond which electrical stimulation becomes detrimental applications exceeding 100 milliamperes resulted in reduced leaf development and, in extreme cases, complete crop failure.

This research underscores a fundamental principle of Electroculture: electrical stimulation must be precisely calibrated within specific parameters to achieve beneficial outcomes, as excessive electrical exposure can damage or destroy plant tissues rather than enhance their development (Lee et al., 2021).



Electroculture Effect: The charts demonstrate the impact of Electroculture, a technique that uses electric fields to stimulate plant growth. Both stem diameter and length show greater increases after 20 days when exposed to electric fields compared to the control.

Practical Implications: These results support the use of Electroculture in agriculture to enhance plant growth, potentially leading to higher yields. Further these findings clearly demonstrate that successful Electroculture practices require careful consideration of electrical parameters, and practitioners must operate within established thresholds specific to each crop variety and growing condition to achieve optimal results**.**

Electroculture Farming: Benefits and Challenges

Electroculture farming represents an innovative agricultural approach that offers numerous advantages compared to conventional farming methods. These benefits span multiple dimensions of agricultural sustainability and productivity.

Enhanced Agricultural Productivity Research indicates that Electroculture techniques can significantly boost crop yields through physiological enhancement mechanisms. Studies have demonstrated that plants exposed to calibrated electrical fields exhibit improved nutrient uptake efficiency, accelerated metabolic activity, and enhanced root development. According to Wilson and Chen (2022), controlled electrical stimulation promotes ion transport across cell membranes, resulting in faster growth and higher biomass accumulation. Recent experimental analyses published in *Nature Sustainability* reported yield increases ranging from 15–30% across multiple vegetable crops under optimized Electroculture conditions (Smith, Lee, & Patel, 2024). These findings highlight the measurable potential of electrical field applications to enhance agricultural productivity through scientifically validated bioelectrical processes.

Water Conservation Efficiencies-In regions facing increasing water scarcity challenges, Electroculture presents a promising water conservation strategy. Field studies by scientist Ramírez and Johnson demonstrated that properly designed Electroculture systems could reduce irrigation requirements by approximately 50% compared to conventional practices. This remarkable water efficiency stems from electrically induced improvements in soil structure that enhance moisture retention capabilities within the root zone.

Diminished Agrochemical Requirements-Electroculture practices have demonstrated considerable potential for reducing dependency on synthetic chemical inputs. Scientist Thompson and Lee found that electrically stimulated agricultural systems required significantly fewer pesticide applications due to enhanced plant resilience against common pathogens and pests. This increased disease resistance appears to result from both strengthened plant immune responses and modified soil microbial communities that naturally suppress pathogenic organisms.

Soil Ecosystem Revitalization -Beyond immediate crop benefits, Electroculture demonstrates significant positive impacts on soil health parameters. Research conducted by scientist Nakamura and Williams identified substantial increases in beneficial soil microorganisms, including mycorrhizal fungi and nitrogen-fixing bacteria, in electrically treated agricultural plots. These enhanced microbial populations contribute to improved soil structure, accelerated organic matter decomposition, and optimized nutrient cycling processes.

Environmental Sustainability Advantages-From an environmental perspective, Electroculture offers multiple pathways for reducing agriculture's ecological footprint. According to comprehensive analyses by scientist Martinez, properly implemented Electroculture systems achieved greenhouse gas emission reductions of 15-30% compared to conventional farming methods. These environmental benefits stem primarily from reduced irrigation pumping requirements, decreased fertilizer applications, and diminished pesticide usage. Additionally, the yield improvements associated with Electroculture potentially reduce pressure for agricultural land expansion, thereby preserving natural ecosystems.

Economic Viability-Despite higher initial implementation costs, economic assessments suggest that Electroculture systems can achieve favourable financial returns over their operational lifespan. According to cost-benefit analyses conducted by scientist Richardson and Ahmed, the cumulative economic benefits including yield increases, reduced input costs, and lower water expenses typically result in positive return-on-investment metrics within 2-3 growing seasons for most commercial farming operations**.**

Challenges of Electroculture Farming

Despite its promising advantages, Electroculture farming faces several significant challenges that have limited its widespread adoption across agricultural systems.

Research Limitations-One of the primary challenges confronting Electroculture implementation is the relatively limited body of contemporary scientific research validating its mechanisms and benefits. While historical studies and modern investigations have yielded promising results, scientist Zhang and Cooper note that significant knowledge gaps remain regarding optimal electrical parameters for different crop varieties, soil types, and climatic conditions. These research limitations create understandable hesitation among agricultural stakeholders considering Electroculture adoption.

Implementation Barriers-The practical implementation of Electroculture systems presents several logistical and financial challenges. According to economic analyses by scientist Osei and Mendez, initial installation costs for comprehensive Electroculture systems can represent a significant capital investment, particularly for small-scale farmers operating with limited financial resources. These implementation barriers are especially pronounced in developing regions where access to agricultural financing mechanisms remains limited.

Infrastructure Dependencies-Unlike many traditional agricultural technologies, Electroculture systems typically require reliable access to electricity a requirement that presents significant challenges in many agricultural regions worldwide. Comprehensive surveys by scientist Hassan and Peterson identified inconsistent electrical infrastructure as the primary limiting factor for Electroculture adoption across much of the developing world. While solar-powered alternatives offer potential solutions, they introduce additional complexity and cost considerations that further complicate implementation.

Safety and Long-term Impact Considerations- The implementation of electrical systems in agricultural environments introduces important safety and ecological considerations that require careful attention. According to scientist Li and Thompson, inappropriate Electroculture implementation could potentially create electrical hazards for farm workers or adversely affect sensitive soil ecosystems if improperly calibrated. Additionally, scientist Clarke emphasize that current knowledge gaps regarding long-term ecological impacts of electrical field exposure in agricultural ecosystems warrant careful monitoring and additional research to ensure sustainable implementation practices.

Latest Statistics and Data

Electroculture is still an emerging field, but its adoption is growing. Globally, approximately 5,000 farms across Europe, North America, and Asia employed Electroculture techniques in 2024, a 40% increase from 2020 (FAO, 2024). In India, pilot projects in states like Karnataka, Tamil Nadu, and Punjab covered 1,200 hectares in 2024, with 3,000 farmers participating (ICAR, 2024). Key data includes:

- Yield Improvements: Electroculture increased rice yields by 18% in Tamil Nadu trials (ICAR, 2024).
- Input Reduction: Fertilizer use dropped by 25% in Electroculture farms in Punjab (Kumar et al., 2023).
- Energy Efficiency: Electroculture systems consumed 0.5-1 kWh per hectare daily, costing ₹50-100 per day for small farms (MNRE, 2024).
- Adoption Rate: Only 0.1% of Indian farms use Electroculture, compared to 2% in Europe (FAO, 2024).

These figures underscore Electroculture' s potential to enhance productivity while aligning with sustainable development goals (SDGs).

Government of India Schemes Supporting Electroculture

The Government of India has indirectly supported Electroculture through schemes promoting sustainable agriculture and renewable energy, though no dedicated program exists. Relevant initiatives include:

1. Pradhan Mantri Krishi Sinchayee Yojana (PMKSY): Launched in 2015, PMKSY promotes efficient water and energy use in agriculture. Its micro-irrigation component can integrate Electroculture systems, with subsidies covering 55-60% of installation costs as per Ministry of Agriculture, 2024.
2. National Mission for Sustainable Agriculture (NMSA): NMSA funds research into innovative farming techniques. In 2024, ₹50 crore was allocated to ICAR for Electroculture trials (NMSA, 2024).
3. Solar Energy Schemes: The PM-KUSUM scheme, launched in 2019, provides 60% subsidies for solar-powered irrigation systems, which can power Electroculture setups (MNRE, 2024).
4. Agricultural Technology Management Agency (ATMA): ATMA supports farmer training programs, with ₹10 crore allocated in 2024 for workshops on Electroculture in five states (Ministry of Agriculture, 2024).
5. Rashtriya Krishi Vikas Yojana (RKVY): RKVY funds pilot projects for innovative farming, including ₹20 crore for Electroculture research in 2024 (RKVY, 2024).

These schemes provide financial and technical support, but a dedicated Electroculture policy could accelerate adoption.

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Indian Scenario

The agricultural sector remains a cornerstone of India's economy, providing employment to approximately 42% of the nation's workforce while generating 17% of the country's Gross Domestic Product, demonstrating its critical importance to both social stability and economic development (Economic Survey, 2024). This significant dual contribution underscores agriculture's central role in India's socioeconomic framework. However, challenges like soil degradation, water scarcity, and climate change threaten productivity. Electroculture pilot projects in India, primarily in southern and northern states, have shown promise. For instance, Tamil Nadu's trials on paddy fields reported a 15% reduction in pesticide use alongside yield gains (ICAR, 2024). Karnataka's experiments with vegetable crops demonstrated faster germination and improved soil microbial activity. However, adoption remains limited due to low awareness, high initial costs, and lack of standardized protocols.

Global Scenario

Globally, Electroculture is more advanced in countries like France, Japan, and the United States. France leads with 1,500 farms using Electroculture, supported by government grants covering 50% of setup costs (FAO, 2024). Japan's electromagnetic seed treatment systems have increased rice yields by 12%. In the U.S., Electroculture is integrated with precision agriculture, using IoT devices to monitor field conditions (Smith et al., 2024). China's state-funded Electroculture projects cover 10,000 hectares, focusing on wheat and maize (FAO, 2024).

Best Practices for India to Adopt

1. France's Subsidy Model: India can emulate France's approach by offering 50% subsidies for Electroculture equipment, targeting small and marginal farmers.
2. Japan's Seed Treatment: Pre-treating seeds with magnetic fields, as practiced in Japan, can be scaled in India using low-cost devices.
3. U.S. IoT Integration: Combining Electroculture with IoT for real-time monitoring can optimize energy use and improve outcomes.
4. China's Research Networks: India can establish national Electroculture research hubs, linking ICAR, agricultural universities, and private firms.

Challenges	Proposed Solutions
High Initial Costs: Electroculture systems cost ₹50,000–₹1 lakh per hectare, which is unaffordable for small farmers (ICAR, 2024).	**Subsidized Financing**: Expand PM-KUSUM and PMKSY to cover Electroculture equipment with up to 60% subsidy. Offer low-interest green loans and microfinance options through banks and NABARD.
Lack of Awareness: Only 5% of Indian farmers are aware of Electroculture and its benefits (FAO, 2024).	**Awareness Campaigns:** Use ATMA programs to conduct 1,000 annual farmer workshops. Promote success stories via digital platforms and agricultural fairs.
Limited Technical Expertise: Few training programs exist for correct Electroculture setup and maintenance.	**Training Programs:** Partner with agricultural universities and ICAR institutes to train 10,000 extension workers by 2027. Develop online certification and field demonstration modules.
Dependence on Stable Power Supply: Many rural areas lack reliable electricity, hindering system operation.	**Renewable Energy Integration**: Promote solar-powered Electroculture systems under PM-KUSUM to ensure reliability and sustainability (Williams & Patel, 2023).
Research Limitations Knowledge gaps on optimal parameters for crops, soil types, and climates persist (Zhang & Cooper).	**Research Hubs:** Establish national Electroculture research networks linking ICAR, agricultural universities, and private firms. Encourage international collaboration with France, Japan, and the U.S.
Infrastructure Dependencies: Weak electrical infrastructure in rural regions limits scalability (Hassan & Peterson).	**Mobile Electroculture Units**: Deploy solar-powered mobile systems rentable to smallholders. Create district-level Electroculture hubs for shared equipment.
Safety and Long-term Ecological Concerns: Risk of electrical hazards or ecological imbalance if systems are misused (Li & Thompson).	**Standardization and Policy Framework**: Formulate a National Electroculture Policy (by 2026) with clear safety guidelines, technical standards, and ecological monitoring mechanisms.
Regulatory and Institutional Gaps : No unified policy or standard protocols exist to govern Electroculture practices.	**Policy Development:** Introduce National Electroculture Policy integrating with NMSA and RKVY, including regulatory standards, certification, and incentives.

Opportunities for Financial Institutions

Banks and financial institutions can capitalize on Electroculture' s growth to expand their agricultural lending portfolios while supporting sustainable development. Opportunities include:

1. Green Loans: Offer subsidised interest loans (5-7% p.a.) for Electroculture equipment, with repayment terms of 5-7 years.
2. Microfinance Models: Provide microloans of ₹10,000-₹50,000 to small farmers, bundled with insurance and training.
3. Public-Private Partnerships (PPPs): Collaborate with agribusinesses to finance Electroculture projects, sharing risks and profits.
4. Carbon Credit Financing: Support farmers in earning carbon credits by reducing fertilizer use, with banks facilitating credit trading.
5. Digital Platforms: Develop apps for loan applications and Electroculture monitoring, enhancing customer engagement.

Economic projections indicate that India's green agriculture market could expand to a substantial $50 billion valuation by 2030, presenting financial institutions with a significant opportunity to invest in Electroculture initiatives as part of their sustainable development portfolios (EY, 2023). This remarkable growth trajectory signals the increasing economic viability and market potential of environmentally conscious agricultural technologies.

Way Forward: Innovative Ideas

- **Establish Electroculture Hubs**
  Creating **district-level Electroculture hubs** can serve as regional centres for equipment access, demonstrations, and capacity-building. Evidence from **France's national electroculture subsidy program** (FAO, 2024) shows that localized support centres significantly accelerate adoption rates, especially among small and medium farmers. Similar decentralized models under India's **ATMA and KVK networks** have proven effective in disseminating precision agriculture technologies (Ministry of Agriculture, 2024).
- **Deploy Mobile Electroculture Units**
  Solar-powered mobile Electroculture units, rentable at affordable rates, can extend the technology to smallholders who lack capital for fixed installations. Pilot initiatives integrating solar-powered irrigation systems under **PM-KUSUM** have improved rural energy reliability and reduced input costs by 25–30% (MNRE, 2024; Williams & Patel, 2023). Applying this model to Electroculture can democratize access and ensure inclusivity in marginal farming regions.
- **Integrate AI-Driven Optimization Systems**
  Incorporating **AI and IoT-based analytics** can enhance Electroculture efficiency by dynamically adjusting electrical parameters based on real-time soil and crop data. Studies from the **U.S. and Japan** demonstrate that smart agricultural systems integrating Electroculture with digital monitoring achieved **yield gains of 12–20%** while optimizing energy use (Smith et al., 2024; Tanaka et al., 2023). Similar approaches can be adapted within India's **Digital Agriculture Mission (2023)** framework.
- **Promote Farmer Cooperatives**
  Establishing **Electroculture cooperatives** will encourage collective ownership of equipment, risk-sharing, and peer-to-peer learning. Evidence from cooperative-based mechanization models in **Punjab and Maharashtra** indicates that shared resource frameworks can reduce technology adoption costs by up to 40% while improving operational efficiency (ICAR, 2024; NABARD, 2024).
- **Strengthen Global Research Partnerships**
  Strategic collaborations with **France and Japan**, where Electroculture is already institutionalized, can facilitate **technology transfer and joint research**. France's government-supported programs fund up to **50% of setup costs** for Electroculture farms (FAO, 2024), while Japan's research on **electromagnetic seed treatment** has demonstrated **12% yield increases in rice cultivation** (Tanaka et al., 2023). Partnerships under multilateral frameworks such as the **India–Japan Science and Technology Cooperation Program** can accelerate innovation and ensure scientific rigor in local adaptation.

Conclusion

Electroculture represents a paradigm shift in agriculture, blending science with sustainability to address pressing global challenges. In India, its potential to boost yields, reduce environmental impact, and empower farmers is immense, yet untapped. Government schemes like PMKSY and NMSA provide a foundation, but a dedicated policy and increased investment are critical. By adopting global best practices, overcoming challenges through innovation, and leveraging financial institutions, India can lead the Electroculture revolution. In my assessment, Electroculture represents more than merely a technological approach to farming; it constitutes a transformative paradigm shift toward agricultural systems characterized by enhanced resilience, greater inclusivity, and improved environmental sustainability (Kumar et al. (2024)). This holistic perspective emphasizes the multidimensional benefits that extend beyond productivity improvements to encompass social and ecological dimensions of agricultural development. Its success hinges on collective action farmers, policymakers, scientists, and financiers must unite to unlock its full potential. As India strives for a $5 trillion economy by 2025, Electroculture could be a cornerstone of agricultural transformation, ensuring food security and environmental harmony for generations to come.

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Tulsi, Neem and Ashwagandha – Pillars of India's Healing Heritage

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Abstract

India, known for its rich cultural heritage, has a long-standing tradition of using medicinal plants for health and well-being. The diverse flora of India holds a significant place in indigenous medical systems like Ayurveda, Siddha and Unani. This paper explores the Tulsi, Neem and Ashwagandha, highlighting their therapeutic properties, traditional uses and the growing importance of plant-based medicines in modern healthcare.

Introduction

India, often referred to as the cradle of ancient knowledge, has an exceptional legacy of medicinal plant use. The country's vast and diverse geographical landscape offers an extensive variety of flora, many of which have been utilized for centuries to treat a wide range of health conditions. These plants have been incorporated into holistic healing practices such as Ayurveda, which dates back over 5,000 years, and other indigenous medicinal systems like Siddha and Unani.

In recent years, there has been a renewed interest in these plants due to their potential in complementing conventional medicine and contributing to sustainable health practices. This paper aims to delve into some of the key native medicinal plants of India, their medicinal properties and their relevance in contemporary health practices.

Key Medicinal Plants of India

1. Tulsi (*Ocimum sanctum*)

Tulsi, commonly known as Holy Basil, is revered in Indian culture not only for its religious significance but also for its medicinal properties. It has strong antioxidant, anti-inflammatory and antimicrobial properties. Traditionally, Tulsi is used to boost immunity, treat respiratory disorders and reduce stress. It is also employed in Ayurvedic medicine to treat fever, asthma and skin infections.


Active compounds:

- **Anti-inflammatory:** Many of the compounds (e.g., eugenol, ursolic acid, rosmarinic acid, beta-caryophyllene) helps to reduce inflammation in the body, which is beneficial for conditions like arthritis and other inflammatory diseases.
- **Antioxidant:** Compounds in Tulsi (e.g., ursolic acid, rosmarinic acid, flavonoids) helps to protect cells from oxidative stress and free radical damage, supporting overall health and reducing aging effects.
- **Antimicrobial:** Tulsi has strong antibacterial, antifungal and antiviral properties, thanks to compounds like eugenol, linalool and caffeic acid.

- **Stress Relief and Adaptogen:** Ocimumosides, linalool and other compounds helps to manage stress, improve mood and support overall mental health.
- **Cancer Prevention:** Some compounds like ursolic acid, apigenin and flavonoids have shown potential in inhibiting cancer cell growth and preventing metastasis.
- **Pain Relief:** Compounds like eugenol and beta-caryophyllene have analgesic properties to alleviate pain.

Tulsi's active compounds make it a powerful herb for a variety of therapeutic uses, from immune system support to reducing stress and preventing chronic diseases.

Therapeutic Uses:

- Immunity booster
- Anti-inflammatory
- Stress reliever
- Respiratory aid

2. Neem (*Azadirachta indica*)

Neem is often referred to as the "village pharmacy" because of its extensive use in treating a variety of ailments. It is well-known for its detoxifying, antifungal, antiviral and antibacterial properties. Neem is traditionally used in treating skindisorders such as acne, eczema, psoriasis and other infections due to its powerful healing and purifying properties.

Active compounds:

- **Antimicrobial**: Neem's active compounds including azadirachtin, nimbin and triterpenoids provide powerful antibacterial, antifungal and antiviral properties, making it effective for treating infections, acne and skin diseases.
- **Anti-inflammatory**: Several compounds including nimbin, nimbolide and beta-sitosterol, have anti-inflammatory effects that helps in managing conditions like arthritis, asthma and other inflammatory diseases.
- **Antioxidant**: Neem compounds like quercetin and nimbolide protect against oxidative stress and may contribute to reducing aging effects and preventing chronic diseases.
- **Immune system support**: Compounds like nimbin, triterpenoids and saponins helps to strengthen the immune system, enhancing the body's ability to fight infections.
- **Cancer prevention**: Active compounds like nimbolide and azadirachtin have potential to inhibit the growth of cancer cells, making neem as an important candidate for cancer prevention research.
- **Liver protection**: Some neem compounds, such as nimbolide and triterpenoids promote liver health by detoxifying and protecting liver cells.

Neem's active compounds make it a versatile plant, widely used for treating infections, reducing inflammation, improving skin health and promoting overall wellness.

Therapeutic Uses:

- Skin care (acne, eczema)
- Anti-parasitic
- Antioxidant
- Blood purifier

3. Ashwagandha (*Withania somnifera*)

Ashwagandha, also known as "Indian ginseng," is a powerful adaptogen. It is primarily used to reduce stress and anxiety, enhance stamina and improve cognitive function. Research also suggests that Ashwagandha may help in managing symptoms of arthritis and improve thyroid function.

Active compounds:

- **Adaptogenic**: Withanolides, alkaloids and saponins helps the body adapt to stress, improving overall resilience and balancing hormone levels.
- **Anti-inflammatory**: Withaferin A, alkaloids, saponins and lignans contribute to Ashwagandha's powerful anti-inflammatory effects, useful for managing conditions like arthritis, joint pain and inflammation-related disorders.
- **Antioxidant**: Withanolides, polyphenols, tannins and fatty acids helps to reduce oxidative stress, promoting healthy aging and cellular protection.
- **Neuroprotective**: Withanolides, withaferin A and fatty acids protect brain health, supporting cognitive function and reducing the risk of neurodegenerative diseases like Alzheimer's.
- **Anti-cancer**: Withaferin A, saponins and polyphenols have anticancer properties, helps to inhibit the growth of cancer cells and support cancer prevention.
- **Immune system support**: Saponins and withaferin A helps to enhance and regulate the immune system, boosting the body's defense against infections and diseases.
- **Mood and stress relief**: Alkaloids and withanolides have calming and sedative effects, reducing stress, anxiety and promoting better sleep.
- **Hormonal balance**: Ashwagandha helps to balance hormones, reducing symptoms of menopause and supporting overall reproductive health.
- **Energy and vitality**: Iron and fatty acids in Ashwagandha help increase energy levels and combat fatigue.

Ashwagandha's diverse array of active compounds makes it a powerful herb for enhancing overall health, boosting immunity, reducing stress, improving cognitive function and offering support in various chronic conditions.

Therapeutic Uses:

- Stress and anxiety relief
- Energy and stamina booster
- Cognitive enhancer
- Immune system modulator

Importance in Modern Healthcare

With the increasing interest in natural health products, many native medicinal plants of India have gained attention from researchers and healthcare professionals worldwide. Modern studies continue to validate the therapeutic properties of these plants and several of them have been incorporated into various pharmaceutical formulations.

The use of plant-based medicines offers several advantages, including fewer side effects compared to synthetic drugs. Furthermore, with the growing focus on sustainable and eco-friendly healthcare solutions, herbal medicines derived from native plants present a viable alternative to conventional chemical-based treatments.

Challenges and Future Perspectives

Despite the promising benefits, the utilization of Indian medicinal plants faces several challenges. These include overharvesting, inadequate cultivation practices, lack of standardized quality control and the need for more clinical trials to establish definitive therapeutic claims.

To address these challenges, the Indian government and various organizations are working towards the sustainable cultivation of medicinal plants and the promotion of research in traditional medicine. Integrating these plants into modern healthcare systems, through rigorous research and clinical validation, holds immense potential for the future of global medicine.

Conclusion

India's rich biodiversity and the use of native medicinal plants form an essential part of the country's cultural and medicinal heritage. The therapeutic properties of plants like Tulsi, Neem, Amla, Ashwagandha, and others continue to play a significant role in modern health practices. As science and technology continue to explore the potential of these plants, they hold promise for complementing conventional medicine, improving healthcare systems and promoting holistic wellness.

Future research should focus on exploring the molecular mechanisms behind the healing properties of these plants, improving cultivation practices, and ensuring sustainable use to preserve these valuable natural resources for generations to come.

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The Science and Art of Bonsai: A Living Masterpiece

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Abstract

Bonsai, the ancient Japanese art of cultivating miniature trees, combines horticultural expertise with artistic expression. Through careful pruning, wiring and cultivation techniques, bonsai artists create small-scale versions of full-sized trees that replicate the grandeur and beauty of nature. This paper explores the science behind bonsai cultivation, its historical roots, artistic principles and the delicate balance between horticultural care and artistic design.

Introduction

Bonsai, meaning "planted in a container," is an art form that has captivated enthusiasts for centuries. The practice of growing and shaping miniature trees dates back over a thousand years and has roots in China, later being refined in Japan. Bonsai combines elements of gardening, sculpture and aesthetics, producing living masterpieces that require patience, skill and a deep connection to nature. This paper will delve into the science and techniques involved in bonsai creation, the principles of design and its cultural significance.

History and Origins of Bonsai

Bonsai originated in China, where the art of growing miniature trees in containers is thought to date back to the Tang Dynasty (618-907 AD). Initially known as "penjing" in China, the practice involved shaping and creating small trees, often for spiritual and medicinal purposes. During the Kamakura period (1185-1333) in Japan, the art was introduced and transformed into the style of bonsai that is recognized today. Over time, bonsai became a cultural symbol of harmony, balance, and patience in Japan, spreading to other parts of the world during the 19th and 20th centuries.

The Science of Bonsai Cultivation

The process of growing and shaping a bonsai tree is not simply a matter of pruning and bending branches; it is a careful science that involves understanding plant biology, growth patterns and environmental factors.

- **Soil and Container**: The soil used in bonsai cultivation must be well-draining, allowing for proper aeration of the roots. Different species of bonsai require different soil compositions, typically made up of a mix of akadama, pumice and lava rock. The container, or pot, is crucial for restricting root growth, ensuring that the tree remains small while maintaining its health.
- **Watering**: Bonsai trees are highly sensitive to overwatering or underwatering. Consistent moisture levels are essential, as the small volume of soil in the container can dry out quickly. Watering must be done carefully to maintain proper hydration while avoiding root rot.
- **Pruning and Root Management**: Pruning plays a central role in bonsai cultivation, both for shaping the tree and for encouraging healthy growth. Regularly trimming branches and roots helps maintain the desired shape, while root pruning encourages a dense and compact root system. Careful attention is paid to the development of new shoots and buds to ensure the tree maintains a natural, balanced appearance.
- **Fertilization**: Bonsai trees require regular fertilization to maintain healthy growth. Special bonsai fertilizers are used to provide the necessary nutrients, though the amount and frequency of fertilization depend on the species, time of year and growing conditions.

Art of Bonsai Design

Bonsai is not just about maintaining a tree; it is about creating an artistic representation of nature. The aesthetic aspect of bonsai involves shaping the tree to resemble a mature, aged tree in a miniature form. There are several design principles that guide bonsai artists:

- **Proportion and Balance**: The size of the tree, its branches and its pot must all be in proportion to one another. The tree's overall shape should convey harmony, balance and symmetry, while avoiding rigid, geometric patterns. The artist's goal is to evoke the feeling of a mature tree growing in nature.
- **The Five Basic Styles of Bonsai**: Bonsai artists follow traditional styles to shape trees. These include:
    - **Formal Upright (Chokkan)**: A straight trunk with symmetrical branches, evoking a strong, dignified appearance.
    - **Informal Upright (Moyogi)**: A slightly curved trunk with asymmetrical branches, resembling trees found in nature.
    - **Slanting (Shakan)**: The trunk slants to one side, symbolizing resilience and survival.
    - **Cascade (Kengai)**: The tree's branches cascade downward, representing a tree growing in a rugged, mountainous environment.
    - **Semi-Cascade (Han-Kengai)**: Similar to the cascade style but with the trunk slightly inclined upward before the branches cascade.
- **Wiring and Shaping**: Wiring is an essential technique in bonsai cultivation. Flexible wires are wrapped around the branches and trunk, gently bending them into the desired position. Over time, the branches take on the shape of the wire, and the wires are carefully removed once the desired structure is established.
- **Aging and Patina**: Bonsai artists often seek to create the appearance of age and maturity, even in young trees. This can be achieved through techniques such as bark peeling, scar formation and the careful selection of branches that resemble natural aging patterns. The aim is to evoke the sense of a tree that has stood for centuries.

The Cultural Significance of Bonsai

In addition to its artistic and horticultural aspects, bonsai has deep cultural significance, particularly in Japan. The practice of growing bonsai is often seen as a form of meditation, requiring patience, mindfulness and a deep connection to nature. Bonsai is associated with Zen Buddhism, where it symbolizes the philosophy of living in harmony with the natural world. The cultivation of bonsai is a spiritual practice that teaches the importance of balance, impermanence and the passage of time.

Bonsai also represents the values of craftsmanship, artistry and dedication. It is a tradition spans generations, with bonsai artists passing down their knowledge and techniques through apprenticeships and mentorship.

Conclusion

Bonsai is both a science and an art, a living representation of the harmony between nature and human creativity. Through careful cultivation, pruning and design, bonsai artists transform small, ordinary trees into stunning miniature masterpieces that capture the beauty and majesty of full-sized trees. The practice of bonsai not only offers insight into the science of plant growth but also provides a profound way of connecting with nature, patience and mindfulness. Whether as a hobby or a professional pursuit, bonsai remains a timeless tradition that continues to inspire people around the world.

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Vertical Gardening: A Sustainable Solution for Urban Food Production

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Abstract

As Urban populations continue to grow, the demand for sustainable food production methods has increased. Vertical gardening, a practice that involves growing plants in stacked layers, offers a viable solution to urban food insecurity. This paper explores the concept of vertical gardening, its techniques, benefits, challenges and its potential in transforming urban landscapes into sustainable food production zones.

Introduction

Urbanization has resulted in limited space for traditional agriculture, leading to concerns over food security in cities. Vertical gardening, an innovative farming method, addresses the need for food production in limited spaces, making it particularly suitable for urban environments. This paper examines the role of vertical gardening in promoting sustainable agriculture, increasing food production and reducing the ecological footprint of urban farming.

Vertical Gardening

Vertical gardening involves cultivating plants on structures that allow crops to grow upward rather than outward. This method uses walls, towers, or other vertical structures to maximize space and optimize light exposure for plant growth. It can be implemented in both indoor and outdoor settings, using various systems such as hydroponics, aeroponics, or traditional soil-based approaches.

Techniques of Vertical Gardening

Vertical gardening involves growing plants on structures that allow crops to grow upward rather than spreading out horizontally. Various techniques are employed in vertical gardening depending on the type of plants being grown, available resources and space constraints. Below are some of the most common techniques:

1. Hydroponics

- **Description**: Hydroponics is a soil-free growing method where plants are cultivated in nutrient-rich water solutions. In vertical hydroponic systems, plants are typically grown on stacked trays or towers, allowing them to grow vertically with their roots submerged in water.
- **Types of Hydroponic Systems**:
  - **Nutrient Film Technique (NFT)**: A thin film of water flows over plant roots, supplying nutrients.
  - **Deep Water Culture (DWC)**: Plant roots are submerged in water containing a nutrient solution.
  - **Wick System**: Uses a wick to draw nutrient solution from a reservoir to the plant roots.

Advantages

- Water-efficient, using up to 90% less water than traditional farming.
- Can grow plants faster due to optimal nutrient and water conditions.

2. Aeroponics

- **Description**: Aeroponics is a soil-free method where plant roots are suspended in the air and misted with a nutrient solution. This system is commonly used for vertical gardening, where the plants are stacked vertically, allowing each plant to receive mist directly on its roots.

Advantages

- Highly efficient in water use since misting systems use minimal water.
- Provides better oxygenation to roots, leading to faster plant growth.
- Reduces the risk of soil-borne pests and diseases.

3. Soil-Based Vertical Gardening

- **Description**: In soil-based vertical gardening, traditional growing methods are adapted to vertical structures. This may involve planting in containers, raised beds, or vertical towers filled with soil or potting mix. In Vertical garden system, walls, hanging planters, and trellises can all be used to support plants that naturally grow upward, such as climbing vines and vegetables.

Common Techniques:

- **Stacked Planters**: Plants are grown in stacked pots or containers that are arranged vertically, with a watering system ensuring water distribution to all layers.
- **Vertical Raised Beds**: Raised beds or boxes can be stacked on top of each other to create a vertical structure. Soil is filled into each box, and plants are placed accordingly.
- **Garden Walls**: Plants grow on a vertical structure that mimics a wall, either through pocket systems (where plants are placed in fabric pockets) or modular grid systems.

Advantages:

- Can be relatively easy to set up and maintain.
- Suitable for growing a wide variety of plants, including herbs, vegetables, and small fruits.

4. Green Walls (Living Walls)

Green walls, or living walls are vertical systems where plants are grown directly on the exterior or interior walls of buildings. They are usually supported by a frame with pockets or modules filled with soil or hydroponic media. The plants grow on these systems, creating a "wall" of greenery.

Types:

- **Modular Green Walls**: Pre-planted modules are attached to a wall to create a green surface.
- **Freestanding Green Walls**: Independent vertical gardens that can be placed anywhere.

Advantages:

- Adds aesthetic value to buildings and urban spaces.
- Helps improve air quality and reduce urban heat island effect.

5. Aquaponics

- **Description**: Aquaponics is a hybrid system that combines hydroponics and aquaculture (fish farming). In this system, fish waste provides organic nutrients to the plants, while plants help filter and clean the water for the fish. Vertical gardening can be implemented in aquaponics to maximize space and increase production efficiency.

Advantages:

- Symbiotic relationship between plants and fish leads to a balanced ecosystem.
- Reduces water usage and waste in both plant and fish cultivation.

Benefits of Vertical Gardening

Vertical gardening offers several advantages, particularly in urban settings where space is limited. Some key benefits include:

Maximized Space Utilization

- Vertical gardening allows for the cultivation of plants in confined spaces, such as walls, rooftops, balconies and even indoor areas. This method maximizes the use of vertical space, which is typically underutilized in urban environments.

Reduction of Carbon Footprint

- Growing food locally in vertical gardens reduces the need for transportation, packaging, and refrigeration, all of which contribute to carbon emissions. This makes vertical gardening an environmentally friendly alternative to conventional farming and food distribution systems.

Faster Growth and Harvest

- Controlled environments in vertical gardens (e.g., through hydroponics or aeroponics) can lead to faster plant growth due to optimal conditions like nutrient-rich water, proper light and temperature. This can result in quicker harvesting cycles and a continuous supply of fresh produce.

Reduced Pest and Disease Pressure

- Vertical gardens, particularly those grown indoors or in controlled environments, can reduce the risk of pests and diseases, which are common challenges in traditional soil-based farming. The use of automated systems also minimizes human intervention, reducing the potential for contamination.

Aesthetic and Psychological Benefits

- Vertical gardens can enhance the aesthetic appeal of urban spaces by adding greenery to otherwise gray and concrete-dominated environments. These gardens not only beautify the space but can also have psychological benefits, promoting mental well-being and reducing stress for those who interact with them.

Potential for Urban Agriculture Integration

- Vertical gardens can be integrated into various urban spaces, including public buildings, schools, restaurants, and even in private homes. This enables communities to produce their own food sustainably, promoting local agricultural initiatives and self-sufficiency.

Energy Efficiency

- Vertical gardens can be integrated with energy-efficient technologies, such as solar panels or LED grow lights, to reduce energy consumption. Additionally, by growing food locally, vertical gardens can help reduce the energy footprint associated with transporting food long distances.

Challenges and Limitations

Despite its benefits, vertical gardening presents several challenges:

- **Initial Setup Costs**: Establishing a vertical garden, particularly using hydroponics or aeroponics, requires significant initial investment in equipment, infrastructure and technology.
- **Technical Expertise**: Vertical gardening systems may require specialized knowledge, such as understanding nutrient management in hydroponics or optimizing lighting for indoor gardens.
- **Maintenance and Monitoring**: Vertical gardens require consistent monitoring for water quality, nutrient levels, and pest control. Automation systems can alleviate this, but they add to the cost.
- **Limited Crop Variety**: Not all crops are suitable for vertical gardening. Typically, leafy greens, herbs, and small fruits like strawberries perform well, but larger crops like grains or root vegetables are more difficult to grow in such systems.

The Future of Vertical Gardening

As technology advances, vertical gardening techniques are likely to become more efficient and accessible. Innovations such as LED grow lights, automated irrigation systems, and improved nutrient solutions are making vertical gardens more cost-effective and sustainable. Additionally, vertical farming could become a major component of the future of urban agriculture, with municipalities integrating these practices into public spaces, building structures and even food deserts.

Conclusion

Vertical gardening offers a promising solution to the challenges of urban food production. By utilizing limited urban space efficiently, it can increase food security, promote sustainability, and contribute to more resilient cities. However, it requires overcoming challenges related to cost, expertise and system maintenance. With continued research and innovation, vertical gardening could play a key role in the future of urban agriculture

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Sustainable Utilization of Fish By-Products and Their Sources

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Abstract:
The fish processing industry plays a crucial role in global food production, yet it generates a large amount of waste in the form of heads, bones, viscera, skins, scales, and shells. Improper disposal of these by-products leads to serious environmental pollution due to their high organic content. However, these materials are valuable sources of proteins, lipids, minerals, and chitin, which can be converted into a variety of high-value products. The efficient utilization of fish by-products supports the concept of zero-waste processing, reduces environmental impact, and adds significant economic value to the fishery sector. Fish by-products such as fishmeal, fish oil, fish silage, chitin, chitosan, and fish protein concentrate are extensively used in aquaculture, agriculture, pharmaceuticals, cosmetics, and other industries. Products like fish maw, caviar, dried shark fins, and mollusc shells also contribute to luxury food and industrial markets. The recovery and conversion of these by-products promote circular bio economic practices, ensuring sustainability, profitability, and environmental protection. Thus, the effective management of fishery waste not only enhances the economic efficiency of the seafood industry but also plays a key role in advancing sustainable fisheries and the blue economy framework.

Keywords: Fish by-products, Source, Waste utilization, by-product uses.

Introduction:

The fish processing industry not only produces valuable edible products but also generates a significant quantity of waste materials such as heads, bones, viscera, skins, scales, and shells. These materials, when discarded, can lead to environmental pollution due to their high organic load. However, these wastes are rich in proteins, lipids, minerals, and chitinous materials that can be effectively converted into a variety of useful byproducts. Approximately one-third of world fish catches are converted into byproducts for various uses including animal feed, pharmaceuticals, fertilizers, and industrial application. The systematic utilization of these wastes adds economic value, reduces pollution, and promotes the concept of zero-waste processing in the fishery sector.

The fishery and aquaculture industries are essential to the world's economic growth, employment, and food security. Fish by-products are used as raw materials to make fish meal, fish oil, gelatin, collagen, chitin, and chitosan, all of which have several uses in the culinary, pharmaceutical, cosmetic, and aquaculture sectors. By using a circular bio economic strategy, the sustainable use of these resources not only reduces environmental pollution from waste disposal but also increases the total profitability of the fishing industry. Fish by-product sources differ based on the kind of fish and how it is processed. Large amounts of waste materials are produced every day in fish markets, filleting companies, and fish processing facilities, which are major sources. The fishing sector may make a substantial contribution to both economic expansion and sustainable resource management by turning these byproducts into commodities with additional value. Therefore, the effective recovery and utilization of fish by-products is increasingly recognized as a key strategy in achieving sustainable fisheries development, reducing environmental impact, and promoting resource efficiency in the blue economy framework. The fish byproducts seen and their sources are given below.

1. Fishmeal

- Fishmeal is a high-protein powder produced by drying and grinding fish processing waste and small, low-value fish.
- It is rich in protein, minerals, and essential amino acids, making it the preferred ingredient in aquaculture, livestock, and poultry feeds.
- Fishmeal supports sustainable animal nutrition and helps recycle nutrients back into the food chain.

- Approximately four to five tons of fish are required to produce one ton of fishmeal.
- A high-protein feed ingredient commonly used in aquaculture, poultry and livestock feeds.

2. **Fish Oils**
   - Fish oils are extracted either from the bodies of oily fish (body oil) or from the livers of large fish species (liver oil).
   - Rich in omega-3 fatty acids (EPA and DHA), fish oils have significant nutritional and pharmaceutical value.
   - They are used in dietary supplements, animal feed, and as raw materials for various industrial products.
3. **Fish Maw**
   - The swim bladder or air bladder of some fish species, when dried, is known as fish maw.
   - It is prized in Asian cuisine for its high collagen content and is valued for its texture and health benefits, including promoting skin elasticity and joint health.
   - Used in gelatin, isinglass, collagen and luxury food markets
4. **Fish Silage**
   - Fish silage is a fermented liquid produced by acid preservation of fish processing waste or low-value fishes.
   - It retains proteins, lipids, and minerals and can be used as a nutrientrich feed ingredient and plant fertilizer.
   - Utility: Ensiled, acidified, or fermented to produce liquid/semiliquid feed.
5. **Chitin and Chitosan**
   - Derived mainly from crustacean shell waste (prawns, crabs, squilla), chitin is a natural polysaccharide with biocompatible and biodegradable properties.
   - Its derivative, chitosan, is obtained by deacetylation of chitin.
   - Both are utilized in medicine, agriculture, and biotechnology due to their diverse biochemical properties, including plant growth promotion, enzyme stabilization, and water purification.
6. **Fish Protein Concentrate (FPC)**
   - FPC is a concentrated form of protein extracted from whole low-value fishes by removing water, oil, and minerals.
   - It serves as a high-protein supplement for human foods like bread and biscuits, enhancing nutritional content.
7. **Fish Manure**
   - Fish manure is produced by composting fish waste with organic materials.
   - It is rich in nitrogen, phosphorus, and potassium and acts as an excellent organic fertilizer for agricultural crops.
   - Utility: Raw or composted wastes used in agriculture, horticulture.
8. **Dried Shark Fin**
   - Dried shark fins are obtained from the fins of different shark species.
   - They are traditionally used in soups and are also a source of high quality collagen used in biomedical and cosmetic applications.
9. **Fish Cavior:**
   - Fish roes are the mature ovaries of fish, and caviar is the processed form of fish roe.
   - Fish roes are nutritionally rich, containing lipids with essential fatty acids and proteins with essential amino acids.
10. **Molluscs shell:**
    - Mussel shells provide calcium carbonate for industrial applications.
    - Oyster shells are used in building construction and production of quicklime (calcium oxide).
    - Shells can be processed into pearl powder.
    - Scallop and mussel shells are used in handicrafts, jewelry, and button manufacturing.

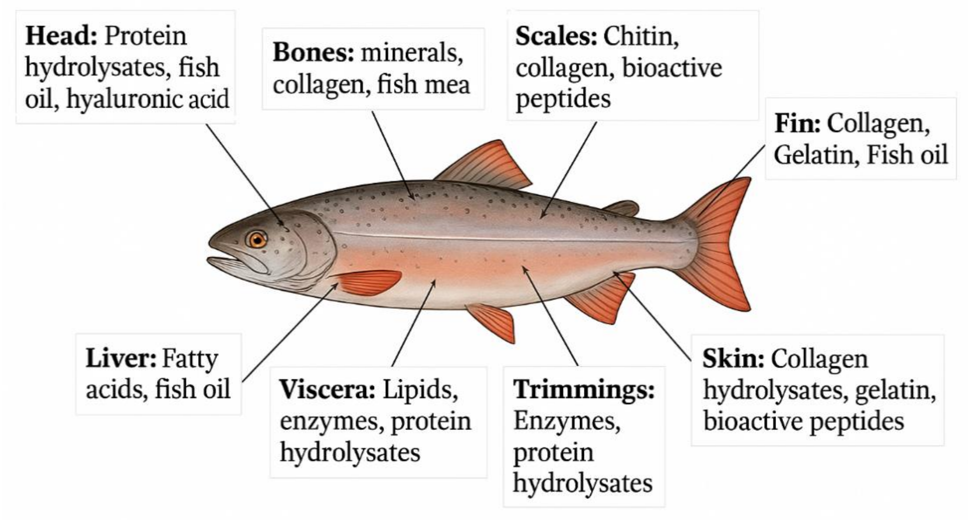

Table.1 Fish Parts, Fish by products and Uses

Fish parts	Fish by products	Uses
Fish liver	Fish liver oil, Vitamin A	Pharmaceutical
Fish body	Fish body oil	Pharmaceutical
Fish protein & trimming	Fish protein concentrate	Human consumption
	Fish meal, Fish silage, Fish soluble	Animal feed
	Fish manure	Agriculture
	Fish albumin	Human consumption
Fish skin & Fish bone	Collagen, Gelatin, Fish leather	Industrial
Fish scales	Animal charcoal, guanine, Shagreen	Industrial
Fish eggs	Fish roe (Caviar)	Human consumption
Fish viscera	Enzymes, Hormones	Pharmaceutical, Industrial
Fish swim bladder	Isinglass	Industrial
Shark fins	Shark fin rays	Human consumption
Shark liver	Shark liver oil, Squalene	Human consumption
crustaceans shell	Chitin, Chitosan, Pigments	Pharmaceutical, Industrial
Molluscs shell	Calcium carbonate, pearl powder, handicrafts, jewels	Industrial

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Bio-Inspired Technology: How Animals and Plants Are Shaping Future Innovations

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Abstract:

Nature has spent billions of years perfecting designs that are efficient, resilient, and sustainable—making the living world an extraordinary source of ideas for modern technology. Bio-inspired technology, or biomimicry, draws lessons from plants, animals, and microorganisms to solve human problems in smarter ways. Researchers are now adapting the gecko's remarkable grip to create advanced adhesives, copying the lotus leaf to develop self-cleaning and water-repellent materials, and studying bird flight and insect wings to build more agile drones and aircraft. Even microscopic features found on shark skin and butterfly wings are guiding innovations in medicine, engineering, and environmental protection. This article highlights how observing nature's ingenuity is shaping the next generation of scientific and technological breakthroughs, offering solutions that are efficient, eco-friendly, and remarkably creative.

Key Words: Biomimicry**,** Bio-inspired technology**,** Sustainable innovation**,** Natural adaptations**,** Bionics**,** Eco-engineering

Introduction

Technology is often seen as a product of human creativity, but the deepest inspiration for innovation comes from a much older designer—nature. Over billions of years, every living organism has adapted, refined, and perfected its survival strategies. These natural solutions, developed through evolution, are often far more efficient, sustainable, and elegant than many human inventions. Today, engineers and scientists are increasingly turning to nature as a mentor to design next-generation technologies. This exciting field, known as **bio-inspired technology** or **biomimicry**, blends biology with engineering and is transforming industries ranging from medicine and architecture to robotics and environmental conservation.

This article explores how organisms—both tiny and gigantic—are shaping modern innovation and why biomimicry is becoming one of the most promising approaches for developing sustainable, eco-friendly technologies in the 21st century.

Learning from Nature's Engineering Masterpieces

Nature constantly faces constraints—limited energy, harsh climates, predators, and competition. As a result, living organisms have evolved highly optimized structures and systems. These designs are not only efficient but also sustainable, using minimal energy and leaving no waste.

Some examples include:

- **Spider webs** that are stronger than steel by weight
- **Bird wings** that allow effortless long-distance flight
- **Shark skin** that reduces drag in water
- **Lotus leaves** that repel dirt and water
- **Gecko feet** that cling strongly yet detach easily

Such biological features serve as blueprints for modern technological advancements. The core principle of biomimicry is simple: *Nature has already solved many of the problems we face—our task is to observe, understand, and innovate.*

1. Gecko Feet: Revolutionizing Adhesion Technologies

Geckos can climb walls, hang upside down, and run across ceilings without slipping. Their remarkable grip comes from millions of nano-sized hair-like structures called *setae* on their toes. These setae create temporary molecular attractions known as **van der Waals forces**, allowing geckos to stick to surfaces without glue.

Inspired by this mechanism, scientists have developed:

- **Dry adhesives** that can be attached and removed repeatedly

- **Climbing robots** for inspection and rescue operations
- **Medical bandages** that adhere without causing irritation
- **Micro-grippers** used in delicate surgeries

These technologies aim to mimic the gecko's ability to maintain strong adhesion while still being completely residue-free and reusable—qualities that traditional glues lack. Research continues to refine these materials for industrial and biomedical applications.

2. Lotus Leaf: Designing Self-Cleaning Surfaces

Lotus plants grow in muddy waters, yet their leaves always remain spotless. This purity comes from a special **micro- and nano-textured surface** that prevents water droplets from spreading. Instead, water forms spherical beads that roll off, carrying dust and dirt away. This phenomenon is known as the **lotus effect**.

Engineers have used this principle to create:

- **Self-cleaning paints and building walls**
- **Waterproof fabrics and footwear**
- **Anti-fogging and anti-stain glass**
- **Dust-resistant solar panels**

Such surfaces reduce maintenance costs, conserve water, and increase the longevity of structures. For hot and dusty regions, lotus-inspired solar panels can significantly enhance energy output by keeping themselves clean naturally.

3. Shark Skin: Enhancing Speed, Efficiency, and Hygiene

Shark skin feels rough because it is covered with tiny tooth-like structures called *dermal denticles*. These denticles reduce water resistance and prevent microorganisms from attaching to the surface.

This structure has inspired multiple technological innovations:

- **Drag-reducing swimsuits** used in professional sports
- **Ship coatings** that lower fuel consumption
- **Antimicrobial hospital surfaces** that reduce infection risks
- **Aircraft surfaces** that improve aerodynamics

In hospitals, shark-skin-patterned materials are being tested to limit bacterial growth without using chemicals—an eco-friendly alternative in infection control.

4. The Color Secrets of Butterfly Wings

The vivid blue of a morpho butterfly does not come from pigments but from complex tiny structures on its wings that reflect light in specific ways. These **optical nanostructures** produce iridescent colors that do not fade with time.

Inspired by butterflies, researchers have developed:

- **Color-changing sensors** used in environmental monitoring
- **Anti-counterfeiting security features** for currency
- **High-efficiency optical devices**
- **Non-fading, energy-efficient display technologies**

These innovations use structural color instead of chemical dyes, making them durable and eco-friendly.

5. Bird and Bat Flight: Shaping the Future of Aviation

For centuries, birds have inspired humans to dream of flying. Modern aviation still learns from their flight patterns. Birds adjust their wings' shape, angle, and size to glide efficiently, conserve energy, and navigate turbulent winds.

Engineers are applying these principles to create:

- **Morphing wings** that change shape mid-flight
- **Silent drones** inspired by owl feathers
- **Wingtip designs** modeled after eagles to reduce fuel consumption
- **Bat-inspired micro-air vehicles** with flexible wings

These bio-inspired aircraft aim to fly more quietly, consume less fuel, and navigate complex environments—ideal for future transportation and environmental monitoring.

6. Termite Mounds: A Blueprint for Energy-Efficient Architecture

In many African and Indian regions, termite mounds reach impressive heights and maintain constant internal temperatures despite extreme weather. Their ventilation system uses carefully arranged tunnels and pores that regulate airflow naturally.

Architects have applied this principle to design:

- **Low-energy cooling systems**
- **Naturally ventilated office buildings**
- **Eco-friendly shopping complexes**
- **Sustainable housing designs**

One famous example is the *Eastgate Centre* in Zimbabwe, which uses termite-inspired ventilation and consumes nearly 90% less energy for cooling compared to conventional buildings. These models show how biomimicry can make architecture greener and more climate-resilient.

7. Velcro: A Simple but Iconic Biomimetic Invention

The invention of **Velcro** is one of the earliest success stories of biomimicry. In 1941, Swiss engineer George de Mestral noticed tiny burrs sticking to his dog's fur. Curious, he examined them under a microscope and saw tiny hooks that gripped onto loops in fabric.

This observation inspired:

- **Velcro fasteners** used in shoes, clothes, bags, spacecraft, and medical devices

Velcro remains a powerful example of how paying attention to the natural world can lead to global innovations.

8. Spider Silk: Inspiring Ultra-Strong Materials

Spider silk is incredibly strong—stronger than steel when compared by weight. It is also lightweight, flexible, and biodegradable. Scientists are trying to replicate these qualities to develop next-generation materials.

Spider silk-inspired technologies include:

- **High-strength fibers** for sports equipment
- **Lightweight armor**
- **Biodegradable surgical sutures**
- **Flexible electronics**

Although producing artificial spider silk on a large scale is challenging, recent advances in biotechnology—such as using genetically engineered yeast or silkworms—are bringing this closer to reality.

Why Biomimicry Matters for Our Future

As humanity faces climate change, pollution, overconsumption of resources, and environmental degradation, biomimicry offers solutions that are inherently sustainable.

Nature teaches us to:

- **Reduce energy use** (like termites)
- **Design without waste** (like ecosystems)
- **Use non-toxic materials** (like marine organisms)
- **Build strong yet lightweight structures** (like bones and bamboo)
- **Adapt to changing environments** (like migratory species)

Biomimicry helps engineers replace harmful industrial processes with environmentally friendly alternatives. It encourages a shift from "take-make-waste" to **circular, regenerative design**.

Conclusion

The natural world is an endless source of innovation. Whether it is the grip of a gecko, the shine of a butterfly, or the cooling system of a termite mound, each biological feature holds a lesson. Biomimicry bridges biology with technology, helping us create smarter, greener, and more efficient systems.

As research advances, the next decades will likely see an explosion of bio-inspired solutions—from medicine and robotics to architecture and environmental engineering. Nature has already tested millions of ideas; our task is simply to observe carefully, learn deeply, and apply these principles responsibly.

By embracing nature as a guide, humanity can design technologies that not only improve our lives but also protect the planet. Biomimicry is not just innovation—it is a pathway to a sustainable future.

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Role of Plankton Communities in Water Quality Management in Shrimp Ponds

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Abstract

Ponds typically contain an abundance of phytoplankton. These organisms play an important role in pond ecology and influence water quality. Although phytoplankton usually are beneficial, under some conditions, they can be quite problematic in fish and shrimp production. These microscopic photosynthetic organisms serve as the primary producers in the aquatic food chain, supplying essential oxygen through photosynthesis and forming a natural source of nutrition for shrimp, especially during their early life stages. Phytoplankton help stabilize water quality by absorbing dissolved nutrients such as nitrogen and phosphorus, thereby reducing the risk of harmful algal blooms and toxic accumulations. Additionally, they regulate pond pH levels and provide shade that limits the growth of undesirable microorganisms. Proper management of phytoplankton populations ensures optimal water quality, enhances shrimp growth, and supports sustainable aquaculture practices. Hence, understanding the composition, density and dynamics of phytoplankton communities is crucial for improving the health and productivity of shrimp culture systems.

Keywords: Phytoplankton, Zooplankton, Algae, Dinoflagellates, Shrimp pond

1. Introduction

Plankton, which include phytoplankton (microscopic plants) and zooplankton (microscopic animals), play a central role in maintaining water quality in shrimp aquaculture ponds. Their presence directly influences the physical, chemical, and biological dynamics of pond water. One of the most important contributions of phytoplankton is oxygen production. Through photosynthesis, phytoplankton generate significant amounts of dissolved oxygen during daylight hours, which supports shrimp respiration, promotes aerobic microbial breakdown of organic wastes, and prevents the accumulation of toxic gases such as ammonia and hydrogen sulfide in the pond bottom. This continuous oxygenation is vital for maintaining a stable and healthy pond environment. Phytoplankton are algae, consists of thousands of species distributed primarily among the phyla Pyrrophyta, Euglenophyta, Chlorophyta, Heterokontophyta and Cyanophyta. The Pyrrophyta are motile, flagellate organisms, and this phylum includes the common green algae. The Euglenophyta is a diverse group of unicellular, flagellated organisms that are typically microscopic and found in both fresh and marine water. The Heterokontophyta contains many freshwater and marine species and includes the yellow-green, golden and brown algae as well as diatoms. The Cyanophyta are prokaryotic like bacteria and many authorities consider them to be bacteria (cyanobacteria).

Phytoplankton form the base of the food web in aquaculture ponds, but the natural abundance of phytoplankton is not sufficient to provide desired levels of shrimp and fish production. Fertilizers increase the natural fertility of ponds and allow greater yields. Many producers however, have switched to feed-based aquaculture to increase production beyond that possible with fertilizers. Natural productivity is still important in ponds with feeding, especially soon after stocking, because young post-larvae and fingerlings cannot use feed as efficiently as older animals. Some aquaculturists, and particularly shrimp producers, evaluate the abundance and taxonomic composition of phytoplankton communities in pond waters. They also apply various treatments in attempts to control the abundance and composition of the phytoplankton communities. Algal propagules are ubiquitous – fill a new pond with water and many phytoplankton species will find their way into it. Phytoplankton growth is regulated by water temperature, solar radiation, pH, turbidity and nutrient concentrations. Acidic pond water normally is treated with liming materials to increase pH. Turbidity caused by suspended soil particles usually settles from water held in ponds, and nutrients are supplied by fertilizers and feeds. Aquaculture ponds typically have ideal conditions for the growth of phytoplankton.

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2. Density and Species composition

The density of phytoplankton blooms is strongly dependent upon the availability of nutrients, especially nitrogen and phosphorus. Intensive aquaculture ponds with large inputs of feed usually have an abundance of phytoplankton and phytoplankton blooms also reach fairly high densities in semi-intensive ponds. A pond might have a phytoplankton bloom consisting primarily of various species of green algae, but within a few weeks, the phytoplankton community might be made up almost entirely of a single species of blue-green algae. Alternatively, the green algae bloom in a pond might continue, but the species in the bloom might change during a period of a few weeks. The total abundance of phytoplankton also increases and decreases even when nutrient inputs are relatively constant.

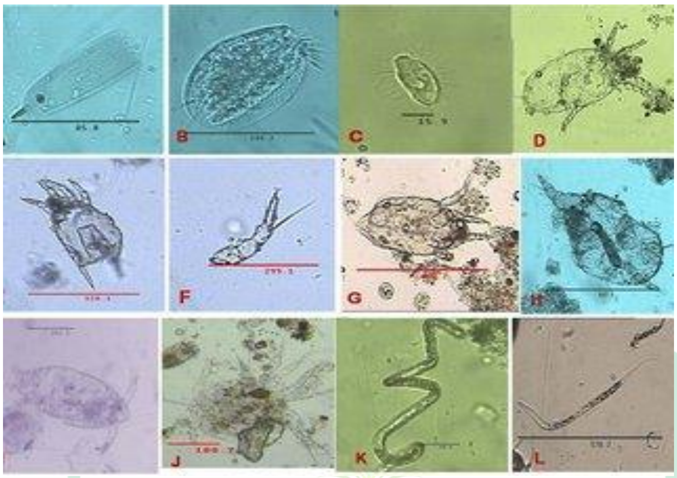

Fig.1. Common phytoplankton and zooplankton

(A. Tintinids, B&C. Ciliates, D&J. Copepods, K. Spirulina, L. Nematodes)

3. Nutrient assimilation and recycling

Phytoplankton rapidly absorb dissolved inorganic nutrients such as ammonia, nitrite, nitrate, and phosphate, which originate from shrimp feed residues, excreta, and microbial decomposition. This nutrient uptake prevents toxic buildup and helps stabilize overall water chemistry. Zooplankton also contribute by grazing on excess phytoplankton, thereby preventing uncontrolled plankton blooms that might otherwise lead to eutrophication or sudden bloom crashes. Balanced grazing by zooplankton keeps phytoplankton density within desirable limits, maintaining proper water quality and preventing fluctuations in dissolved oxygen, pH, and turbidity.

4. Regulation of light penetration and water temperature

Moderate phytoplankton density provides a natural shading effect, reducing excessive sunlight penetration that can trigger the growth of filamentous algae and undesirable aquatic weeds. This shading helps maintain stable pond temperatures and prevent thermal stress in shrimp. In addition, plankton populations support the formation of bioflocs, microscopic aggregates of organic matter and bacteria that help reduce turbidity and convert waste materials into beneficial natural feed for shrimp. Biofloc formation further enhances water quality by improving nitrogen utilization, reducing suspended solids, and minimizing foul odors from the pond bottom.

Fig.2. Shrimp pond

5. Regulation of pH

During photosynthesis, they absorb carbon dioxide, which helps prevent drastic pH drops and keeps water within the optimal range needed for shrimp health. In a well-managed pond, plankton populations promote a balanced nutrient cycle, improve sediment conditions, and prevent harmful substances such as nitrite and hydrogen sulfide from reaching toxic levels. Overall, plankton act as natural environmental engineers, supporting oxygen balance, nutrient control, waste reduction, pH stability, and biological productivity. Their proper management is essential to maintaining superior water quality, promoting shrimp health and growth, and ensuring the long-term sustainability of shrimp aquaculture systems.

6. Biofloc formation

Plankton communities are also essential in biofloc formation, which enhances water quality by binding suspended organic particles and promoting the growth of beneficial microbes. Bioflocs act as natural filters, recycling nutrients, reducing turbidity, and converting waste materials into protein-rich biomass that shrimp can feed on. This not only improves water quality but also enhances feed efficiency and overall pond productivity. Additionally, plankton-based nutrient cycling limits the accumulation of sludge, reduces harmful metabolites, and supports healthy benthic conditions.

7. Advantages

7.1. Reduce production costs: Feed occupies the highest portion in the allocation of cultivation costs. By using plankton as a natural food for shrimp, the dependence on expensive artificial feeds can be reduced. This is also one of the efforts to maintain pond finances.

7.2. Rich in natural nutrients: Plankton has a high nutritional content to help shrimp growth. Shrimp will get balanced natural nutrition so they can grow more optimally.

7.3. Maintaining the balance of the ecosystem: Cultivation of the plankton system can help maintain the balance of the pond ecosystem. Apart from serving as natural feed, plankton also maintains water quality and minimizes the risk of harmful algae.

8. Disadvantages

However, the plankton system in shrimp farming also has disadvantages because it must be monitored intensively. This requires extra time and effort from the farmer. In addition, the stability of plankton is also quite vulnerable and can be affected by several factors. These factors are fluctuations in temperature, poor water quality and the presence of disease. Unstable plankton conditions can disrupt the availability of natural feed for shrimp.

Conclusion

Plankton serve as the biological foundation for effective water quality management in shrimp ponds. Their ability to produce oxygen, assimilate nutrients, stabilize pH, regulate light and temperature, support biofloc formation, and maintain ecological balance makes them indispensable for sustainable shrimp farming. Proper monitoring and management of plankton populations not only improve water quality but also enhance shrimp health, growth, and overall pond productivity. Thus, maintaining a healthy plankton community is a key strategy for ensuring long-term success in shrimp aquaculture.

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Role of Boron in Potato Crop Production

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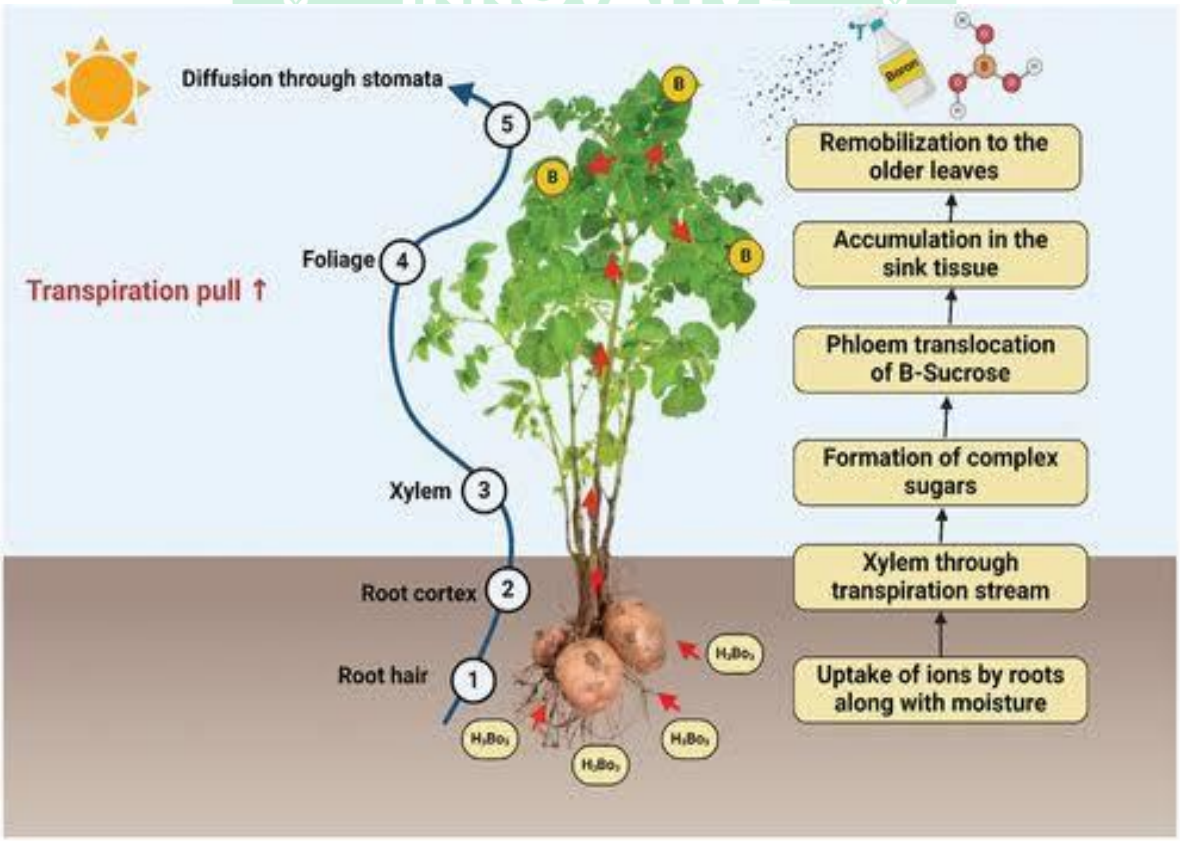
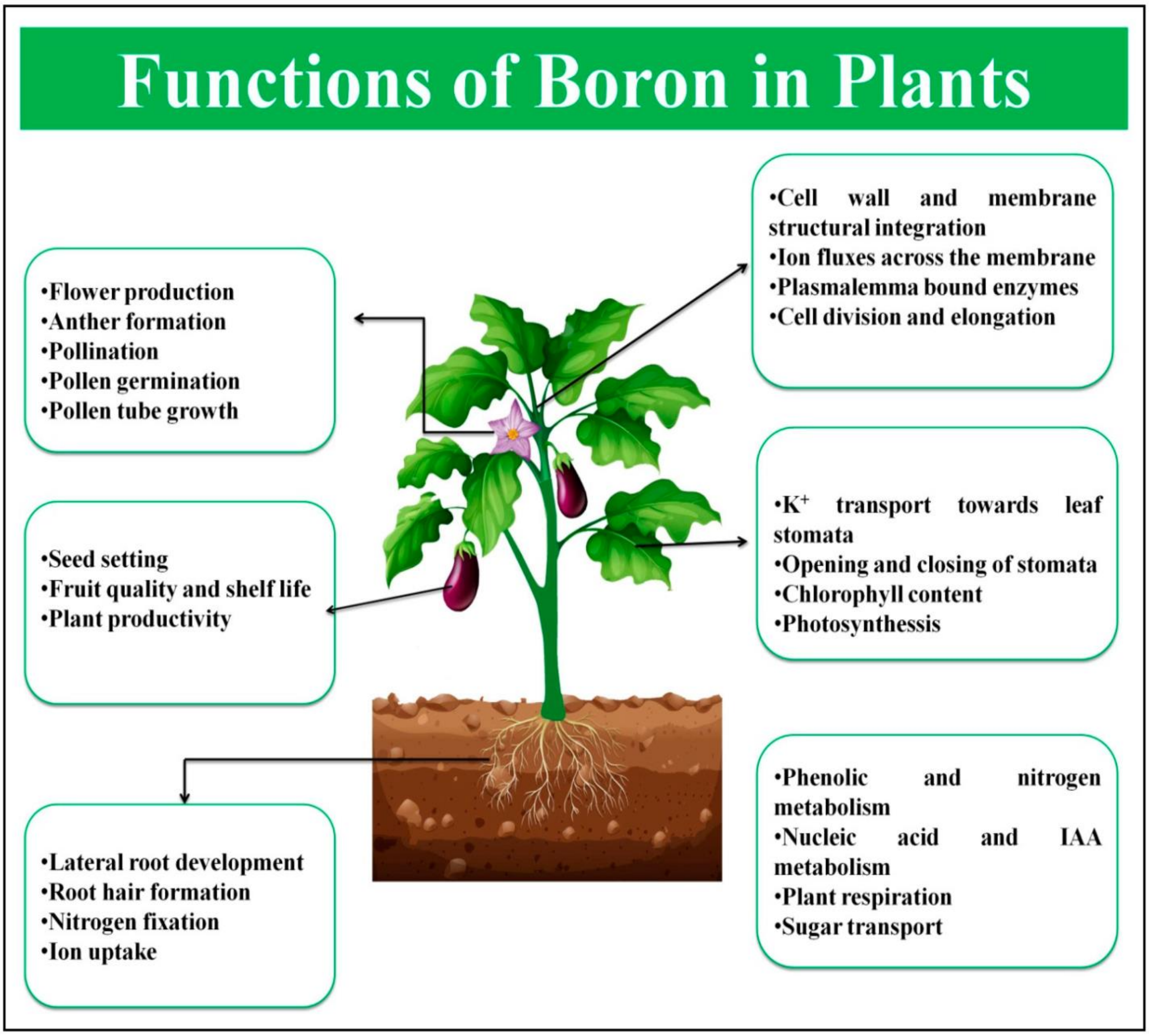
Boron (B) is a micronutrient critical to the growth and health of all crops. It is a component of plant cell walls and reproductive structures. It is a mobile nutrient within the soil, meaning it is prone to movement within the soil. Because it is required in small amounts, it is important to deliver B as evenly as possible across the field. Traditional fertilizer blends containing B struggle to achieve uniform nutrient distribution. Despite the need for this critical nutrient, B is the second most widespread micronutrient deficiency problem worldwide after zinc. Boron is essential for tuber crops because it plays a key role in **cell division, tuber initiation, and quality.** It is crucial **for starch accumulation,** which is vital for tuber development, and also **improves skin quality, reduces internal rust spots, and enhances stress tolerance.** Proper boron levels ensure adequate growth, yield, and produce quality, as low levels can lead to stunted growth and poor tuber development. Boron is a crucial micronutrient for potato production, playing a key role in increasing tuber yield and improving quality, such as reducing discoloration and increasing starch content. It is essential for processes like cell wall synthesis, sugar transport, and overall plant health. Boron deficiency can lead to reduced yields and smaller, lower-quality tubers, especially in alkaline and coarse-textured soils.



Role in potato crop production:



- **Increases yield and tuber size:** Boron application can significantly increase tuber yield, tuber weight, and the proportion of large and medium tubers, while decreasing the number of small tubers.
- **Enhances quality:** It improves tuber quality by increasing dry matter, starch, and vitamin C content.
- **Reduces discoloration:** Boron helps reduce enzymatic discoloration in tubers by inhibiting the oxidation of phenols, which is a major cause of internal discoloration.
- **Strengthens cell walls:** As a component of cell walls, boron provides structural integrity to plant tissues, which is vital for storage quality and stress tolerance.
- **Improves stress tolerance:** It helps stabilize calcium in the cell wall, improving the plant's resistance to pests, diseases, and environmental stresses like drought and heat.
- **Supports growth and development:** Boron is critical for shoot and root growth, cell division, and the translocation of carbohydrates to the tubers.

Application and deficiency:

Boron deficiency in potatoes causes symptoms like **thickened, crinkled, and upward-cupping young leaves,** the **death of growing points**, and **stunted growth.** In severe cases, plants may have **a bushy appearance,** and tubers can develop **internal rust spot** and other **internal discoloration.**

Above-ground symptoms

- **Leaves:** Young leaves become thick, crinkled, and curl upwards, sometimes with light brown tissue extending between the veins. The leaves can also be brittle and break easily.

- **Growth:** The plant's overall growth is stunted, with short internodes and a bushy appearance.
- **Growing points:** The terminal growth (shoot tips) dies off, and in severe cases, the axillary buds can also become necrotic. This loss of apical dominance can lead to a rosette-like growth pattern.
- **Wilting:** Young leaves may wilt even with adequate water due to disrupted water transport.

Below-ground symptoms

- **Tubers:**
  - **Internal Rust Spot:** Boron deficiency is a major cause of internal rust spot.
  - **Discoloration:** Brown necrotic patches can appear inside the tubers.
  - **Hollow tubers:** This symptom can also be caused by calcium deficiency, making it difficult to diagnose based on tubers alone.

Boron application improves potato yield, quality, and stress tolerance by aiding in photosynthesis and nutrient uptake. The most effective method is **foliar spray** at stages like tuber initiation or hilling, but soil application is also beneficial. Common sources for boron application in India include **borax** and **boric acid,** and deficiency is common in alkaline and sandy soils.

Application in potatoes

- **Foliar spray:** This is often the most effective method, leading to higher yield, better tuber quality (like reduced internal rust spots), and increased nutrient use efficiency.
- **Timing:** Apply boron during critical growth stages such as "hilling" to improve skin quality and stress tolerance, and at "tuber initiation" to aid cell division and growth.
- **Soil application:** Applying boron directly to the soil is also effective, though generally less efficient than foliar spray.
- **Benefits:** Boron improves photosynthesis, enhances the translocation of photosynthates to the tubers, increases the number and weight of tubers, and improves stress tolerance.

Boron sources in India

- **Borax and boric acid:** These are the most common boron fertilizers used in India. Borax can be applied directly to the soil.
- **Boric acid:** This is the source of choice for foliar sprays.
- **Calcium nitrate-based products:** Some products, like Yara Leiva Nitrobore, contain both calcium and boron and can be applied either pre-plant or as a top dressing.
- **Organic sources:** While less common, manure and compost can also contain boron.

Conditions requiring boron application

- **Soil type:** Boron deficiency is most common in light, sandy, and acidic soils with low organic matter content.
- **Soil pH:** High soil pH levels are often associated with a lack of available boron.
- **Regional factors:** Boron deficiency is widespread in many parts of India, especially in alkaline soils and humid regions with high rainfall, which can lead to leaching.

General guidelines for boron application

Boron is the micronutrient needed in the greatest quantity to ensure several key growth processes. It influences root and shoot growth, plant development and pollination. Alongside potassium, calcium and magnesium, boron is an important element present in the cell wall. Here it acts as a cement between pectins, providing cohesive strength for cell tissues. Therefore boron affects tuber storage quality characteristics. Boron also affects calcium absorption, so supplies are important to ensure a balanced nutrition.

In conclusion, boron (B) is a **vital micronutrient** for potatoes, essential for achieving optimum yield and quality, especially in B-deficient soils. Its importance lies in a narrow window between deficiency and toxicity, requiring careful application.

Key conclusions regarding the importance of boron fertilizers in potato cultivation:

- **Improved Yield:** Boron application significantly increases the total number and size of tubers per plant, leading to higher overall yields.
- **Enhanced Tuber Quality:** Adequate boron nutrition improves internal and external quality parameters of the tubers, making them more suitable for processing (e.g., chips, fries).

- It increases the content of starch and Vitamin C.
- It improves specific gravity, tuber hardness, and reduces moisture loss, thus increasing shelf life.
- It helps prevent physiological disorders such as hollow heart, corky tissue, and cracking.
- It contributes to lighter chip color by reducing phenolic compounds and enzymatic discoloration.

- **Essential Physiological Functions:** Boron plays a crucial role in fundamental plant processes:
  - **Cell Wall Integrity and Formation:** It provides structural strength to cell walls by cross-linking pectins, which is vital for proper growth and resistance to stress and disease.
  - **Carbohydrate and Sugar Transport:** It facilitates the movement of sugars and carbohydrates from the leaves to the developing tubers (the "sink"), directly contributing to tuber bulking and yield.
  - **Nutrient Uptake and Metabolism:** Boron enhances the uptake and utilization of other essential nutrients like nitrogen, phosphorus, and potassium by improving membrane function and enzymatic activities.
  - **Root and Shoot Growth:** It is necessary for healthy root and shoot development and cell division in meristematic tissues.
- **Optimal Application Method:** Foliar application of boron (e.g., 0.1% boric acid at specific growth stages like tuber initiation) is often more efficient and effective than soil application for improving yield, quality, and nutrient use efficiency, especially in alkaline or light-textured soils where B can be immobile or leach easily.
- **Sensitivity to Dosage:** Potato plants are highly sensitive to the balance of boron. While deficiency causes severe problems, excessive application can quickly lead to toxicity symptoms and yield reduction; therefore, judicious and balanced application based on soil and tissue testing is crucial.

Boron application in potato crops can significantly increase tuber yield and quality by enhancing growth and nutrient uptake. Foliar application is often more effective than soil application, leading to increased tuber numbers, higher tuber weight, and improved dry matter and starch content. Additionally, boron fertilization can improve the soil's availability of nitrogen and boron for subsequent crops.

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Speed breeding a need of crop improvement

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Introduction:

Speed breeding is a critical need for crop improvement because it dramatically accelerates the breeding cycle, allowing for faster development of new, improved crop varieties that can help address challenges like population growth and climate change. By manipulating light, temperature, and humidity, speed breeding can reduce the time to develop new crops from years to months, enabling quicker adaptation and the creation of high-yielding, resilient, and disease-resistant varieties. Speed breeding is an advanced plant breeding technique that accelerates crop development by manipulating environmental conditions like light, temperature, and photoperiod to shorten the time between generations. It is an advanced technique because it is often combined with other modern tools like genomics, marker-assisted selection, and gene editing to make breeding faster, more precise, and more efficient, allowing for multiple generations to be grown per year. Speed breeding is a powerful technique to shorten the breeding cycle by accelerating the plant growth, flowering, and seed maturation time by controlling all environmental conditions (including photoperiod, temperature, and light intensity) from seedling to maturity. In 2003, researchers of Queensland coined the term "Speed Breeding". It reduces the generation time by five times compared to field conditions and 2.5 times compared to normal greenhouse conditions. Speed breeding is important because it significantly accelerates crop development by shortening the time from one generation to the next, which is crucial for addressing global food security, climate change, and other agricultural challenges. By manipulating environmental conditions like light and temperature, it enables breeders to achieve up to six or more generations per year for some crops, a major improvement over the traditional breeding cycle. This allows for faster selection and testing of new traits, as well as the more efficient use of advanced techniques like marker-assisted selection and gene editing.

Speed breeding originated from NASA's 1980s experiments to grow plants in space, a concept developed further at the University of Queensland in 2003, where researchers coined the term "speed breeding" to describe their technique of manipulating photoperiods and controlled conditions to accelerate crop generation cycles. This led to the development of advanced techniques and facilities, with the first commercial speed breeding facility opening in the Netherlands in 2006.

Early research and inspiration

- **1980s:** NASA, in collaboration with Utah State University, explored growing plants in space. Their work on rapid generation cycling of wheat for potential space missions laid the groundwork for modern speed breeding.
- **1990s:** NASA further experimented with growing rapid cycling wheat in a space station, which led to the development of the 'USU-Apogee' variety.

Coining the term and advancement

- **2003:** Researchers at the University of Queensland coined the term "speed breeding" to describe their method for accelerating crop breeding**.**
- **2006:** The first commercial speed breeding facility opened in the Netherlands.
- **2010:** The first wheat variety developed using speed breeding, named 'USU-Apogee', was introduced.

BENEFITS:

Speed breeding is advantageous for long duration crops as it overcomes the limitation of seasons, enabling rapid generation cycling. It fetches only light-emitting diode (LED) and other regulators which saves labor, cost, and time for researchers. It promises to be an efficient technique for new variety release when coupled with modern techniques like CRISPR, high throughput phenotyping, genome editing, and genomic selection. It is highly cost-effective than single seed descent (SSD) and double haploids (DHs). It is efficient for gene insertion of distinct phenotypes followed by marker-assisted selection (MAS). It employs breeders to expedite genetic improvements such as yield gain, disease resistance, and climate resilience in certain crops. The 'RapidGen' technology at ICRISAT reduced the breeding cycle by 40%.Speed breeding offers significant advantages by accelerating the development of new crop varieties, which shortens breeding cycles from years to months and allows for multiple generations per year. This leads to faster crop improvement for desired traits like higher yields, disease resistance, and resilience to climate change. Other benefits include year-round production, more efficient resource use in a controlled environment, and improved integration with other advanced breeding technologies.

Faster crop development and improvement

- **Shorter breeding cycles:** Speed breeding can shorten the time to develop new crop varieties from 5–10 years to as little as 2 years, enabling 3-4 or more generations per year for some crops.
- **Rapid trait incorporation:** It allows for the quick introgression of desirable traits, such as disease resistance or improved nutrition, through repeated backcrossing cycles.
- **Increased genetic gain:** By accelerating the process, speed breeding boosts the rate of genetic gain in breeding programs.

Improved crop resilience and food security

- **Climate change adaptation:** The ability to rapidly develop new varieties helps create crops that are better suited to changing environmental conditions, which is crucial for global food security.
- **Enhanced traits:** It facilitates the development of crops with higher yields, better nutritional profiles, and greater resistance to pests and diseases.

More efficient and flexible breeding

- **Year-round production:** Controlled environments allow for continuous crop production regardless of the season.
- **Efficient resource use:** The controlled environment minimizes the need for excessive water, fertilizer, and pesticides, leading to more sustainable practices.
- **Flexibility:** It is flexible and adaptable to a diverse range of crops and can be integrated with other advanced techniques like marker-assisted selection, genomic selection, and gene editing.
- **Efficient data generation:** It speeds up experiments and data collection, helping researchers test hypotheses more quickly and advance their understanding of plant physiology.

LIMITATIONS:

The protocol needs to be customized according to the crop, the species, temperature, and lighting conditions since the photoperiod is independent of the crops and their agro-climatic conditions. It affects quality, quantity, and phenotype such as loss of awn suppressor, dwarf genes, etc. The main limitations of speed breeding include the high cost of infrastructure and technology, the need for a continuous and stable electricity supply, and the requirement for specialized expertise. Other challenges are the difficulty in optimizing protocols for every crop, potential risks to genetic diversity, and the need for scientific validation of controlled environments before applying results to field conditions.

Infrastructure and cost

- **High setup costs:** Implementing speed breeding requires advanced controlled environment facilities, which are expensive to establish.
- **Limited access in developing countries:** Many regions with limited resources lack the necessary infrastructure and funding for speed breeding technology.
- **Continuous financial support:** Sustaining research and development for speed breeding requires ongoing financial support.

Environment and management

- **Unstable electricity supply:** Maintaining constant temperature and photoperiods requires high energy use and reliable backup systems, which can be a challenge in areas with unreliable power grids.
- **Precise control:** Maintaining stable environmental conditions like temperature and photoperiod is demanding and requires precise management to prevent damage or genetic loss.

• **Crop-specific optimization:** Protocols must be specifically optimized for each crop, which can be a time-consuming process.

Genetic and biological challenges

• **Genetic diversity:** There is a risk of genetic loss if management of the accelerated process is not carefully controlled.

• **Pest and disease control:** Managing pests and diseases can be difficult when focusing on tracking individuals for gene discovery within a controlled environment.

• **Field validation:** The results from a controlled environment may not directly translate to real-world field conditions, and crops must be validated in diverse environments.

Expertise and labor

• **Skilled personnel:** Speed breeding requires specialized expertise, and the lack of trained plant breeders can be a significant limitation.

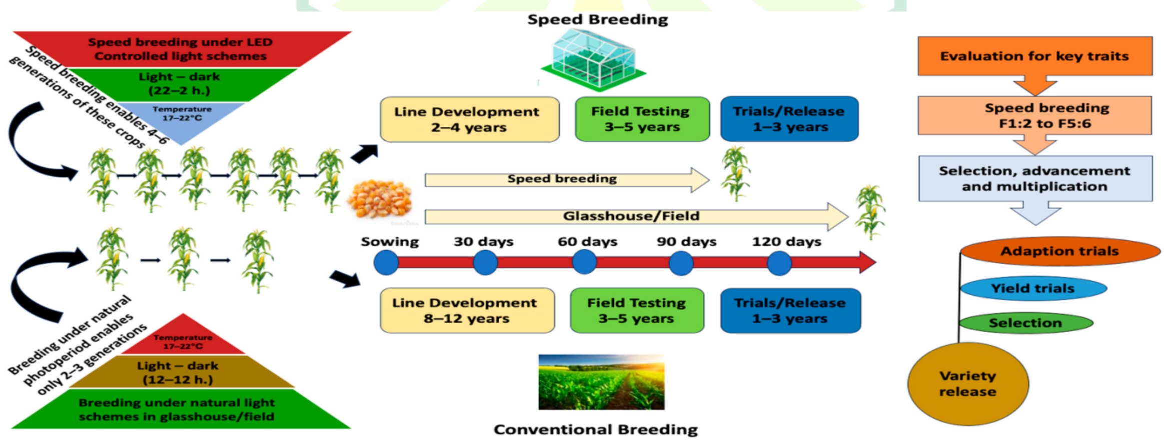
• **Complementary facilities:** Integrating speed breeding with other advanced techniques, such as molecular breeding and embryo rescue, requires additional resources and expertise.

Speed breeding methods:

• **Environmental control:** Manipulating key growth variables is central to the technique.
  ○ **Light:** Using high-intensity, specific-wavelength LED lighting with extended photoperiods (e.g., 22 hours) significantly accelerates growth and flowering.
  ○ **Temperature:** Regulating temperature to optimize plant progression and maturation is crucial for faster development.
  ○ **Humidity and CO2:** While less central, these can also be modified for optimal growth.

• **Population management:** Specific methods are used to manage populations and advance generations quickly.
  ○ **High-density planting:** Growing more plants per area accelerates flowering and maturation.
  ○ **Single seed descent (SSD):** A method where only one seed is selected from each plant to advance to the next generation, which rapidly develops homozygous lines.

• **In vitro techniques:** These are often integrated to overcome challenges like long maturation times.
  ○ **Embryo culture:** Immature embryos are rescued and cultured in vitro to accelerate seed maturation and bypass post-harvest dormancy.
  ○ **Doubled haploid (DH) production:** A technique that generates homozygous lines very quickly and is enhanced by speed breeding.



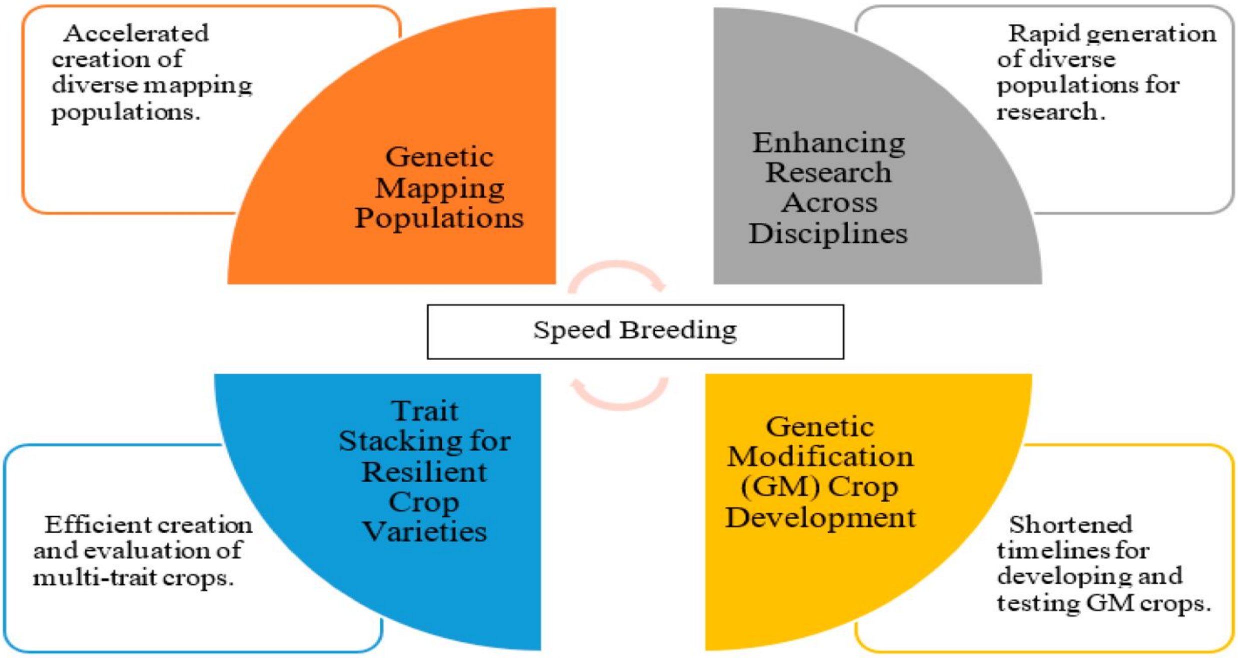
Applications

• **Rapid trait development:** Speeds up the development of new crop varieties with improved traits like yield, quality, and disease resistance.

• **Genetic improvement:** Allows for the rapid introgression of desirable traits into elite varieties through accelerated backcrossing.

• **Gene discovery and mapping:** Enables the fast creation of mapping populations and the phenotypic evaluation of traits like root architecture and disease resistance.

• **Integration with modern technologies:** Works synergistically with other tools, such as:
  - Marker-assisted selection (MAS) and genomic selection (GS)
  - CRISPR/Cas gene editing
  - High-throughput phenotyping and genotyping platforms



Future prospects and advancements

• **Integration with genomics:** Speed breeding is being combined with modern genomic tools such as marker-assisted selection (MAS) and genomic selection to increase genetic gain per year. Integrating these methods allows for more rapid identification of desirable traits and selection of parents for the next generation.

• **Genome editing**: The technology is set to be integrated with genome editing, which will require breakthroughs to avoid tissue culture methods, further speeding up the process of creating new crop varieties.

• **Automation and AI:** Future developments will likely include greater automation and the use of artificial intelligence to predict traits, optimize breeding programs, and manage large datasets.

• **Expansion to new crops:** Speed breeding protocols are being developed and optimized for a wider range of crops, including underutilized cereals and legumes, to increase global food and nutritional security.

CONCLUSION:

Speed breeding approaches can double the annual genetic gains as compared to the winter nurseries. It is highly convenient for crossing studies, gene transformation, plant phenotyping, and mutation studies when combined with speed breeding. Speed breeding is a crucial need for crop improvement, allowing for accelerated development of new crop varieties to address challenges like climate change and food security. It significantly shortens breeding cycles by using controlled environments to hasten plant growth, and when combined with modern techniques like genomic selection, it can lead to faster genetic gain for traits like yield, resilience, and nutritional value. While challenges such as resource intensity and potential impacts on genetic diversity exist, speed breeding is a transformative technology with the potential to greatly enhance global food security and sustainability.

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The Power of Pollinators: Supporting Bee Health in Vegetable Production

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Introduction

Vegetable farms worldwide depend on a quiet workforce- pollinators. Of these, bees are the most important pollinator group with regard to fruit set, fruit shape, and good yields. Due to habitat loss, pesticide use, climate change, and disease, these bee populations are under ever-growing pressure. For vegetable growers, supporting the health of bees is not only an environmental duty, but also sensible agricultural investment. Healthy pollinator communities translate directly into more productive fields and higher-quality produce. This article explores the key link between pollinators and vegetable farming, describes the various threats to bees, and outlines practical steps that growers can take to protect and encourage healthy bee populations.

Why Pollinators Matter in Vegetable Production

Pollination is the transfer of pollen from the male part of the flower, the anther, to the female part, the stigma. While some crops are self-pollinating, many vegetables require insects, mainly bees, to effectively transfer pollen. Without this service, yields drop, fruits become misshapen, and sometimes plants don't produce anything at all.

Most vegetable crops that benefit heavily from bee pollination include:

- Cucumbers
- Squash and pumpkins
- Watermelon and other melons
- Tomatoes and peppers
- Eggplants
- Beans

It has been demonstrated that fields with an abundance of pollinators see higher yields, better fruit quality, better uniformity, and a reduced need for manual pollination. The bottom line is that bees ensure the farm's hard work pays off.

Meet the Pollinators — More Than Just Honey Bees

Though the European honey bee is the most well-known pollinator, vegetable farms rely on a diverse community of species for pollination.

Fig.1. Honey bee and Bumble bees involved in pollination of vegetable crops

1. Honey Bees

Commercial honeybees are widely used for pollination services. Commercial honey bees form large colonies that can be moved readily from field to field and have a cooperative nature, particularly when it comes to the performance of many crops.

2. Bumblebees

Bumblebees are powerful, cold-resistant pollinators. Their "buzz pollination" method makes them especially suitable for plants like tomatoes and peppers, whose pollen is released only with vibration.

3. Solitary Bees

Examples of these are mason bees, leafcutter bees, squash bees, and mining bees. These solitary bees do not stay in hives but nest in the soil, reeds, holes in wood, and stems. They are highly efficient pollinators, often far more effective per bee than honey bees.

4. Other Pollinators

Butterflies, hoverflies, and even some beetles are pollinators. There is a resilience in a diverse pollinator community: if one population declines, others can help play the role.

The Challenges Facing Bee Populations

Multiple interacting factors drive pollinator decline. Understanding these challenges is the first step toward supporting bee health in agricultural systems.

1. Habitat Loss

Large-scale agriculture often replaces natural habitats with regular expanses of uniform fields offering limited food and nesting opportunities. Bees require flowering plants throughout the growing season, not just during crop bloom.

2. Exposure to Pesticides

Certain insecticides, in particular neonicotinoids and other systemic chemicals, may disrupt navigation in bees, diminish reproductive success, and, in extreme cases, kill them. Fungicides and herbicides also have indirect impacts on bees through the reduction of floral diversity.

3. Parasites and Diseases

Varroa mites, Nosema, and various viruses threaten bee colonies. Isolated bees have diseases caused by contaminated nesting materials.

4. Climate Change

Unpredictable weather can lead to early or delayed bloom times of crops or wildflowers, affecting the synchrony between the time of flowering and the activity of its pollinators.

5. Nutritional Stress

Bees need a diverse diet of pollen and nectar. Monoculture farms can sometimes give plenty of food for short lengths of time but can leave very long periods of scarcity.

Pollination Benefits for Vegetable Growers

When pollinators thrive, farmers benefit directly. Improved pollination can result in:

1. Higher Yields

More pollen transfer increases the percentage of flowers that develop into fruits. For example, cucurbits (cucumbers, squash, pumpkins) often rely on dozens of pollen grains for proper fruit formation.

2. Better Fruit Shape and Size

Poorly pollinated vegetables may grow unevenly or become misshapen. Enough pollination reduces variability, so standardization for markets is achieved.

3. Improved Shelf Life

Some studies indicate that fruits from good pollination remain firmer for a longer period, which minimizes post-harvest losses.

4. Less Labour and Lower Costs

Natural pollination eliminates or reduces the need for hand pollination-a very time-consuming and expensive process.

5. Increased Biodiversity

By creating pollinator-friendly atmospheres, beneficial insects, which include predators and parasitoids, will be attracted, helping in the biological control of pests.

How Growers Can Support Bee Health — Farm-Level Practices

1. Plant Pollinator-Friendly Habitats

Planting flowering plants in field edges, irrigation ditches, and buffer zones provides for constant food sources for the bees. Plants should be native species, as they are well adapted to local conditions and offer high-quality nectar and pollen.

2. Provide nesting sites

Different bees have different nesting habits:

- Solitary ground-nesting bees require undisturbed soil patches.
- Cavity nesters benefit from bee hotels, hollow stems, or dead wood.
- Bumblebees favor brush piles, tall grasses, or old rodent burrows.

Avoid over-tilling in areas designated as pollinator habitat to avoid damaging nests.

3. Adopt Bee-Friendly Pest Management

Integrated management or IPM helps in minimizing the use of pesticides while maintaining crop health. Key strategies include:

- Monitoring the population before spraying.
- Applying chemicals only when thresholds are exceeded
- Choosing products with low toxicity to bees
- Spraying late in the evening when bees are less active
- Whenever possible, avoid application during crop bloom

4. Avail water bodies

Bees need clean water for drinking and cooling their colonies. Shallow dishes with stones for landing are simple and effective.

5. Supporting Bees During Crop Bloom

During flowering, fields of vegetables become critical resources to pollinators. Farmers can take steps to maximize bee safety and effectiveness during this period.

6.Avoid Spraying When Bees Are Active. If a crop must be treated

- Spray at night or early morning
- Choose short-residual products
- Use targeted rather than broadcast applications

Increase floral diversity along the field edges Bees prefer diversity in both the shape and colour of flowers. Growing a diverse "pollinator strip" can help support bees during the pre- and post-main crop periods.

7.Hive Placement Strategies

- Place hives when about 5–10% of plants are in bloom
- Make sure hives face morning sunlight to promote early foraging
- Keep water sources nearby to reduce stress
- Reduce Mechanical Disturbance Limit mowing, tilling, and heavy machinery traffic near nesting sites during active pollination periods.

Long-Term Strategies for Sustainable Pollinator Support

1. **Landscape-Level Planning**
   Neighbouring farms have to work together to realize great effectiveness in pollinator conservation. Coordinated efforts-like community wildflower plantings or shared pollinator corridors-create very large, stable habitats that support bee populations year-round.
2. **Diversifying Cropping Systems**
   Crop rotation or cover cropping with flowering species (such as clover, buckwheat, vetch) brings added nutrition for pollinators and improves the condition of the soil.
3. **Participating in Pollinator Certification Programs**
   Programs such as Bee-Friendly Farming™, Xerces Society habitat certifications or local agricultural extension programs offer guidance, recognition and marketing opportunities.

4. **Supporting Research and Extension Services**
   Collaboration with universities and agricultural organizations informs growers regarding, new solutions for pest management Emerging pollinator diseases and best habitat restoration practices.
5. **Community Engagement**
   Educating farm workers, neighbours, and local schools about pollinators improves awareness and increases support for farming that is friendly to the pollinators.

A Future Built on Partnership with Pollinators Vegetable production and the health of pollinators are deeply intertwined. By nurturing the bees and other insects that perform pollination, growers tend to the very foundation of their farming systems. Benefits don't stop at the farm gate; healthy populations of pollinators support food security, biodiversity, and resilient ecosystems. Supporting bees is not just an environmental initiative; it's a practical, profitable, and forward-thinking approach to agriculture. As growers integrate pollinator-friendly practices into their fields, they help build a future, where farming and nature work in harmony together.

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CLIMATE CHANGE MITIGATION AND ADAPTATION THROUGH AGROFORESTRY

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Intergovernmental Panel on Climate Change (IPCC) defines Climate Change as "a change in the state of the climate that can be identified by changes in the mean and/or the variability of properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal process or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use." United Nations Framework Convention on Climate Change (UNFCCC), in its Article 1, defines Climate change" as "a change of climate which is attributed directly or indirectly to human activity alters the composition of the global atmosphere and which in addition to natural climate variability observed over comparable time periods". The effect of climate change can be directly seen in agricultural crop yields because of alterations in temperature and rainfall, and indirectly through changes in soil quality, pests and diseases. Climate change can also affect the structure and function of forest ecosystems. It may worsen many of the threats to forests such as pest outbreaks, fires, drought, etc. Climate changes directly and indirectly affect the growth and productivity of forests and it also affects the frequency and severity of many forest disturbances. Agroforestry is the intentional integration of trees or shrubs with crops and/or livestock at the plot, farm, and/or landscape scale, is one of the potential to climate change adaptation strategy to increase the resilience of farmers and agricultural systems against climate risk, providing a range of biophysical and socioeconomic benefits. As highlighted by recent Intergovernmental Panel on Climate Change (IPCC) reports, agroforestry is a promising agroecological approach to climate change adaptation because of the multitude of benefits that many agroforestry systems provide in addition to climate change adaptation, including synergies with climate change mitigation through carbon sequestration, enhanced food security and income opportunities, the provisioning of ecosystem services, and biodiversity conservation. Initial evaluations of national and global terrestrial CO_2 sinks highlight two key advantages of agroforestry systems, their capacity for short to medium-term carbon storage in trees and soils, and their potential to reduce immediate greenhouse gas emissions from deforestation and shifting cultivation. The amount of carbon sequestered largely depends on the agroforestry system put in place, the structure and function of which are, to a great extent, determined by environmental and socio-economic factors. Several other factors are also influencing carbon storage in agroforestry systems such as tree species and its management practices. The trees play various functions, including shading crops to reduce evapotranspiration, erosion control and nutrient cycling. The regular harvesting of crops, wood and other products, decline in soil fertility can be considered as minimal in complex agroforestry systems. Abundant litter and pruning biomass returned to the soil combined with the decay of roots, contribute to the improvement of soil physical and chemical properties. Considering the significance of agroforestry, India has formed an exclusive national agroforestry policy (2014) to promote the holistic growth of agroforestry practices. Further, the Green India Mission has exclusively highlighted agroforestry interventions. Moreover, recognizing the importance of agroforestry in India, the National Bamboo Mission has been rechristened as National Agroforestry and Bamboo Mission. To mitigate atmospheric carbon and balance their storage in the terrestrial biosphere it is a vital way to compensate for the emission of greenhouse gases. Due to the limited forest area, agroforestry and social forestry plantations serve as pivotal tools to mitigate climate change.

Carbon sequestration potential of agroforestry

The amount of carbon sequestered per unit area by agroforestry is substantial due to the large amount of carbon sequestered in the woody biomass. However, unlike afforestation, agroforestry plantings do not result in a change in land use to forest. Indeed, the appeal of agroforestry as a carbon sequestering activity on agricultural lands rests in large part on its ability to sequester significant amounts of carbon on a relatively small land base. Agroforestry can give the owner the biggest net gain of carbon per unit area generally without compromising agricultural activity. Although the carbon fixed within a single agroforestry planting is small, when considered in the context of the whole farm, the amount can become significant. The extent of C sequestered in any agroforestry system will depend on a number of site-specific biological, climatic, soil, and management factors. The carbon sequestration in agroforestry occurs in two major segments: aboveground and belowground. The aboveground tree carbon pool: This component represents the most easily and reliably reported pool in agroforestry plantings and captures majority of carbon sequestered by this system. Overstorey trees are prime importance and virtually, all the C sequestration projects require aboveground tree biomass estimation. Belowground biomass is a major carbon pool. However, belowground biomass is difficult to measure. There is a constant relationship between aboveground biomass and below ground biomass and root-to-shoot ratio is therefore commonly used to estimate belowground living biomass.Long rotation agroforestry systems such as windbreak, shelterbelts, woodlots, boundary plantation, agrihorticulture, silvipasture, home gardens, and multi-storeyed systems have large potential in carbon storage in biomass. Short rotation systems (agrisilviculture) have high potential for soil carbon sequestration. Fast-growing hardwoods (Eucalyptus, Poplar, Melia, Casuarina, Leucaena, etc.) and tropical bamboos have a large potential for biomass compared to slow-growing species. Carbon sequestration in agroforestry systems varies widely, ranging from 0.29 t C ha^{-1} yr^{-1} in West African Sahel fodder banks to 15.21 t C ha^{-1} yr^{-1} in mixed-species stands in Puerto Rico. In humid tropics, such systems can store over 70 Mg C ha^{-1} in vegetation and up to 25 Mg C ha^{-1} in the topsoil (Nair et al., 2009; Mutuo et al., 2005).

Carbon storage in Agroforestry practices

Agroforestry practices can be better climate change mitigation option than ocean and other terrestrial options because of vast protective and productive benefits. Carbon storage in plant biomass is feasible in the perennial agroforestry systems (perennial–crop combinations, agroforests, wind-breaks, boundary plantations etc.), which allow full tree growth and where the woody component represents an important part of the biomass and can be significant sink of carbon due to their fast growth and high productivity. One comparative advantage of these systems is that sequestration does not have to end at wood harvest. C storage can continue way beyond if boles stem or branches are processed in any form of long-lasting products. The amount of C sequestered largely depends on the agroforestry system being practiced. Other factors influencing C storage in agroforestry systems include tree species, system management, environment and socio-economic aspects. The carbon storage potential of agroforestry systems in different regions of the world varies from 12 to 228 Mg C ha^{-1}. (Handa *et al*.,2020).

Table 1: Carbon Storage Potential of Agroforestry Systems Across Different Regions and Eco-regions (Standardized to a 50-Year Rotation (Source:Murthy *et al.*,2013).

Geographic Region	Eco-Region Type	Agroforestry Practice	Estimated Carbon Storage (Mg C ha^{-1})
Africa	Humid tropical highlands	Agrosilviculture	29–53
South America	Humid tropical lowlands (dry)	Agrosilviculture	30–102 / 39–195
Southeast Asia	Humid tropical dry lowlands	Agrosilviculture	22–228 / 68–81
Australia	Humid tropical lowlands	Silvopastoral	28–51
North America	Humid tropical high and low dry lowlands	Silvopastoral	133–154 / 104–198 / 90–175
Northern Asia	Humid tropical lowlands	Not specified	15–18

Agroforestry and climate change mitigation

Climate Change Mitigation may be defined as any attempt to reduce the rate at which greenhouse gases are accumulating in atmosphere. This can be done by considering two ways by reducing emissions and locking up the main source of carbon through carbon sequestration. Agroforestry attracted special attention as a C sequestration strategy following its recognition carbon sequestration activity under the afforestation and reforestation. AFS provide the climate change mitigation mechanism through CO_2 assimilation and improvement in production environment. Agroforestry systems spread over one billion ha in diverse ecoregions around the world and these woody perennial based land use systems have relatively high capacities for capturing and storing atmospheric CO_2, in vegetation, soil and biomass products. According to the Intergovernmental Panel on Climate Change, agroforestry offers important opportunities of creating synergies between both adaptation and mitigation actions with a technical mitigation potential of 1. 2.2 Gigaton C in terrestrial ecosystems over the next 50 years. The total carbon storage in both aboveground and belowground biomass in an agroforestry system is generally much higher than that of land use without trees under comparable conditions.

Agroforestry and Climate Change Adaptation

UNFCCC defines climate change adaptation as the actions taken to help communities and ecosystems cope with changing climate condition. The IPCC describes it as adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Agroforestry has been proposed as a potential strategy for helping subsistence farmers reduce vulnerability to climate change. Agroforestry trees can also reduce soil erosion in agricultural lands by providing long-term vegetation cover. Finally, trees are considered to be less sensitive to climate-related shocks such as floods and droughts due to their deep root systems. Many research studies have confirmed the specific role of agroforestry which can play a vital role in helping farmers to reduce their vulnerability to climate change. In a nutshell, agroforestry improves farmer well-being by improving farm productivity and incomes. Agroforestry extension services will play an important role in helping farmers understand the value of tree planting. Case study reports of many agroforestry practices have highlighted the role of agroforestry in boosting adaptive capacity. When farmers choose to plant trees on farms, it will help to improve the soil and water quality, leading to increased ecological resilience against drought. Most literatures on adaptation in agricultural landscapes mention the value of agroforestry systems as an adaptation strategy.

Land Use, Land-Use Change and Forestry (LULUCF)

The Intergovernmental Panel on Climate Change (IPCC) 6^{th} assessment report finds that the "Agriculture, Forestry and Other Land Use (AFOLU)" sector on average, accounted for 13-21% of global total anthropogenic GHG emissions in the period 2010-2019. The exchange of carbon cycle between the terrestrial biosphere and the atmosphere could be altered by human activities impact through Land Use, Land-Use Change, and Forestry (LULUCF). The LULUCF sector is important for climate change mitigation as it has the potential to reduce greenhouse gas emissions and sequester carbon. The IPCC report finds that the LULUCF sector offers significant near-term mitigation potential while providing food, wood and other renewable resources as well as biodiversity conservation.

AGROFORESTRY- An option for LULUCF

Among various tools to mitigate carbon cycle, under climate-smart agriculture, agroforestry is a LULUCF activity that is gaining attention because of its potential to build carbon sinks on agricultural lands while allowing food production. The IPCC report issued on 2000 on LULUCF showed significant sequestration potential from activities, particularly in grassland and forest management and agroforestry. The IPCC Special Report suggested an average C accumulation rate in an agroforestry system was about 3.1 tonnes per ha for a 30 to 50-year time horizon. However, these values could be more appropriate for multi-strata agroforestry system like homegarden. Various studies identified the ecological services and carbon potential of the agroforestry practices, makes it a beneficial tool in the LULUCF activities. Additionally, the costs generated in the system can be shared with rural farmers who will benefit from these profitable systems. In most cases agroforestry systems are more profitable than subsistence agriculture.

Challenges and constraints in carbon agroforestry

Despite some of the potential benefits associated with agroforestry systems and carbon sales, there are also challenges and trade-off. Following are the challenges associated with carbon agroforestry:

- The amount of carbon stored in agroforestry systems is minimal and hence may only provide small improvements in income if sold. In order for carbon market, the tree cover need to be expanded which declines the agricultural production.
- Carbon storage in trees may only be temporary if the trees are converted in the future.
- The initial costs associated with entering the carbon market can be high
- Limited access to carbon markets

Another challenge is the fact that currently the exact global area covered by different agroforestry systems is unknown making it difficult to predict the extent to which agroforestry practices may be able to counter carbon emissions. This is further exasperated by the fact that carbon sequestration in agroforestry systems also depends on the system and the environment in which it exists.

Consequently, there is still some work to be done to improve our understanding of C sequestration and GHG mitigation. Critical data and research need in agroforestry includes: Quantifying C dynamics in agroforestry systems, developing effective strategies for measuring and monitoring C sequestration in soil and woody components, more powerful methods to implement cost/benefit analyses of agroforestry-based GHG mitigation and to define incentives for wide scale adoption of agroforestry and developing or implementing a national inventory of agroforestry.

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Carbon Farming - Earning Income from Soil Carbon Storage

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Abstract

Carbon farming, a sustainable agricultural approach that enhances soil carbon sequestration, offers a promising pathway for farmers to generate additional income through carbon credits while simultaneously improving soil health and mitigating climate change. This article explores the principles of carbon farming, economic opportunities from carbon credit markets, global case studies, policy frameworks and challenges to adoption. It synthesizes recent scientific and market insights, highlighting how farms can benefit financially by storing carbon in soils.

Keywords: Carbon farming, soil carbon sequestration, carbon credits, sustainable agriculture, climate change mitigation, regenerative farming, ecosystem services

Introduction

Faced with the urgent challenge of climate change, agriculture is increasingly seen both as a source of greenhouse gas emissions and a potential carbon sink. Carbon farming, sometimes termed regenerative agriculture, focuses on using agronomic practices that increase the organic carbon content in soil, thereby sequestering CO_2 from the atmosphere and improving ecosystem functions (Norton *et al*., 2024). Beyond climate benefits, carbon farming can open new revenue streams for farmers through generation and sale of verified carbon credits, creating economic incentives aligned with environmental stewardship (Earth.org, 2025).

Soil organic carbon (SOC) is a critical metric. Farming practices that build SOC-such as cover cropping, reduced tillage and agroforestry-not only enhance soil fertility and water retention but also offer measurable climate benefits quantifiable for carbon markets (Boomitra, 2025). This article delves into the mechanisms of soil carbon accrual, the pathways to monetization and real-world examples of farmers earning income while benefiting the planet.

Principles and Practices of Carbon Farming

Carbon farming hinges on adopting agronomic techniques scientifically proven to increase SOC stocks or reduce emissions from soils and livestock (Norton *et al*., 2024). Key practices include:

1. **Reduced or no-till farming:** Minimizes soil disturbance preserving organic matter and soil structure.
2. **Cover cropping:** Planting non-cash crops during off-season to improve soil cover and carbon inputs.
3. **Agroforestry:** Integrating trees/shrubs with crops or pasture, adding woody biomass and root carbon.
4. **Organic amendments:** Adding compost or biochar to increase stable carbon pools.
5. **Improved nutrient and manure management:** Optimizing inputs to reduce N_2O emissions and nutrient losses.
6. **Rotational grazing:** Managed grazing increases carbon capture in grassland soils.

Together, these practices create soil systems that act as carbon sinks, measurable across landscapes (Agreena, 2024). Precise soil testing and baseline carbon quantification underpin verification for carbon credits.

Carbon Credits: Financial Incentives for Farmers

Carbon credits represent quantified greenhouse gas emissions reductions or removals. One credit typically equals one metric ton of CO_2 equivalent ($MtCO_2e$) sequestered or avoided (EOS, 2025). Farmers earn credits by shifting to carbon farming practices, which are independently verified and certified for participation in voluntary or compliance carbon markets (Drishti IAS, 2024).

How Carbon Credits Work on Farms

1. **Baseline Establishment:** Measuring existing SOC stocks.
2. **Practice Implementation:** Adoption of carbon-enhancing farming practices.

3. **Monitoring and Verification:** Using standardized protocols to measure carbon changes over time.
4. **Certification:** Through recognized carbon registries and standards (e.g., Verra, Gold Standard).
5. **Credit Issuance and Sale:** Credits can be sold to corporations seeking to offset their emissions.

This process connects farm-level actions to global climate goals while providing direct financial rewards (Grow Indigo, 2025).

Table 1: Examples of Carbon Farming Practices and Credit Generation Potential

Practice	Estimated SOC Gain (t C/ha/year)	Credit Potential (t CO2e/ha/year)	Income Potential (at $15/t CO2e)	Source
No-till	0.2 - 0.6	0.7 - 2.2	$10 - $33	Nortion *et al.* (2024)
Cover Cropping	0.3 - 1.0	1.1 - 3.7	$17 - $55	Boomitra (2025)
Agroforestry	0.5 - 2.0	1.8 - 7.3	$27 - $110	Agreena (2024)
Organic Amendments	0.3 - 1.2	1.1 - 4.4	$17 - $66	Earth.org (2025)
Rotational Grazing	0.2 - 1.0	0.7 - 3.7	$10 - $55	EOS (2025)

Global Case Studies and Market Trends

United States and Europe

Programs like the USDA's Conservation Reserve Program and various EU carbon market pilots have integrated carbon farming incentives with credit trading platforms (Welthungerhilfe, 2023). US companies such as Indigo Ag have pioneered soil carbon programs offering farmers direct payments for verified carbon sequestration, with millions of dollars invested annually (Science.org, 2024).

India's Emerging Carbon Market

India's policy landscape is rapidly evolving with the Energy Conservation Act amendment 2022 facilitating voluntary carbon markets, with the Council on Energy, Environment and Water (CEEW) promoting carbon farming projects (PIB, 2024). Early projects demonstrate how smallholder farmers can engage in carbon credit generation alongside crop production (Boomitra, 2025).

Developing Country Challenges and Opportunities

While emission reductions and income opportunities are promising, transaction costs, verification challenges and equitable benefit distribution remain areas for policy focus to maximize participation and climate benefits (ICAR-CRIDA, 2025).

Financial and Environmental Co-benefits

Carbon farming reduces input costs (fertilizers, fuel), improves soil health and water retention, enhances biodiversity and lowers air and water pollution (Grow Indigo, 2025); (Noble Research Institute, 2024). These co-benefits strengthen the business case for adoption beyond carbon credit revenues.

Policy and Institutional Support

A robust carbon farming strategy requires integration across:

- ✓ **Legal frameworks** supporting carbon rights and credit trading (Drishti IAS, 2024).
- ✓ **Technical support** for measurement, reporting and verification (MRV).
- ✓ **Financial incentives** including subsidies, loan preferential rates and carbon banks.
- ✓ **Public-private partnerships** fostering markets, farmer education and technology transfer (Welthungerhilfe, 2023).

Challenges and the Path Forward

- Low carbon prices relative to transaction costs limit farmer participation.
- Transparent, affordable monitoring technologies are needed for smallholders.
- Integration with existing cropping systems must be farmer-friendly and context-specific.
- Scaling market access while ensuring environmental integrity is paramount (ICAR-CRIDA, 2025).

Continued innovation, policy coherence and inclusive frameworks are essential for carbon farming to become a mainstream, profitable land stewardship pathway globally.

Conclusion

Carbon farming offers farmers a dual opportunity: to contribute meaningfully to climate change mitigation and to earn new income through soil carbon storage. Supported by verified carbon credit markets, enabling policies and co-benefits like enhanced soil health, farmers can transition toward more sustainable and resilient operations while positioning their land as a critical climate asset.

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Agri Business Incubation Centres and Youth Entrepreneurship

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Abstract

Agricultural business incubation centres have emerged as vital platforms fostering innovation, entrepreneurship and sustainable enterprise development in the agrarian sector, especially among youth. By providing access to technology, mentorship, finance and market linkages, these centres empower young agripreneurs to launch and scale innovative agri-startups. This article presents an exhaustive overview of agri incubation ecosystems, explores strategies to integrate youth into agribusiness, highlights successful incubation models in India and discusses policy frameworks catalysing youth entrepreneurship in agriculture. The synthesis illustrates how incubators are shrinking rural unemployment and driving rural economic transformation.

Keywords: Agribusiness incubation, youth entrepreneurship, agripreneurs, agriculture startups, rural employment and innovation ecosystems.

Introduction

The demographic dividend and rising youth populations in rural India and globally create immense potential to energize agricultural modernization through youth-led entrepreneurship (Geza, 2023). However, young rural inhabitants face structural barriers including limited access to land, capital, technical know-how and markets (India Mongabay, 2024). Agri business incubation centers (ABICs) provide dedicated physical and virtual spaces offering training, mentoring, shared infrastructure and financial support, thus reducing barriers to entry and fostering innovative solutions to critical agricultural challenges (CTCRI, 2025); (ICAR, 2025).

Incubation centers underpin policy initiatives like India's Rashtriya Krishi Vikas Yojana-RKVY Innovation Program and Startup India campaign, which incentivize agritech startups and rural enterprises deploying cutting-edge technologies including precision farming, bio inputs, AI-driven advisory services and value-added products (Manage.gov.in, 2023); (AgriStartup.gov.in, 2024).

Agri Business Incubation Ecosystem: Roles and Functions

Agri business incubation centres offer holistic support to early-stage startups and aspiring entrepreneurs in agriculture and allied sectors. Core functions include:

- ✓ **Training and Skill Development:** Focused on agronomic knowledge, business planning, finance management and digital literacy essential for agri startups (CTCRI, 2025).
- ✓ **Mentorship and Networking:** Access to experienced agripreneurs, technologists and business experts to guide innovation scaling (MANAGE, 2021).
- ✓ **Infrastructure and Shared Facilities:** Provision of laboratories, pilot-scale processing units, cold storage and demonstration farms lowers capital expenditure (KCAET Tavanur, 2012).
- ✓ **Market Linkages and Funding Facilitation:** Assistance for connecting to buyers, venture capital and government subsidy programs (NAARM, 2024).

Youth Entrepreneurship in Agriculture: Potential and Challenges

Youth infuse agriculture with innovation but often suffer from:

- ❖ Limited ownership of land, limiting collateral for credit (Geza, 2023).
- ❖ Gaps in entrepreneurial skills and exposure to modern agritech tools (India Mongabay, 2024).
- ❖ Social and familial pressures to seek urban employment over rural agribusiness (RKVY-RAFTAAR, 2025).

- Environmental variability and market uncertainties deterring risk-taking (Agri startup impact report, NAARM, 2024).

Incubators address these by offering tailored capacity building, incubation and assured market access (ICAR ABI units, 2025).

Noteworthy Incubation Centres and Models in India

ICAR-CTCRI Agribusiness Incubation Centre (ABI)

Established in 2019 to catalyse agri startups through skill upgradation, technology demonstration and product incubation. The centre has trained 763 agripreneurs and nurtured diverse ventures from processing to precision farming (CTCRI, 2025).

MANAGE Centre for Innovation and Agripreneurship

A national nodal agency facilitating incubation, innovation-based startup scaling and entrepreneurship promotion. Offers grant support, market facilitation and mentorship to young agripreneurs across states (MANAGE, 2021).

RKVY-RAFTAAR Innovation Program

Supports early-stage agri startups via seed funding (up to ₹25 lakh), mentorship and industry linkage under the Ministry of Agriculture's innovation drive (RKVY-RAFTAAR, 2025).

Impact and Success Stories

An evaluation (AgriClinics.net, 2024) documented over 1,500 agripreneurs generating employment for farmers' children through ventures in organic farming, value-added processing, poultry, agro-tourism and agri-consultancy.

Example:

Mr. Rahul Kumar of Muzaffarnagar transformed from traditional cereal growing to vegetable value addition, expanding income by over 40% and employing local youth (AgriClinics.net, 2024).

Innovation and Technology in Incubation

Agri incubators foster use of:

- **Precision Agriculture Tools:** Drones, sensors for resource optimization.
- **Biotechnology and Microbial Products:** Biofertilizers, biopesticides.
- **Digital Advisory Systems:** AI-driven weather forecasting, soil analytics.
- **E-commerce Platforms:** Direct-to-consumer sales, online marketplaces.

Integrating technology enhances sustainability and income while attracting youth to agriculture (India Mongabay, 2024).

Policy Support and Future Directions

Sustaining agri business incubation requires:

- Increased funding for incubation infrastructure and programs.
- Public-private partnerships for technology transfer and market access.
- Integrating incubation with rural development and employment schemes.
- Entrepreneurship curricula in agricultural education.
- Fostering gender-inclusive policies to empower women in Agripreneurship.

Conclusion

Agri business incubation centres are catalysts transforming the rural economy by nurturing youth entrepreneurship, promoting innovation and creating sustainable agribusiness ventures. By bridging technical knowledge gaps, offering infrastructure and facilitating market linkages, incubators enable young agripreneurs to overcome traditional barriers, enhance farm incomes, generate employment and secure India's agricultural future.

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The Rise of Plant-Based Eating: Changing the Future of Agriculture

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Abstract:

In today's fast-changing world, food choices are not only about taste but also about health, ethics, and the environment. The plant-based diet has emerged as a growing global movement, emphasizing the power of seeds, legumes, grains, fruits, and vegetables in promoting both personal and planetary well-being. Shifting from meat-heavy diets to plant-based ones is useful to reduce the risk of chronic diseases, diabetes, and hypertension, while also minimizing our ecological footprint. This article examines the numerous benefits of plant-based eating—ranging from improved health outcomes to reduced greenhouse gas emissions—and highlights how India, with its rich cultural heritage in vegetarianism, is now spearheading a modern wave of plant-based innovations.

Introduction:

In this modern 20s era, a Plant-based diet is a new approach that has become more popularized in recent years, with the consciousness among people on health, ethics, and the environment. As the name suggests, it mainly includes plant-derived foods such as nuts, legumes, fruits, seeds, and vegetables. Plant-based diets are getting more popular along with an increase in population due to health concerns, as well as ethical concerns regarding animal welfare and climate change (Alcorta et al., 2021). Changing diet to a plant-based based helps to maintain good health but also helps to maintain our climate, preserve our biodiversity, and reduce many negative impacts on our environment. Research studies on plant-based meals have several health benefits, including a reduced risk of cardiovascular diseases, blood sugar control, better bone health, and lowering blood pressure (Wang et al., 2023).

Benefits of eating plant-based diets:

A nutritious plant-based diet focuses on eating plenty of whole, nutrient-rich plant foods while limiting the diet that have already been processed, oils, and animal products such as dairy and eggs. Primarily focuses on consumption of vegetables (both raw and cooked), fruits, legumes like beans, peas, and lentils, as well as soy products, seeds, and nuts (in moderation), with an overall low-fat approach.

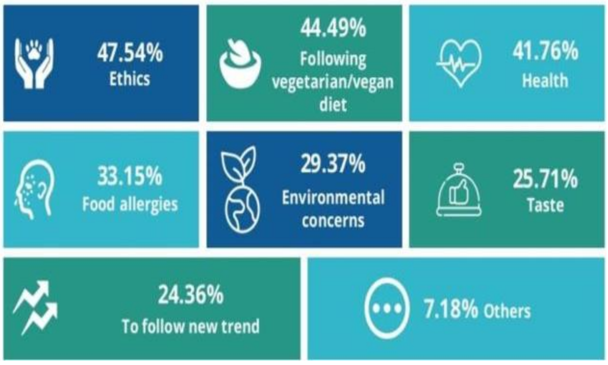

Fig 1: Major reasons for choosing plant-based diets

In America, a study was conducted in 2019 from a previous record of health of a group of middle-aged adults between 1987 to 2016 to explore the connection between plant-based diets and health outcomes. From this study, it was found that people with a good plant-based diet and vegans have a benefit of a decrease in all-cause mortality (18 – 25%), risk of cardiovascular diseases (16%), and cardiovascular disease mortality (31-32%) (Kim et al., 2019).

Naturally, the diets based on plants that are vegan are low in cholesterol and saturated fat. Plant diets are also associated with lower blood pressure levels. This is because the diet does not include too much sodium, fats, or cholesterol, which all raise blood pressure. In addition, vegetarian diets are rich in potassium, which is known to lower blood pressure (Xia et al., 2024).

A vegetarian diet may also help reduce the risk of developing type 2 diabetes, and for those who are suffering from diabetes helpful for maintaining good blood sugar control. This is because vegetarian diets are typically rich in low glycaemic index (Pollakova et al., 2021). Plants are naturally rich in fiber, which is found in all unprocessed plant foods. Fiber forms the structure of plants, and consuming more of it provides numerous health benefits. It helps lower cholesterol, regulate blood sugar levels, and support healthy digestion and bowel movements. Fiber also helps in reducing the risk of cancer (Chibuzo Carole Nweze et al., 2021).

Impact of the animal industry on the environment:

Among all the sources of greenhouse gas emission livestock industry plays a vital role behind all. Actually, the livestock production is responsible for about 11% to 18% of global greenhouse gas emissions, which is more than the entire transportation sector combined. When we talk about climate change, we often think of cars and planes, but the maximum amount of greenhouse gas is produced by ruminant animals like cows and sheep during digestion (Giamouri et al., 2023).

Pollution is another consequence of animal agriculture that we often overlook. The runoff from Animal Farms carries chemicals, antibiotics, and pesticide residues into the waterways, leading to eutrophication, which creates dead zones where Aquatic Life cannot survive. The air around concentrated animal feeding operations can become so polluted that it contributes to respiratory issues and smog (Espinosa-Marrón et al., 2022).

India in choosing plant-based diets:

In recent years, India's interest in plant-based meat products has grown significantly. The country has seen the development of innovative meat alternatives such as kebabs, burgers, and sausages, which can be prepared from plant-based ingredients, viz., mushrooms, soya, and others. This sector is poised for rapid expansion, with the market size projected to rise from its current US$30-40 million to an estimated US$500 million. The number of companies producing plant-based foods has grown to three times what it was in 2010. Additionally, research on plant-based foods has increased threefold over the past three years (Ali & Bharali, 2025).

The Indian government, through the Ministry of Health and Family Welfare's #EatRightIndia campaign, has released posters endorsing the benefits of plant-based diets for fighting climate change and promoting sustainable living.

Conclusion

Adopting a plant-based diet offers a pathway to better health and a cleaner environment. It helps reduce the risks of heart disease and diabetes while cutting down greenhouse gas emissions and pollution caused by animal farming. With India's growing interest in plant-based alternatives, this shift reflects not just a dietary choice but a collective move towards sustainable living and a healthier future.

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Lasora: An underutilized fruit crops

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Abstract:
Underutilized fruit crops, often referred to as neglected or minor fruits, are those fruit species that possess significant nutritional, medicinal and economic value but remain largely unexploited in mainstream agriculture. These crops are traditionally grown in specific regions by local communities and have adapted well to harsh climatic conditions, making them resilient and sustainable options for future horticulture. Despite their rich sources of vitamins, minerals, antioxidants and bioactive compounds, underutilized fruits receive limited attention in research, commercialization and market development.

Introduction:

Lasora (*Cordia myxa* L.), also known as Gonda or lehsua, belongs to the family Boraginaceae. It can be found in moist and dry forests of India, except in high hills and temperate climates. Lasora is a medium-sized, perennial tree with a crooked stem and it bears smooth, small cherry-sized fruits in bunches from March to August.

Use and Composition:

Lasora (*Cordia myxa* L.) stands as a versa-tile botanical gem with wide-ranging applications. Culinarily, its berries, known for their distinctive sweet and sour notes, infuse diverse dishes, from jams to refreshing beverages, adding a burst of favor. Immature green fruits are used as vegetable and pickles. Some time fruits are de-hydrated after blanching for used as vegetable during off season Medicinally, Lasora plays a crucial role in traditional herbal reme-dies, leveraging various plant parts for their anti- infammatory, antipyretic and anti-diabetic properties. Rich in essential nutrients such as Vitamin C, Vitamin A, potassium, and dietary fiber, Lasora's nutritional composition positions it as a health-enhancing food source with potential preventive health benefits.

Soil and Climate Requirement:

Lasora exhibits a preference for well-drained soils with a loamy texture. The ideal pH range for soil is typically neutral to slightly alkaline. Lasora flourishes in tropical and subtropical climates, showcasing its adaptability to a range of temperature and precipitation regimes.

Important varities: CAZRIG-2021, CAZRIG-2025, Maru Samridhi

Thar Bold A prolific and early bearing lasora (*Cordia dichotoma*) has been identifed as "Thar Bold" (CIAH/ LS-3) through selection

Karan Lasora Variety released by Sri Karan Narendra Agriculture University (SKN), Jobner centre with the name 'Karan Lasoda'

Propagation Methods: Seed Propagation, Vegetative propogation, Air layering, Grafting,

Planting Methods: Lasora (*Cordia myxa* L.) cultivation involves strategic planting methods to ensure optimal growth and development.

The following techniques outline the key considerations for successful establishment of Lasora plants. Under arid conditions, the best planting time is during July-August. Systematic planting can be done at a spacing of 5-7m depending upon the rainfall and soil types. Pits of the size of 60 x 60 x 60 cm are dug out during May- June to ensure natural sterilization of soil through intense solar radiation. Pits were filled with using FYM and top soil in the ratio of 1:1. Lasora can be planted as a boundary plantation for shelter belt purpose, for this planting should be done at 5 meters spacing while commercial plantation of improved varieties in arid region should be done at 6x6 m spacing

Seedbed Preparation, Direct seedling, Transplanting seedlings, Grafting and Planting Grafted Seedlings,

Spacing and Plant Arrangement: Proper spacing is critical for Lasora plants to receive adequate sunlight, air circulation, and nutrients. The recommended spacing between plants depends on the specifc variety and the cultivation goals. A well-thought-out plant arrangement maximizes the efficient use of resources and promotes healthy development.

Training and Pruning:

Training involves guiding the growth of Lasora plants to achieve a desired shape or structure. This process typically begins early in the plant's development and continues throughout its life cycle. The budded plants tend to grow laterally. Heading back of the main shoot is done after about two months of the planting leaving about 20-25 cm from ground level. This induces secondary shoots from the remaining portion of the shoots. The upright growing shoots are retained and the rests are pruned. In due course of time 3-4 well spaced upright growing limbs are allowed to develop as main scaffold. The sprouts coming from rootstock portion should in variably be removed as and when they appear. All dried up and over crowded branches should be pruned during the first week of February. Many branches get dried due to gummosis during March-April, such branches should be thinned out after fruit harvest

Flowering, Pollination Behavior and Fruit Set

Harvesting and Yield: Hand picking of green fruit bunches with twigs is a common practice. It ensures picking of mature but unripe fruits for vegetable and pickle preparation and hence there is no need for their further grading. Smaller sized fruit (1–2 cm diameter) are preferred for vegetable or pickle purpose as such fruits have lesser mucilaginous content. Budded trees of C. myxa L. started fruiting at the age of 3–4 years while seedling trees took 5–6 years. Green fruits of 5–10 g are suitable for vegetable and pickling purposes. Fruits should be harvested after 25–35 days of fruit setting during April -May to fetch better price in the market because there is a lean period for availability of other vegetables in the market

Economic yield is obtained after 4 – 5 years from budded plant and 6 – 8 years from seedling plant. Yields vary from 20 to 120 kg depending upon genotype/variety and age of trees.

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Plant-Based Bioplastics: Synthesis Method for Polylactic Acid (PLA)

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Abstract

Polylactic acid (PLA) is ideally one of the most commercially important biopolymers from plant resources, produced using various processes, each of which has its own advantages and disadvantages. This article extensively focuses on the five major pathways of PLA synthesis: melt polycondensation, solution polycondensation, ring-opening polymerization (ROP), solid-state polymerization (SSP), and enzymatic polymerization. General melt polycondensation involves directly heating lactic acid under controlled vacuum and provides a less expensive way through simple procedures and equipment without much need. Solution polycondensation uses organic solvents to remove moisture from the system, thus making superior control of molecular weight at lower temperatures. Ring-opening polymerization (ROP) is the main industrial standard, using a lactide monomer and tin-based catalysts for efficient polymer synthesis. Solid-state polymerization (SSP) acts as a post-polymerization upgrading process under the polymer's melting temperature to increase the molecular weight of the prepolymers. Enzymatic polymerization employing lipase biocatalysts provides an environmentally friendly pathway with mild aqueous or organic solvent conditions and no toxic heavy metal catalysts. This contemporary synthesis methodologies, process parameters, catalyst systems, and emerging technologies which can be thoroughly evaluated for optimizing industrial and commercialization strategies.

Keywords: *Polylactic Acid, Polymerization, Polycondensation, Enzymatic Reaction, Ring Opening.*

Introduction

PLA is one of the most commercially developed plant-based biopolymers, synthesized primarily through lactic acid derived from carbohydrate fermentation or renewable chemical synthesis. The basic polymerization method used in this case is polycondensation, in which monomers having some functional groups such as hydroxyl and carboxyl react directly with one another to form long polymer chains and eliminate small molecules like water or methanol as a byproduct. Polycondensation involves three steps in sequence: activation of monomer, condensation reaction, and driving the reaction to completion. Lactic acid, with its hydroxyl and carboxyl functional groups, undergoes thermal dehydration, which essentially results in the formation of ester bonds under temperature and appropriate vacuum conditions. In the respective identity of lactic acid molecules, the interaction of the hydroxyl functional group of one molecule of lactic acid with the carboxyl functional group of the second molecule results in the elimination of a water molecule, forming ester linkages that gradually further grow into oligomers and ultimately polymers with an ever-increasing molecular weight.

2. Direct Polycondensation Method

The polycondensation method is a polymerization technique in which monomers with functional groups, like -OH and -COOH, react directly to form polymer chains by removing small molecules like water. Polycondensation involves three steps i.e, driving the reaction, condensation reaction, and monomer activation. Both carboxyl and hydroxyl groups are typically present in lactic acid, under vacuum and heat, these groups thermally dehydrate to form an ester bond. One lactic acid molecule's hydroxyl group interacts with another's carboxyl group. By removing water and creating an ester bond, it progressively accumulates oligomers and eventually polymers.

2.1 Melt Polycondensation

Melt polycondensation refers to the bulk polymerization technique which runs above the melting point of polymer without any solvent medium. The process usually involves direct heating of lactic acid or low molecular weight PLA prepolymer at high temperature (180-200 °C), which results in elimination water because of condensation reaction between hydroxyl and carboxyl group. Initially the water content in the product is reduced by dehydration process, which is followed by polycondensation to create intermediate chains and finally it will undergo melt polycondensation process to gain high molecular weight. Throughout the process the system should be kept in molten state in order to support the interaction between molecular chains and progress ion polymerization (Alfa Chemistry, 2025; Theodorou et al., 2023; Kenawy et al., 2024; Kricheldorf et al., 2000).

2.1.1 Critical Operational Parameters

Water must be removed in order to advance the polymerization process because condensation reactions are equilibrium dependent and reversible. The produced water molecules could be efficiently removed by continuous vacuum extraction (often less than 10 mmHg) or purging with inert gas, like nitrogen, to prevent the reversal of equilibrium, which promotes depolymerization. The use of particular catalysts, like tin-based ones, speeds up the reaction and encourages condensation rather than depolymerization. In particular, one of the most widely used catalysts is tin (II) chloride, or $SnCl_2$.

2.2 Solution polycondensation

Solution polycondensation is the process of using organic solvents for azeotropic water removal. It is a sophisticated, direct polycondensation method that produces high-molecular-weight PLA compounds. This process operates at lower temperatures, typically 130-140 °C, compared to the melt polycondensation method, enabling greater control over the polymer's characteristics and noticeably higher molecular weights (Alfa Chemistry, 2025; Kenawy et al., 2024; Kricheldorf et al., 2000; Theodorou et al., 2023).

2.2.1 Solvent Selection and Mechanism

Organic solvents with high boiling points such as toluene, xylene, diphenyl ether or decalin, can be used as solvent in this process. The water released during the condensation reaction can react with high boiling point solvents to form an azeotropic mixture (mixture of two or more liquids that produces vapour with same composition as the liquid, when it is boiled). These solvents dissolve lactic acid and the expanding polymer chains, while a Dean-Stark apparatus or continuous recycling effectively removes water. Diphenyl ether is particularly useful among them due to its high boiling point, which quickens the kinetics of polycondensation.

2.2.2 Process Protocol

The working principle of solution polycondensation involves two steps:1) the initial dehydration of hygroscopic lactic acid using solvent-azeotropic distillation to remove free water; 2) Continuous polymerization with solvent recycling through molecular sieves at lower pressure to remove condensation-formed water. In terms of catalysts, tin-based ones are typically employed, particularly tin(II) chloride [$SnCl_2$] or stannous octanoate [$Sn(Oct)_2$], in combination with a co-catalyst such as 4-toluenesulfonic acid (TSA) for the best reaction acceleration.

2.3 Solid-State Polycondensation Method (SSP)

In this method PLA is synthesized by heating l-lactic acid in solid state at elevated temperature. The temperature usually ranges between 140-160 °C, in the presence of catalyst such as tin (II) 2-ethyhexanoate (SnOct2. SnCl2 or toluenesulfonic acid (TSA)). This technology also addresses a number of melt polycondensation's drawbacks, including racemization, thermal degradation, and operating at extremely low temperatures (120–160 °C for PLA) in contrast to the generally high temperatures of melt polycondensation processes. The selection of catalyst play a major role in reaction rate and resulting molar mass of compound (180-200 °C) (Vírseda et al., 2024; Beltrán et al., 2020; Vouyiouka et al., 2013; Fukushima et al., 2007).

2.3.1 Process Mechanism

SSP processes with chain-end condensation reactions occurring only in the amorphous region of the polymer, while the crystalline domains physically protect the reactive groups and give conversions close to 100 % without reverse depolymerization. Depending on the percentage crystallinity in the prepolymer (preferably about 25-40 %), this value is achieved through controlled thermal annealing before the SSP treatment. Water and other low molecular weight byproducts produced during condensation are eliminated by constant flushing with inert gas (nitrogen) or vacuum systems, which shifts reactions away from hydrolytic degradation and toward chain elongation.

2.3.2 Operational Parameters

SSP treatment consists of heating crystallized prepolymer chips or powder bulk into a fixed bed under flow of controlled nitrogen for a long period of time (6-72 hours, depending on initial molecular weight). Temperature profiles are strictly controlled to avoid pellet agglomeration and thermal runaway. Greater the surface area within the polymerizing solids favors faster evolution of small molecules. The effects of crystallinity have been critically established: the polymerization rate significantly increases when prepolymer crystallinity exceeds 25 %. This indicates that high crystallinity allows for better access to the reactive ends in amorphous regions.

3. Ring-Opening Polymerization (ROP) Process for PLA Synthesis

ROP is the prevailing industrial method used for the synthesis of high-molecular-weight PLA through polymerization of cyclic diester of lactic acid (lactide), with a global annual market of around 300 million pounds. Polymerization of lactide, a cyclic dimer of lactic acid, is carried out under controlled melt conditions, contrasting with direct polycondensation methods in thermodynamic driving force and degree of molecular weight control. (Kricheldorf et al., 2000; Rao et al., 2021; Metkar et al. 2019).

3.1 Monomer Preparation and Mechanism

This monomer preparation process involves creation of lengthy chains of PLA by cleaving cyclic esters' ester bonds in lactide monomers. The process of dehydration and cyclization is involved in formation of lactic acid monomers, which is then followed by ring opening polymerization to obtain PLA with high degree of polymerization. ROP commences with lactide formation and its subsequent vacuum distillation. This process is controlled by selectivity of monomer, initiator and catalyst. The subsequent ring-opening polymerization is thermodynamically driven by relief of ring strain and switching from (E) to (Z) ester conformation upon ring opening. Polymerization follows a coordination-insertion mechanism verified through density functional theory (DFT) calculations, where lactide carbonyl oxygen activates preferentially over ester oxygen for ring cleavage, with stannous octoate operating as a catalyst rather than an initiator.

3.2 Catalyst System and Operational Parameters

It includes a catalyst that quickens the reaction and an initiator that opens the first ring to start the polymerization. Stannous octanoate [$Sn(Oct)_2$], as the FDA-approved standard, is used at concentrations of 100-1000 ppm (parts per million). Alcohol co-initiators, typically benzyl alcohol or fatty alcohols, increase catalytic activity by generating alkoxide species, which create additional active polymerization sites. Polymerization is conducted in bulk at temperatures of 140-180 °C lasting for 2-5 hours. Very recent optimization studies demonstrate that the concentration of catalysts has a strong influence on the yield: catalyst concentrations of sulfuric acid at 40 % versus 60 % show statistically significant differences in final PLA mass, where higher catalyst loadings would, in general, favor higher conversion rates (Amaya & Vaca, 2025).

4. Enzymatic Polymerization Process

Enzymatic polymerization or enzymatic ring-opening polymerization is a new emerging green chemistry route to PLA rather than the traditional chemical catalysis. It uses lipase enzymes as biocatalysts to promote ring-opening polymerization under mild and safe aqueous or organic solvent conditions. The potential advantages of such a biocatalytic scheme in sustainability compared with the conventional chemical catalysis are that it does not use toxic heavy metal catalysts (tin compounds), operates under physiological or near-physiological temperatures, uses environmentally friendly biocatalysts, and provides polymers that can be used in biomedical applications, free from metallic contamination (Sonti, Gore, & Mahesh, 2010; Champagne et al., 2016; Nobes et al., 1996; Zhao, 2017).

4.1 Enzyme Selection and Catalytic Mechanism

Lipases are naturally occurring hydrolytic enzymes which can catalyze ring-opening polymerization through a "reverse hydrolysis" mechanism. In the catalytic site, a serine-histidine-aspartate (Ser-His-Asp) catalytic triad is present; the hydroxyl group of serine residue serves as a nucleophilic center for polymerization mechanism by acyl-enzyme intermediates: lactone approaches an enzyme active site and forms a complex of enzyme-lactone, which undergoes ring-opening to generate an acyl-enzyme intermediate (enzyme-activated monomer), after which nucleophilic attack occurs from hydroxyl groups attached to chain ends or water molecules, regenerating the enzyme. Candida antarctica lipase B (CALB) is, thus far, the best biocatalyst for this process, reaching 60 % conversion of lactic acid and 55 % recovery of solid polymer products upon immobilization (Novozym 435). Recent advances use immobilized laccase enzymes for enzymatic ROP at temperature ranges of 80-130°C, where reaction time is taken from 0.5 to 6.5 wt % of enzyme catalyst and subjected to preliminary vacuum evacuation up to 1-2 hours in order to remove moisture.

4.2 Operational Parameters

The enzymatic polymerization of lactide usually takes place at temperatures between 45 and 130 °C in bulk or organic solvents including toluene, dichloromethane, supercritical CO_2, or ionic liquids. The duration of whole process can take from 1 to 20 days. Molecular weight of resultant compound is influenced most critically by temperature and lipase concentration. Studies have shown that increasing lipase concentration from 3 wt % to 10 wt % at constant monomer conversion actually reduces final molecular weight (Mn), suggesting that one must optimize enzyme concentration. For laccase-catalyzed enzymatic ROP with immobilized enzyme at 80-130 °C for 1-2 hours of evacuation followed by polymerization, reasonably good molecular weights are attained with monomer incorporation ranging from 50-100 %, depending on the enzyme immobilization support (Zhao, 2017). The yield of 54.1 % was obtained from the ideal enzymatic ROP of L-lactide catalyzed by free CALB in a solvent-free environment at 130 °C for one day.

Conclusions

PLA kills different birds with one stone, with varied synthesis methodologies being used to cater to specific industrial and application requirements. Melt polycondensation appears an economical conjunct to inconveniences of the solution. In comparison, ROP extols an upper hand when weighing the standards of molecular weight control for critical applications. Thus, solid-state polymerization can improve the properties of prepolymers in subsequent polymerization. In this same light, enzymatic polymerization is viewed as a green chemistry tool to promote sustainability by means of biocatalysts free from toxic metals, under physiological processing conditions. Future industrial development should address the integrated evaluation of thermal efficiency, environmental sustainability, and economic feasibility. Further catalyst design innovation, novel alternative reaction media, and process optimization will allow PLA to be competitively commercialized with its petroleum analogue while also contributing toward circular bioeconomy implementation.

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UNDERSTANDING THE DISTRIBUTION, BIONOMICS, SYMPTOMS OF DAMAGE, AND MANAGEMENT STRATEGIES FOR INSECT AND PEST INFESTATIONS IS CRUCIAL FOR EFFECTIVE CULTIVATION OF YAMS AND COLCASIA

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Pests of Yam

1.Yam beetles- *Galerucida bicolor* (Chrysomelidae; Coleptera)

- Grubs are whitish in colour, gregarious on leaves and skeletonize them and gnawing into leaf stalk and main stem.
- Red and blue-black beetle feed on leaves
- Eggs are laid in cluster in soil near the plan

Lema lacordarirei (Chrysomelidea: Coleptera)

Binomics

- It feed on the leaves and tender veins.
- Elytra are shiny blue with rust yellow colour
- Eggs are laid groups on leaves and veins
- Grubs are yellow with small head, narrow thorax and thick fleshy abdomen.

Damage symptoms

❖ Tunneling or mining on leaves: Larva feed inside leaves, creating tunnels.

❖ Infested areas turn yellow or brown

❖ Leaf curling or twisting.

❖ Stunting plant growth.

Management

❖ Spraying Azadiractin 1.0%EC (1000ppm) at 400ml/ ac along with sticking agent 1ml/lit of water is recommended for the control.

2. Sawfly-*Senoclidia dioscoreae* (Tenthredinidae; Hymenoptera)

Binomics

- ➢ Egg are laid on young shoots and leaves
- ➢ Larva feed on the leaves and cause defoliation of the entire crop.
- ➢ Grubs are having seven pairs of proleg.
- ➢ Pupation takes place in the soil.
- ➢ Adult have broadly sessile abdomen and typical ovipositor.

Symptoms of damages

- ➢ Holes or tunnels in stem and leaves.
- ➢ Wilting or yellowing of leaves.
- ➢ Swelling or galls on stem.
- ➢ Reduced plant growth

Management

- ➢ Prune damaged foliage and stems

- Insecticide soap kill exposed sawfly
- Spinosad spray can be used as directed to control sawfly larvae
- Imidacloprid 70% WG @3G/ 10lit of water.

3. Hard sacle- *Aspidiotus hartii*

Symptoms of damge:

- Tubers aerial parts covered with whitish yellow scales and Stubers get shrivelled and unfit for seed purpose
- **Binomics:** Nymph are mnute circular, light brown to grey colour with pale membrane. Adults are yellowish and round inside the hard scale.

Binomics:

- Nymphs are oval translucent and yellowish brown with waxy coating
- Female insect are circular, sent transparent and pale brown

Symptoms of damage:

- Nymph and adult infest the leaves
- Suck the sap from leaves tubers
- Yellowish of leaves in patches
- Stunted growth

Management

- ✓ Collect and destroy the affecyed plant parts
- ✓ Field release of coccinelid predators like *Chilocorus nigritius*, *Symnus coccivora.*

Hard scal-*Aspidiotus destructor*

PESTS OF COlOCASIA

1. Four spotted flea beetle- *Monolepta signata* (Chrysomelidae; Coleoptera)

Distribution and status: This white spotted beetle is the most destructive pest of Colocasia. It is polypagous pest, wide range of host plants such as Beetroot, Cabbage, Cauliflower. More severe in South India.

Identification of pest; Adult having reddish brown body and pale brown elytra with two big white spots on each elytron.

Symptoms of damage

- Adult bite holes in leaves, which affect the development of tubers.
- In young plants, severe damage results in complete gestruction of plants.

2**. Leaf eating caterpillar**- ***Olepa ricini* (Erebidae; Lepidoptera)**

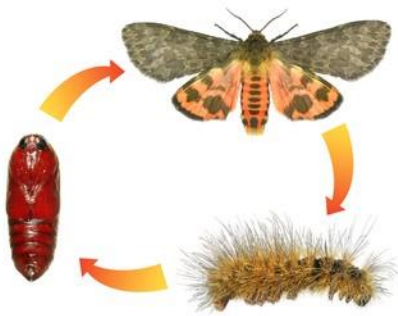
Distribution and status: It is sporadic pest. Larva are nocturnal in habit and caterpillar feed on leaves gregariously and cause defoliation.

Identification of pest:

- ❖ Egg: The female moths lay egg in large number on the lower surface of leaf. Egg are transparent, white to yellow in color.
- ❖ Larva: Black with brown head having long brown hairs
- ❖ Adult: Grey coloured with dark spots on the pimkish hind wings.

Management:

- ❖ Collect and destroy egg masses and caterpillars
- ❖ Use burning torch to kill the congregating larvae
- ❖ Use light trap to attract and kill the adults
- ❖ Spray Chlorpyriphos 20 EC or Quinalphos 25EC 2ml/lit.



Life cycle of Olepa ricini

3. **Sphinx caterpillar-** ***Theretra gnoma*** **(Sphingidae; Lepidoptera)**

Binomics

- ✓ Adult are greenish brown head and thorax with a white lateral stripe
- ✓ Abdomen is brown with a black dorsal patch
- ✓ Forewings are brown with one discal line parallel to outer margin
- ✓ Full grown caterpillar are long with green head .

Management:

- ✓ Collect and destroy the egg masses and caterpillars
- ✓ Use burning torch to kill the congrerating larvae
- ✓ Use light trap to attract and jill the adults
- ✓ Spray Endosulfan35 EC or Malathion 50EC 1.0L
- ✓ Hand picking and destruction of caterpillar in initial stage of attack
- ✓ Spray Emamectin benzoate 5SG- 200gm/ha

4. **Aphid-** ***Pentalonia nigronervosa, Aphis gossypii*****(Aphididae; Hemiptera)**

Binomics:

Aphis gossypii

- ➢ Nymphs and adults are suck the cell sap from tender shoots and leaves and secrete honeydew.
- ➢ As a result, affected parts turn yellow, curl, become deformed and ultimately die away.

Management:

- ✓ Clip – off and destroy the affected shoots and twisting along with crowed pest population.
- ✓ One or two spraying of Acephate 95% SG – 790gm/ha or Fipronil 5% SC – 800- 1000ML/ha.
- ✓ Dimethoate 0.5% or Methyl demeton 0.5% will manage the pests.

5. Lacewing bug or Tingid- ***Stephanitis typicus*** **(Tingidae; Hemiptera)**

Identification of pests: Nymph are yellow colour, occur in under surface of the leaves
Adult yellow colour with minute fringed wings, seen in under surface of leaves.

Management

- ➢ Collect and destroy the damaged leaves, flower and fruits along the life stage.
- ➢ Use yellow sticky trap at 15 Nos/ha
- ➢ Spraying of Dimethoate 30 EC – 850ml/ha or Methyl demeton 25 EC 2ml/lit will manage the pest.

Adult

Leaf damage

6. Thirips- ***Helionothrips haemorrhoidalis, Caliothrips indicus*****(Thripidae; Thysanoptera)**

Binomics: Nymphs are pale green to greenish- brown and Adult are dark brown with black.

Symptoms of damage:

- ➢ This is commonly called as green house thrips

- Besides causing usual damage, nymphs also deposit faecal globules all over leaf lamina on which fungus develops and cause browinish patches.

Management

- Spraying of Dimethoate 30% EC- 660ml/ha or Fipronil 5% SC 800- 1000ml/ha or Dimethoate or Methyl demeton 0.5% will manage pest.
- Field release of Coccinelid predators like lacewing ladybird beeles.

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PESTS OF CAULIFLOWER (CRUCIFEROUS VEGETABLES) AND ITS MANAGEMENT

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Introduction

Cauliflower crops are susceptible to several common insect pests that can significantly reduce yield. Major pests include the diamondback moth, cabbage white butterfly, cabbage aphids, and cabbage loopers. These pests can damage leaves, stems, and even the developing heads, impacting the overall health and marketability of the crop. Effective pest management strategies are crucial for successful cauliflower cultivation.

1. **Diamond back moth, *Plutella xylostella*, (Plutellidae: Lepidoptera)**

It is a major pest of all cruciferous vegetables and cabbage and cauliflower are major host crops.It is cosmopolitan pest and enjoys worldwide distribution.

Identification

Adult is a small greyish moth, which when at rest shows a series of three yellowish diamond shaped markings dorsally on the wings.

Eggs are yellowish-white with greenish tinge.

Female lays up to 57 eggs

Larva is a pale-green caterpillar with minute warts and brownish at the anterior end.

It pupates in a thin transparent gauze-like cocoon on the foliage.

Egg

Larva

Pupa

Adult

Symptoms

1. Larva feeds on foliage and causes serious damage by defoliation. Leaves have a withered appearance or eaten up completely.
2. Larva damages cabbage and cauliflower fruits also.
3. It make holes on them and soiling them with excreta.
4. Scraping on leaves causes whitish patches with small windows.

Scrapping on leaves

Larva feeds on foliage

Withered appearance

Management

- Remove all debris and stubbles after harvest – plough the field.

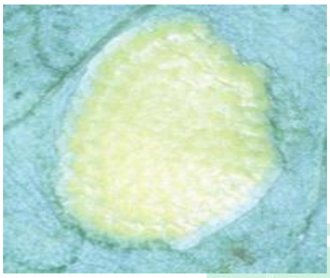
- Cover the nursery with nylon net (50 mesh) to protect the seedlings from DBM attack.
- Intercrop with mustard
- Install pheromone traps at 12 Nos/ha.
- Spray cartap hydrochloride 1 g/lit or Bacillus thuringiensis 2 g/lit or carbosulfan 25 EC 2ml/l or quinalphos 25 EC 2ml/l
- ETL: 2 larvae/plant • Spray NSKE 5 % + Teepol or Sandovit 0.5ml/l after primordial stage
- Release parasitoid *Diadegma semiclausum* / *Cotesia plutellae* at 50,000/ha, 60 days after planting.

2. **Leaf Webber - *Crocidolomia binotalis* (Pyraustidae, Lepidoptera)**

This is a serious pest of cabbage and other crucifers. It is commonly called as **cabbage cluster caterpillar.** It is distributed throughout India, South-east Asia, Australia and Africa.

Identification

- **Egg** – in mass; overlapping flat eggs; 5-15 days
- **Larva** – red headed with brown longitudinal stripes and rows of tubercles with short hairs on its body; 24-27 days
- **Pupa** – cocoon within webbed leaves and flowers or in earthen cocoon
- **Adult** – small, light brownish forewings.


Egg


Larva


Adult

Management

1. Remove and destroy the webbed leaves along with caterpillars.
2. Use light trap at 1/ha to attract and kill adults
3. Spray carbaryl 0.1% or malathion 0.1% at fortnight interval
4. Encourage the activity of parasitoid like *Apanteles crocidolomiae.*

3. **Aphids** – ***Brevicoryne brassicae*** *and* ***Lipaphis erysimi,*** (Aphididae; Hemiptera)

The aphids are yellowish green (*B. brassicae*) and multiply parthenogenetically.

Identification

Aphids are small, soft-bodied, pearl-shaped insects that have a pair of cornicles (wax-secreting tubes) projecting out from the fifth or sixth abdominal segment.

Symptoms of damage:

- Both nymphs and adults suck the sap from leaves, buds and pods
- Curling may occur in infested leaves and at advanced stage plants may wither and die
- Plants remain stunted and sooty molds grow on the honey dew excreted by the insects
- The infected filed looks sickly and blighted in appearance


Sooty mould grow on the curd


Aphids

Management:

- ✓ Use tolerant varieties like JM-1 and RK-9501
- ✓ Destroy the affected parts along with aphid population in the initial stage
- ✓ The crop sown before 20th October escapes the damage
- ✓ Set up yellow stick trap to monitor aphid population
- ✓ Conserve the natural enemies: Ladybird beetles viz., *Coccinella septempunctata, Menochilus sexmaculata, Hippodamia variegata*
- ✓ Spray the crop with one of the following in the flowering stage: oxydemeton methyl, dimethoate @625-1000 ml per ha

4. **Tobacco caterpillar** – ***Spodoptera litura*** (Noctuidae; Lepidoptera)

Symptoms

Eggs are laid in clusters on under surface of leaves. Young larvae feed gregariously and skeletonize the leaves. Large larvae bore into heads. The infestation starts in the nursery itself so one should need to take preventive measures while preparing the nursery beds to avoid the main field infestation.

Identification

Egg: Laid in masses which appear golden brown.
Larva: Pale Greenish with dark margins. Gregarious in the early stages and later turn to dark brown.
Pupa: Brown and pupates in soil.
Adult: Adult Moth is Brownish color.
Forewings are brown color with wavy white markings.
Hindwings are white color with brown patches along the margin.


Egg


Larva


Pupa


Adult

Management

- Place light trap to monitor and kill the attracted adult moths.
- Install sex pheromone trap at 5 Nos./acre to monitor the activity of the pest.
- Grow castor along border and irrigation bunds.
- Remove and destroy the egg masses in castor and other host crops.
- Remove and destroy the early stage larva .
- Hand pick and destroy the gown up caterpillars.

5. Cabbage butterfly - ***Pieris brassicae*** (Pieridae; Lepidoptera)

It is distributed all along the Himalayan regions.

Identification

- Eggs (flask-shaped and yellowish) are laid in cluster of 50 to 80 on leaf surface
- Larva - Velvetty bluish green with black spots, yellow dorsal and lateral stripes covered with white filaments
- Adult is a snow-white butterfly with black markings on wings


Egg


Larva


Adult

Symptoms

- Larva – gregarious in early stage, skeletonize thus it cause defoliation
- Later stage – disperse, bore into heads

Larva defoliage the leaves

Skeletonization

Management

- Field sanitation
- Hand picking of grubs
- Timely irrigation
- Adult prefers seedlings for egg laying + larval feeding
- Early sowing of the crop to escape the damage
- Spraying of chemicals like quinalphos 0.05% / endosulfan 0.07% / dichlorvos 0.05% or Malathion 0.1%

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SUCKING PESTS OF BHENDI AND THEIR MANAGEMENT

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INTRODUCTION

Abelmoschus esculentus is cultivated throughout the tropical and warm temperate regions of the world for its fibrous fruits or pods containing round, white seeds. It is among the most heat- and drought-tolerant vegetable species in the world and will tolerate soils with heavy clay and intermittent moisture, but frost can damage the pods. In cultivation, the seeds are soaked overnight prior to planting to a depth of 1–2 cm (3⁄8–13⁄16 in). It prefers a soil temperature of at least 20 °C (68 °F) for germination, which occurs between six days (soaked seeds) and three weeks. As a tropical plant, it also requires a lot of sunlight, and it should also be cultivated in soil that has a pH between 5.8 and 7, ideally on the acidic side. Seedlings require ample water. The seed pods rapidly become fibrous and woody and, to be edible as a vegetable, must be harvested when immature, usually within a week of pollination. The first harvest will typically be ready about 2 months after planting, and the pods will be approximately 2–3 inches (51–76 mm) long.

Leafhopper: Amrasca biguttula biguttula (Cicadellidae; Hemiptera)

Identification: Adults are small having **wedge shaped body** and greenish yellow in colour

Nymph

Adult

Life-history:

The females lay about 15 yellowish eggs on the underside of the leaves, into the leaf veins. The eggs hatch in 4-11 days and give rise to nymphs which are **wedge-shaped and are very active**. They pass through six stages of growth in 7-21 days. On transformation into winged adults, they live for 5-7 weeks, feeding constantly on the plant juice.

Symptoms of damage:

- This pest attacks the crop at its early stage of growth.
- The adults and the nymphs suck the cell sap from the leaves.
- As a result the **leaves curl upwards** along the margins and have a burnt look **(hopper burn)** which extend over the entire leaf area**. Hopper burn symptom.**
- The affected plants show a stunted growth.

Management:

- Spray 750 ml oxydemeton methyl 25EC or 625 ml of dimethoate 30EC or 100 ml of imidacloprid 17.5SL in 500 litres of water per ha.
- At the time of sowing smear the seed with imidacloprid 75WS or thiamethoxam 30FS @ 5g/kg seed.

Thrips: *Thrips tabaci* (Thripidae; Thysanoptera)

Identification:

- Eggs, inserted into the plant tissue by the female
- Nymphs - Very minute, slender, yellowish and microscopic.

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- Adult - Small, slender, yellowish to brown with fringed wings
- Hatch in about 6 days there are two larval stages that require about 6 days for completion

Nymph **Shrivelling**

Symptoms of damage:

- Shriveling of leaves due to scrapping of epidermis
- Attacked terminal buds – have ragged edges
- Silvery shine on the undersurface of leaves

Management:

- Use resistant / tolerant varieties.
- Spraying of any Neem product (5% Neem oil before egg laying) or 5 kg Neem Kernal extract per acre with any sticky matter
- Predatory thrips, coccinellid beetles, and anthocorid bugs are biological control agents that feed on both nymphs and adult

Whitefly: *Bemisia tabaci* (Aleyrodidae; Hemiptera)

Identification: Adults are winged, they are 1.0-1.5 mm long and their yellowish bodies are **slightly dusted with white waxy powder**. They have two pairs of pure white wings and have prominent long hindwings.

Life history:

The females lay **stalked eggs** singly on the underside of the leaves, averaging 80-110 eggs per female. The total lifecycle completed in 14-100 days depending on weather conditions.

Symptoms of damage:

- The milky white minute whiteflies and nymphs suck the cell sap from the leaves.
- **The affected leaves curl and dry**.
- The affected plants show a stunted growth.
- Whiteflies are also responsible for transmitting **yellow vein mosaic virus (YVMV).**
- Interwoven network of yellow veins encompassing with islands of green tissues on leaves. Later, entire leaves turn yellow.

Whitefly **Damaged symptom**

Management:

- 4-5 foliar sprays of Imidacloprid 17.5SL (0.002%) and Dimethoate (0.05%) at an interval of 10 days effectively controls the whitefly population.

Aphid: *Aphis gossypii* (Aphididae; Hemiptera)

Identification:

- The **adults** are **small, greenish brown and soft-bodied insects** found in colonies on the tender parts of the plants and under surface of the leaves.
- The adults exist in both winged and wingless forms
- **Life-history:** The winged and wingless females multiply parthenogenetically and viviparously. In a day, a female may give birth to 8-20 nymphs. The nymphs moult four times to become adults in 7-10 days.

Symptoms of damage:

- The damage is caused both by the nymphs and adults by sucking plant sap.
- Severe infestation results in **curling of leaves, stunted growth and gradual drying and death of young plants**.
- Black **sooty mould** develops on the honey dew of the aphids which falls on the leaves.
- Dry condition favour rapid increase in pest population and younger plants are more susceptible than older ones.

Nymph

Curling of leaves

Management:

- Spray 750 ml oxydemeton methyl 25EC or 625 ml of dimethoate 30EC or 100 ml of imidacloprid 17.5SL in 500 litres of water per ha.
- At the time of sowing smear the seed with imidacloprid 75WS or thiamethoxam 30FS @ 5g/kg seed.

Solenopsis mealy bug*: Phenacoccus solenopsis* (Pseudococcidae; Hemiptera)

Identification:

✓ The **adult female** is yellowish in colour, oval in shape and **covered with white mealy powder.**

✓ The female adults are wingless; however, **male adults** are having **one pair of wings**.

✓ The **nymphs** are pale yellow with reddish eyes, which are later on covered with white mealy mass

Life history:

A female lays 300-700 eggs usually in an ovisac beneath her body. The newly emerged nymphs **(crawlers)** crawl out and start feeding on tender parts plants. The total life cycle of female is completed in 25- 38 days whereas of male in 17-24 days.

Symptoms of damage:

- Both **nymphs and adults** suck the sap from leaves, flower buds, petioles, twigs, fruits and even from the stem of the plants.
- The insect heavily sucks the sap from the plant and renders it weak, feeble and dehydrated.
- In severe cases development of sooty mould takes on honeydew produced by mealy bugs.
- The **sooty mould reduces the photosynthetic ability of the plants.**
- The fruits infested with mealy bugs reduces the marketability of the fruit.

Mealy bug infestation

Management:

In case of severe infestation, spray 1.25 litres of profenophos 50EC or 2.0 litres of quinalphos 25EC or 625 g of thiodicarb 75WP in 500 litres of water.

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Dusky cotton bug: *Oxycarenus hyalinipennis* (Lygaeidae; Hemiptera)

Identification: Dark brown and have dirty white transparent wings.

Life-history:

The cigar shaped eggs are laid on plant. The eggs are usually laid in groups. The egg and nymphal periods respectively vary from 6-10 days and 30-50 days.

Symptoms of damage:

The **nymphs and adults** suck the sap from immature seeds, whereupon these seeds may not ripen, lose colour and remain light in weight.

Management:

- Spray 750 ml oxydemeton methyl 25EC or 625 ml of dimethoate 30EC or 100 ml of imidacloprid 17.5SL in 500 litres of water per ha.
- At the time of sowing smear the seed with Imidacloprid 75WS or Thiamethoxam 30FS @ 5g/kg seed.

Dusky cotton bug

Dusky cotton bug infestation

Red cotton bug : *Dysdercus cingulatus* (Pyrrhocoridae; Hemiptera)

Identification:

- ✓ In **adult**, the body is predominantly red with transverse white marking on the ventral surface.
- ✓ The forewings are half (anterior) reddish brown with a black dot each and half black the hindwings, black.
- ✓ The eyes, antennae and legs are blackish.

Life-history:

The eggs are laid in clusters of 80-100 in cracks of the soil or dry leaves near the plants. The nymphs hatch out in about 7 days and become adults in 40-85 days.

Symptoms of damage:

- Both **nymphs and adults** suck the leaf and fruit sap.
- The plants become weak and stunted, the **leaves and fruits may curl up**.

Management:

- Spray 750 ml oxydemeton methyl 25EC or 625 ml of dimethoate 30EC or 100 ml of imidacloprid 17.5SL in 500 litres of water per ha.
- At the time of sowing smear the seed with Imidacloprid 75WS or thiamethoxam 30FS @ 5g/kg seed.

Red Cotton Bug

Red cotton bug infestation

Red spider mite: *Tetranychus urticae* (Tetranychidae; Acarina)

Identification:

They are minute in size, and vary in color (green, greenish yellow, brown, or orange red) with **two dark spots** on the body.

Life-history:

Eggs are round, white, or cream-colored; egg period is two to four days. Upon hatching, it will pass through a larval stage and **two nymphal stages (protonymph and deutonymph)** before becoming adult. The lifecycle is completed in one to two weeks. There are several overlapping generations in a year. The **adult lives up to three or four weeks**.

Symptoms of damage:

- The infestation of mites is mostly observed during the warm and dry periods of the season.
- **Nymphs and adults suck cell sap** and whitish grey patches appear on leaves.
- Affected leaves become mottled, turn brown and fall.
- Under severe infestation the top canopy of the **plant is covered by webbing of mites**.
- The mite infested plants can be identified from the distance by the characteristic **mottling symptom** produced on the upper surface of the leaf.

Management:

- Release of predatory mites such as ***Phytoseinlus persimilis, Phytoseinlus ovalis, Amblysius persimilis.***
- Spray any one of the **Acaricides**,
- Abamectin 2ml/liter, Propargite 2ml/liter, Profenophos 2ml/liter, Difenthiuron 2g/2ml/liter and avoid using Wettable Sulphur and dicofol

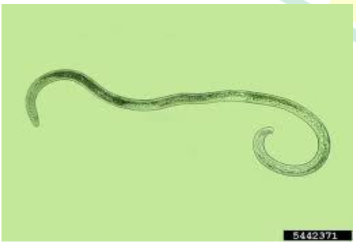
Root-knot nematode: *Meloidogyne incognita* (Heteroderidae; Tylenchida)

Symptoms of damage:

- The root-knot nematode enters the roots causing characteristic **root knots or galls**.
- The **aerial symptoms** consist mainly of stunted plant growth and yellowing of leaves.
- Nematode attack in the seedling stage leads to **pre- and post-emergence damage resulting in reduced crop stand.**

Management:

- Cultural control methods such as rotation with non-host crops such as cereals, fallowing and deep ploughing 2-3 times in summer months is recommended.
- Protect the seedling in its early stage of plant growth.
- Application of Nemagon (30 litres/ha) with irrigation before sowing is recommended



Root Knot Nematode

Root knots or Galls

Integrated pest management practices in Bhendi:

- Sowing of **YVMV resistant cultivars** viz. parbhani kranti, makhmali, tulsi, Anupama1, Varsha Uphar, Hisar Unnat, Arka anamika, Hisar Naveen and Sun-40 etc., especially during kharif season of the crop.
- **Seed treatment** with imidacloprid 70WS or thiomethoxam 30FS @ 5gm/ kg of seed.
- **Grow maize/sorghum on borders** as a barrier to prevent the entry of shoot & fruit borer adults.
- Set up yellow sticky and delta traps for whiteflies.
- Erection of **bird perches** @10/acre in the field for facilitating bird predation.

- Give two to three sprays of NSKE @ 5% alternating with sprays of pesticides, if needed, against leafhopper, whitefly and mites etc.
- Install pheromone traps @ 5/ acre for monitoring of *Earias vittella* moth emergence. Replace the lures after every 30-40 days interval.
- Release **egg parasitoid *Trichogramma chilonis* @1-1.5 lakh/ ha** starting from 30-35 days after sowing, 4-5 times at weekly interval for shoot & fruit borer.
- Shoot & fruit borer, *Earias vittella* if crosses ETL (5 % infestation), spray cypermethrin 25 EC @ 200 g a.i/ha or spinosad 45SC @ 0.3 ml/lit or emamectin benzoate 25WG @ 0.4 gm/lit is effective against.
- Rogue out the YVMV affected plants, if any, from time to time.
- Periodically remove and destroy the borer affected shoots and fruits.
- Need based application of chemical pesticides viz. imidacloprid 17.8SL @ 150 ml/ha, cypermethrin 25EC @ 200 g a.i/ha (0.005%), quinalphos 25EC @ 0.05% or propargite 57 EC @ 0.1 % for control of leafhoppers, whiteflies, borers and mites.

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BORER AND DEFOLIATER PEST OF BHENDI AND THEIR MANAGEMENT

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Introduction:

Bhendi (Okra), scientifically known as ***Abelmoschus esculentus***, is an important vegetable crop cultivated in tropical and subtropical regions worldwide. It is highly valued for its **tender, immature pods**, which are rich in vitamins (A, B and C), minerals and dietary fiber. Bhendi is a **versatile crop** grown in various soils and climate conditions, making it a staple vegetable in many countries, especially in Asia and Africa. Bhendi is susceptible to various pests, which can significantly reduce the yield and quality. Effective pest management in bhendi involves integrated pest management practices (**IPM**), including the use of resistant varieties, cultural methods, biological controls and judicious application of pesticides. The following are the most common pests in bhendi.

1. Shoot and fruit borer: *Earias vitella, E. insulana* (Noctuidae; Hemiptera)

Distribution: Pakistan, India, Sri Lanka, Bangladesh, Myanmar, Indonesia, New Guinea and Fiji. More abundant in South India than North India.

Host range: Oligophagus, cotton, bhendi, hibiscus, holly hock and other malvaceous vegetables.

Bionomics: Egg period: 3-5 days. 385-400 eggs / female. Spherical, **light bluish**, green, crown shaped, laid singly on shoot tips, buds, flowers and fruits. Larva: 10-17 days. Six instars.: Pupa: 6-10 days. Pupates in an **inverted boat shaped silken cocoon**.

Stage	*E. vitella*	*E. insulana.*
Larva	Brown, with longitudinal white stripes on dorsal side as against for	Cream coloured body with orange dots on prothorax
Adult	Forewings are pale white with a broad **wedge shaped** horizontal **green** patch in the middle.	Cream coloured body with orange dots on prothorax
		

Symptoms of damage:

- Larva bores into tender terminal shoots in the vegetative stage and flower buds, flowers and young fruits in the fruit formation stage.
- The damaged shoots droop, wither and dry up.
- The infested fruits present a deformed appearance and become unfit for consumption.
- Bore holes plugged with excreta.

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Management:

- Grow **resistant cultivars** like AE 57, PMS 8, Parkins Long green and Karnual Special
- Collect and destroy infested shoots, buds, flowers and fruits.
- Remove the **alternate hosts** like *Hibiscus cannabinus*, *H. abelmoschus* and *Abutilon indicum* in the cropped area.
- Release egg parasitoid *Trichogramma chilonis* and larval parasitoid *Chelonus blackburnii*.
- Release **first instar larvae of *Chrysoperla carnea* @ 1 lakh/ha.**
- Set up light traps to monitor the moths and their egg laying @ 12/ha
- Set up pheromone traps @ 5/ha.
- Spray *B.t* formulation such as dipel @ 2 g / lit.
- Spray **carbaryl 50% WP 1 kg** or endosulfan 35 EC or monocrotophos 36 WSC 1.0 L or NSKE 5% or Azadirachtin 5% 400 ml or Fenpropathrin 30 EC 250-340 ml or Pyridalyl 10 EC 500-750 ml with 500 L – 700 L water/ha. 2)

2. Okra fruit borer: *Helicoverpa armigera* (Noctuidae; Hemiptera)

Identification:

Adult: Stoutly built, large brown or yellowish brown moth, about 20 mm long and dark specks that make **V- shaped marks** on the **forewings** and a conspicuous black spot in the centre. The hind wings are light and dull-coloured with black border.

Larva: It measures 35-45 mm long and is greenish with dark broken grey lines along the sides of the body.

Life cycle:

Egg Larva Pupa Adult

The female lay eggs singly on the tender parts of the plants. A single adult female can lay 300-500 eggs in 4-7 days. The incubation period of eggs is 3-6 days. The larval period is 13-18 days. The full grown larva pupates in soil. The pupal period last for 815 days.

Symptoms of damage:

The young larvae on hatching feed on foliage for some times and later bore into the fruits with **their bodies hanging outside**.

Management: Collect and destroy the infected fruits and grown up larvae.

- Spray carbaryl 50WP 2 g/lit or profenophos 0.05 per cent or *Bacillus thuringiensis* var. *kurstaki* 2 g/lit.
- Do not spray insecticides after maturity of fruits. Apply nuclear polyhedrosis virus (HaNPV) @250-500 larval equivalent/ha.
- Collect Grow simultaneously **40 days old American tall marigold and 25 days old tomato seedling at 1:10 rows to attract *Helicoverpa* adults for egg laying.**
- Setup pheromone trap with Helilure at 15/ha
- Six releases of *T. chilonis* @ 50,000/ha per week coinciding with flowering time
- Release *Chrysoperla carnea* at weekly interval at 50,000 eggs or grubs / ha from 30 days.

3. Leaf roller: *Sylepta dergota* (Crambiade; Lepidotera)
Distribution: It occurs throughout India
Identification:
Moths are yellowish-white, with black and brown spots on the head and the thorax. They measure about 28-40 mm across the spread of wings and have a series of dark brown wavy lines on the wings.
Life-history:
The female moth lay 200-300 eggs singly on the underside of the leaves. The incubation period of eggs is 2-6 days. The larval period is 15-35 days. They pupate either on the plant, inside the rolled leaves or among the plant debris in the soil. The pupal duration last for 6-12 days. The adult live for a week. The **life cycle is completed in 23-53 days**.
Symptoms of damage:
- The larvae feed on okra leaves.
- In severe infestation, the plants may be completely defoliated.
- Young larvae feed on the lower epidermis of leaves while older larvae roll up the leaves from edges towards the mid-rib.

Life cycle of Leaf roller

Management:
- Release egg parasitoid *Trichogramma chilonis* and larval parasitoid *Chelonus blackburnii*.
- Release **first instar larvae of *Chrysoperla carnea* @ 1 lakh/ha.**
- Set up light traps to monitor the moths and their egg laying @ 12/ha
- Set up pheromone traps @ 5/ha. Spray *B.t* formulation such as dipel @ 2 g / lit.
- Spray **carbaryl 50% WP 1 kg** or endosulfan 35 EC or monocrotophos 36 WSC 1.0 L or NSKE 5% or Azadirachtin 5% 400 ml or Fenpropathrin 30 EC 250-340 ml or Pyridalyl 10 EC 500-750 ml with 500 L – 700 L water/ha. 2)

4. Shoot weevil: *Alcidodes affaber* (Curculionidae; Coleoptera)
Identification of the pest:
Grubs: Apodous and creamy yellow in colour
Adults: Dark greyish brown with pale cross bands on elytra
Symptoms of Damage:
Grub feeds on stem and galls are formed in the stem and petiole and adults feed on leaf buds and terminal shoots and cause withering of shoots
Management
- Soil application of Carbofuran 3 G at 30 kg or Aldicarb 10 G at 10 kg/ha on 20 DAS and earthed up.
- Basal application of FYM 25 t/ha or 250 kg/ha of neem cake.

Shoot Weevil

5. Stemweevil: ***Pempherulus affinis*** (Curculionidae; Coleoptera)

Stem weevil

Identification of the pest:

Grubs are white in colour without leg (apodous)

Adults are very small weevil, dark in colour with two small white patches on the elytra

Symptoms of damage:

- Swellings on the stem just above the ground level.
- Young plants are invariably killed and older plants lack vigor and strength, and **when strong winds blow, these plants break at the nodes.**

Management:

- Neem cake @ 500 kg / ha at the time of last ploughing
- Carbofuran 3G @ 30Kg or phorate 10 G @ 10 kg / ha

6. Semiloopers: ***Anomis flava, Xanthodes graelsii, Tarache nitidula*** **(Noctuidae; Lepidoptera)**

Symptoms of damage: Caterpillar feeds on the leaves and cause defoliation

Identification of the pest

i ***Anomis flava*** - Green coloured semi looper, with five longitudinal white stripes

ii ***Xanthodes graelsi*** - Green coloured semi looper, with horseshoe markings on each segment

iii ***Tarache nitidula*** - Green coloured

Management:

- Release **first instar larvae of *Chrysoperla carnea* @ 1 lakh/ha.**
- Set up light traps to monitor the moths and their egg laying @ 12/ha
- Set up pheromone traps @ 5/ha.
- Spray *B.t* formulation such as dipel @ 2 g / lit.
- Spray phosalone 35 EC @ 2ml/lit

7. Blister beetle: ***Mylabris pustulatus*** **(Meloidae; Coleoptera)**

Identification:

The adult is about 2.0-2.5 cm in length and bears **red or reddish orange and black** alternating bands on the forewing (elytra).

Life-history:

Each female lays about 100-2000 eggs depending on the quality of the food they ingest. The eggs are usually laid in the soil. Upon hatching, the **grub feeds on soil dwelling insects**, including pests, and do not cause any damage to the crop. The grubs have several instars, with two or more different forms of larva. The mobile first instar grub is known as **triungulin** because it has **three-clawed legs**. During later instars, it becomes less active, and then pupates.

Symptoms of damage: The **adult is the destructive stage** and as the insects feed on the flowers and they can cause significant yield losses.

Management: Pick off beetles by hand (wear gloves or use insect nets) and destroy and Spray thiodicarb 0.09 per cent controls the pest.

The Next Generation of GM Crops: CRISPR and Beyond

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1. Introduction:

Global agriculture is entering into a critical phase of transformation as it confronts the intertwined challenges of rapid population growth, adverse climate change, scarcity of natural resources and increased pest and disease incidence. By 2050, the world population is expected to reach nearly 10 billion, requiring food production to increase by at least 50% (FAO, 2021). However, conventional plant breeding is constrained by long generation times, limited genetic variation and environmental instability. These limitations make it difficult for traditional breeding methods alone to respond to rapidly evolving agricultural challenges.

Early genetic modification technologies were introduced in the 1990s marking the significant milestone by enabling the transfer of beneficial genes across species boundaries (James, 2018). These first-generation GM crops, such as Bt cotton, herbicide-tolerant soybean and virus-resistant papaya resulted in improved yield stability and reduced pesticide dependence. Nonetheless, they faced the problems of high regulatory costs, transgene-associated controversies, limited precision and public acceptance surrounding "foreign DNA"

The breakthrough discovery of CRISPR-Cas genome editing has revolutionized plant biotechnology by providing an efficient, flexible and remarkably accurate system for modifying plant genomes (Doudna & Charpentier, 2014). In contrast to traditional GM methods, CRISPR does not require the introduction of foreign genes. CRISPR enables precise edits within a plant's native genome, mimicking natural mutations but in a predictable and targeted manner. This shift dramatically reduces both the developmental timeline and biosafety concerns associated with older GM technologies, marking the beginning of what many consider the **"next generation of genetically modified crops."**

2. Evolution of Genetic Modification: From Transgenics to Gene Editing:

First-Generation GM Crops (Transgenics)

First-generation GM crops, introduced in the mid-1990s, relied on transgenic technology where genes from unrelated organisms were inserted into plant genomes to confer desirable traits. The most common outcomes included insect resistance (Bt crops) and herbicide tolerance, which significantly reduced pesticide use and improved farm productivity. These crops played a major role in boosting yields and stabilizing agricultural systems in many countries. However, the process involved random gene insertion, resulting in potential gene disruption and variable expression levels. Despite their success, reliance on foreign DNA led to public criticism and regulatory challenges highlighting the need for more precise genetic tools.

Limitations of Traditional Transgenics

- Random insertion of foreign genes can disrupt native DNA.
- High development and regulatory costs make the process expensive.
- Long approval timelines slow down deployment of new traits.
- Public skepticism persists due to concerns about "foreign DNA."
- Limited ability to engineer complex, multi-gene traits.

3. Transition Toward Precision Technologies:

As the limitations of traditional transgenics became increasingly clear, researchers began seeking methods that could modify plant genomes with greater accuracy and predictability. Advances in molecular biology revealed the potential of targeted nucleases, enabling scientists to move beyond random gene insertion. Early systems like ZFNs and TALENs demonstrated that precise DNA cuts were possible, but they were technically complex and costly. This growing demand for efficiency, precision and reduced regulatory burden paved the way for breakthrough genome-editing platforms. The emergence of CRISPR-Cas systems revolutionized crop biotechnology by offering a simple, programmable and highly accurate tool for genome modification. This shift marked the beginning of a new era in developing next-generation, climate-resilient and publicly acceptable GM crops.

CRISPR-Cas Systems: A Precision Revolution: CRISPR-Cas systems have transformed genetic engineering by offering an unprecedented level of precision and control in modifying plant genomes. Unlike traditional GM methods, CRISPR relies on a guide RNA to direct the Cas nuclease to a specific DNA sequence, enabling targeted edits with minimal off-target effects. This technology allows scientists to create gene knockouts, introduce beneficial mutations or fine-tune regulatory elements with remarkable efficiency. CRISPR significantly accelerates crop development timelines, reducing years of breeding work to just a few seasons. Its ability to edit native genes without adding foreign DNA has also improved public acceptance and streamlined regulatory pathways. Together, these advantages position CRISPR as a cornerstone of next-generation agricultural biotechnology.

Table 1. Comparison Between Traditional GM and Advanced GM

Feature	**Traditional GM (Transgenics)**	**Advanced GM (CRISPR & Beyond)**
Type of Genetic Change	Random insertion of foreign genes (transgenes)	Precise edits to native genes: transgene-free options
Accuracy	Low–moderate precision	Very high precision
Time Required for Development	10–15 years	2–5 years
Cost of Development	Very high	Lower
Public Acceptance	Lower due to “foreign DNA” concerns	Higher, especially for transgene-free edits
Regulatory Complexity	Strict, lengthy GMO regulations	More flexible
Off-Target Effects	Higher risk due to random integration	Lower due to targeted mechanisms

4. Beyond CRISPR: Next-Generation Editing Tools

While CRISPR-Cas9 revolutionized genome editing, newer tools are pushing the boundaries of what is possible in crop improvement. Base editors allow single-letter DNA changes without making double-strand breaks, enabling precise correction of point mutations. Prime editing goes even further, functioning like a “genetic word processor” capable of targeted insertions, deletions and substitutions with high accuracy. Meanwhile, advanced systems such as Cas12a, Cas13 and epigenome editors offer greater flexibility, improved targeting range and the ability to modify gene expression without altering DNA sequences. These emerging technologies open the door to engineering complex traits like drought tolerance, enhanced nutrition and disease resistance with unprecedented precision. Together, they represent the next frontier in modern crop biotechnology.

Table 2: Crops Improved Using CRISPR-Beyond Tools

Crop	**Advanced Tool Used**	**Trait Improved**	**Key Gene Target(s)**	**Reference**
Rice (*Oryza sativa*)	Prime Editing	Disease resistance, nutrient improvement	*Pi-ta, SWEET genes*	Hua *et* al., 2022
Rice (*Oryza sativa*)	Base Editing (C→T / A→G)	Herbicide tolerance, yield, grain quality	*ALS, Wx, NRT1.1B*	Li *et* al., 2024
Wheat (*Triticum aestivum*)	Base Editing	Enhanced disease resistance	*MLO, TaGW2*	Li *et* al., 2023
Maize (*Zea mays*)	Cas12a (Cpf1)	Multigene editing for yield & stress tolerance	*ARGOS8, ZmPPR*	Wang *et* al., 2023
Tomato (*Solanum lycopersicum*)	Prime Editing	Trait improvement without donor DNA	*ALS, SlAGL6*	Xu *et* al., 2022
Soybean (*Glycine max*)	Base Editing	Oil quality modification	*FAD2, GmSACPD*	Cai *et* al., 2020
Sorghum (*Sorghum bicolor*)	Base Editing	Biofortification, stress tolerance	*BADH2, SUS*	Zuo *et* al., 2022
Rapeseed / Canola (*Brassica napus*)	Base Editing	Fatty acid profile engineering	*FAD2*	Cheng *et* al., 2021

5. Applications of Advanced Genetic Modification (CRISPR and Beyond).

- Developing climate-resilient crops with enhanced tolerance to drought, heat, salinity, and flooding through precise gene edits.
- Engineering disease-resistant varieties by targeting susceptibility genes or creating rapid resistance against viruses, fungi and bacteria.
- Improving nutritional quality by boosting vitamins, minerals and essential amino acids.
- Enhancing crop yield and productivity via edits that influence flowering time, biomass accumulation and resource-use efficiency.
- Accelerating domestication of wild species using multiplex editing to introduce several desirable traits simultaneously.
- Extending shelf-life and post-harvest stability by modifying ripening genes or reducing enzymatic spoilage.
- Developing hybrid seed systems through targeted manipulation of fertility genes for efficient breeding programs.
- Enabling precise trait stacking without the regulatory or biological challenges of traditional transgenics.

6. Limitations of Advanced GM (CRISPR and Beyond)

- Off-target mutations still possible, especially in crops with large or complex genomes.
- Trait expression can vary across environments due to G x E interactions.
- Delivery of editing components (Cas enzymes, gRNAs) remains challenging in certain species, limiting transformation efficiency.
- Regulatory uncertainty persists globally, with differing policies on gene-edited crops slowing adoption and commercialization.
- Ethical and public perception issues continue, particularly around irreversible genome edits and potential ecological impacts.
- Polygenic traits remain difficult to edit, as they require coordinated changes across multiple genes and pathways.

7. Future Prospects for Next-Generation GM Crops

- Ultra-precise editing platforms (prime editing, base editing, RNA editing) will enable fine-tuning of traits without introducing double-stranded breaks, reducing unintended mutations.
- Multiplex genome engineering will allow breeders to edit dozens of genes at once, accelerating improvement of complex traits such as yield, stress resilience and nutrient efficiency.
- De novo domestication of wild species will create entirely new crop varieties tailored for adverse climates and sustainable farming systems.
- Synthetic biology–driven crops will be engineered to produce pharmaceuticals, biodegradable materials, high-value metabolites or carbon-capturing traits.
- Climate-smart GM crops will be designed to thrive in extreme environments, helping secure global food supply amid increasing climate volatility.
- Greater regulatory harmonization is expected as more countries adopt science-based policies distinguishing gene-edited crops from transgenics.
- Public engagement and transparent communication will strengthen societal acceptance, ensuring broader adoption of safe and beneficial GM innovations.
- Field-deployable CRISPR systems may allow on-site editing or rapid response to emerging pathogens, transforming crop protection strategies.

8. Conclusion

The emergence of CRISPR and next-generation gene-editing tools marks a turning point in modern agriculture, offering unprecedented precision and flexibility compared to traditional transgenic approaches. As regulatory frameworks evolve and scientific literacy grows, advanced GM crops are poised to become mainstream components of sustainable food systems. With continued investment in research, ethics and public engagement, next-generation GM technologies will reshape the future of agriculture and strengthen global food security for the decades ahead. India's diverse and vibrant agriculture stands at a pivotal moment, where these modern approaches can help crops thrive despite rising climate pressures, pests and shrinking resources. CRISPR and beyond offer the opportunity to enhance the resilience of staples like rice, wheat, pulses and millets without compromising their traditional value. By blending modern science with India's rich farming heritage, advanced GM technologies can support farmers, strengthen food security and build a more sustainable future for generations to come.

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PHYTOHORMONES –THE HIDDEN FORCES BEHIND PLANT LIFE

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Abstract

Plant hormones, or phytohormones, are natural chemical messengers that regulate every stage of a plant's life—from seed germination to growth, reproduction, and aging. These hormones work in extremely small amounts yet play powerful roles in shaping plant form and function. The major phytohormones, including auxins, gibberellins, cytokinins, ethylene, and abscisic acid, each contribute uniquely to plant development. Auxins guide root and shoot formation, gibberellins promote stem elongation and flowering, cytokinins support cell division and tissue growth, while ethylene and abscisic acid help plants respond to stress, fruit ripening, and senescence. Emerging hormones such as jasmonates, strigolactones, and brassinosteroids further expand our understanding of plant regulation. This article provides a simple overview of how these hormones work, their roles in agriculture, and their importance in maintaining plant health and productivity. It aims to make the complex world of phytohormones accessible to readers and highlight their significance in modern plant science.

Introduction

Plant hormones or phytohormones are organic substances produced naturally in plants that, in very small quantities, regulate physiological processes such as growth and development (Thimann, 1948). The term hormone was coined by Ernest H. Starling and it was derived from the Greek word "hormaein", which literally means "to stimulate" or "to set in motion". Later, research by these scientists showed that certain compounds regulated plant growth, thus giving birth to the concept of plant hormones. Following the identification of auxin in the 1920s as the first growth-regulating substance, the term plant hormone became widely adopted. These compounds regulate plant growth and development throughout the life cycle—from seed germination to maturation and senescence. Though there are many plant hormones, some of the major plant hormones are auxin, gibberellin, cytokinin, ethylene and abscisic acid. However some phytohormones are recently added to this list such as strigolactones, jasmonates and brassinosteroids. This article and the successive paragraphs below mainly focus on the basics of the major phytohormones and their influence on plant growth and development.

MAJOR HORMONES

Plant hormones, or phytohormones, are internally produced signalling molecules that coordinate essential physiological activities in plants, including growth, developmental transitions, reproductive processes, and responses to environmental stress (Taiz et al., 2015; Davies, 2010). These compounds are generally grouped according to their primary functional roles. The **growth-promoting hormones**—such as auxins, gibberellins, and cytokinins—support processes like cell expansion, division, and organ formation (Hopkins & Hüner, 2009). In contrast, **growth-inhibiting hormones,** particularly ethylene and abscisic acid, regulate functions such as dormancy, senescence, and stress adaptation (Taiz et al., 2015). A third class includes **defense- and stress-related hormones,** which do not primarily stimulate or suppress growth but instead enhance the plant's ability to tolerate adverse environmental or biological challenges (Davies, 2010).

AUXIN

Auxin is a type of hormone which is required for cell division. It is found in radicle and plumule of seedlings. Auxin is produced in a plant's shoots and roots, enabling the formation of early root development. Some most common auxin types are indole-3-acetic acid (IAA), Indole-3-pyruvic acid (IPyA), indole-3-acetaldoxime (IAOx), indole-3-acetonitrile (IAN), indole-3-acetamide (IAM), and indole-3-acetaldehyde (IAAld). In modern days, synthetic auxins are produced and widely used as agrochemicals. Auxins are also responsible for tropism in plants. It is caused by the redistribution of auxin across the tissues because of light stimulations. This helps to increase the height of the shoot. Auxins have been effectively applied in modern agriculture for over 60 years. It is used as an herbicide to control grass weeds. Synthetic auxins are primarily used to manage broad-leaf weeds in small-grain crops such as wheat, and they are occasionally applied to control certain sedge species as well. Some of the most commonly used synthetic auxins are 2, 4-dichloro phenoxy acetic acid (2,4D) and dicamba to control weed. Auxin can also be used to control dormancy in seeds and tubers. It can inhibit the germination of seeds; hence the seeds can be stored for a longer time. Regular application of synthetic auxins in fruiting plants can have a huge impact on overall yield as it can reduce the production of an abscission layer on a fruit preventing premature dropping of fruit.

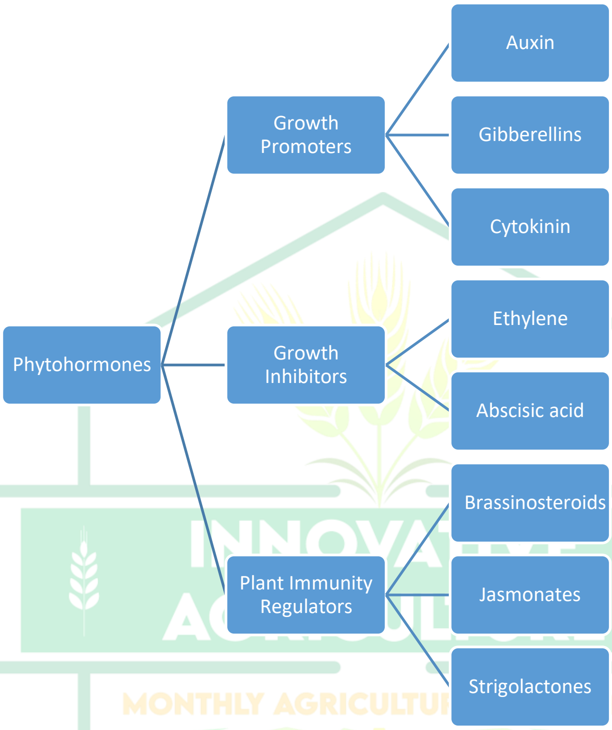

Fig. 1. Classification of Phytohormones based on their role in plant growth and development

GIBBERELLINS

Gibberellins are a class of plant hormones that promote strong growth and vitality in plants. It was first discovered by Takahashi in 1998 when the rice had a disease named Bakanae disease. This disease caused rice plants to grow abnormally tall while preventing them from blooming, resulting in no flower formation. By 2023, almost 100 types of gibberellins had been identified and are labeled as GA1, GA2, GA3…GA10, and so on. Gibberellins are known to induce height in plants thus they can help to increase the height of dwarfs and cancel genetic dwarfism. It is also seen that GA3 can encourage germination in seeds, and it is one of the reasons for the bolting of plants as it elongates the plant internodes. It has also been seen that GAs can move inside the plant in both the direction i.e., from root to shoot and from shoot to root. Excess of gibberellins can cause a plant to bolt resulting in early flowering and this can be used to induce flower production in horticultural and floricultural plants. This method can be applied to obtain early seed production in certain plant species, such as onion and mustard. Gibberellins are 500 times better in inducing parthenocarpy in comparison to auxins. Gibberellins can also delay in ripening of certain fruits like strawberries, pears and tomatoes. Applying GA3 to soybean leaves can increase the internode length of their shoots. Also, it can influence the pith of the xylem and phloem.

CYTOKININ

Cytokinin was first discovered by Miller et al. and has the ability to enhance plant cell division. Cytokinin is a plant hormone that helps control various processes, including cell division, seed germination, and several others. The first naturally occurring cytokinin, Zeatin, was isolated from maize seeds in 1964. Cytokinins are chiefly present in actively developing regions of both the above-ground and below-ground parts of plants. It also aids in regulating the plant's responses to light conditions, stress, and nutrient availability, allowing the plant to grow in a more optimized manner. Cytokines are transported from shoot to root through phloem and if produced by root then the xylem is used to transport it to shoot. Cytokinins can improve seed germination when seeds are exposed to stress conditions such as salinity or heavy metals. They are thought to regulate leaf size by influencing cell division and cell growth. Cytokinins can also either delay or accelerate the process of leaf abscission. In recent times there has been a lot of research done on apples to conduct tissue culture and develop a standard protocol. It has also been seen that cytokinins have an effect on fruit softness.

ETHYLENE

Ethylene is the only hormone that is in gaseous form and is known to regulate numerous functions in plants such as biotic and abiotic stress. It is well-known as an indicator of the final stages of plants thus inducting the senescence of the plant. Ethylene is also recognized for regulating several key stages of plant growth. It also has positive effects on horticultural crops and fruits by helping them to ripen. Due to its gaseous form, this hormone can move easily, so it is typically produced close to where it is needed. Ethylene is extensively utilized in both the fruit-ripening industry and the ornamental flower industry. The production of ethylene is in very small amounts at the start of fruit production, once the fruits are mature enough there is a boost in the production of ethylene thus ripening the fruit. It is also seen that if ready to ripe fruits are exposed to ethylene there is a boost in production in the fruit thus forcing it to ripe. Ethylene is also known to oppose the effects of ABA and GA. It can also enhance seed germination, and root growth and increase oxygen availability in submerged plants.

ABSCISIC ACID

Abscisic acid (ABA) is a hormone which inhibits growth. It is also called the stress hormone as it helps the plant to adapt to stressful situations like dehydration, reduction in daylight and many more factor. Some of the well-known function of ABA includes stomatal regulation, senescence and weakening of the effect of other hormones. ABA is a messenger that shuts down the stomata during drought helping to reduce water loss. ABA is considered a negative hormone because it can counteract the effects of other positive hormones such as GAs, auxins, and cytokinins. At normal conditions, it can play a crucial role in tillering, flowering, production, and maturation of seeds. ABA is the only hormone that opposes all other hormones and can diminish their effects and interfere with the functioning of other hormones. ABA is one of the important hormones which triggers the senescence of the plant. ABA also acts as a negative/inhibiting hormone which can inhibit seed germination and post-germination growth.

CONCLUSION

Plant hormones have been used commercially in agriculture and horticulture for many years. They are being used for various sorts of things ranging from improving quality, increasing yields, increasing shelf life, etc. Each and every plant hormone has its own role in the proper functioning of the plant and getting an optimum result. However, there are many more areas of focus to completely understand the functioning of hormones and how they work by mixing with each other.

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Seaweed Fibre: A Marine-Based Innovation for Sustainable Textiles

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Abstract

Seaweed fibre is an innovative and eco-friendly material gaining prominence in the sustainable textile industry. Derived from marine algae, particularly brown seaweed, this regenerated cellulose fibre—commonly known as *Seacell*—is produced through environmentally friendly processes such as the Lyocell method. It combines the softness, breathability, and strength of cellulose with the bioactive properties of seaweed, including the presence of vitamins, minerals, and antioxidants. These unique characteristics make seaweed fibre not only comfortable and durable but also beneficial to skin health, offering antibacterial, anti-inflammatory, and UV-protective functions. Seaweed fibre is applied in fashion, activewear, baby clothing, and wellness-oriented textiles, as well as in medical applications like bandages and wound dressings. Despite challenges such as high production costs and limited large-scale availability, seaweed fibre represents a sustainable solution for the future textile industry, aligning with global demands for eco-conscious and functional fabrics.

Introduction

The growing concern for environmental sustainability and consumer health has encouraged the textile industry to seek innovative alternatives to conventional fibres. Among various bio-based materials, seaweed fibre has emerged as a promising option due to its renewable origin and functional properties. Seaweed, abundantly available along coastlines, is a rich source of bioactive compounds such as vitamins, minerals, and antioxidants. When incorporated into regenerated cellulose fibres through advanced processing methods, these compounds remain active, making the fibre unique for both ecological and functional textiles.

Commercially known as *Seacell*, seaweed fibre is manufactured using the Lyocell process, which employs a closed-loop system that minimizes chemical waste and energy consumption. This makes the fibre production not only sustainable but also aligned with green textile innovation. Beyond its environmental appeal, seaweed fibre is highly valued for its softness, breathability, moisture absorption, and therapeutic benefits, making it suitable for a range of applications from fashion to medical textiles.

Despite these advantages, challenges remain regarding large-scale production, cost competitiveness, and consumer awareness. Nevertheless, seaweed fibre is gaining recognition as a material of the future, merging marine resources with textile technology to create fabrics that are not only sustainable but also enhance human well-being.

Applications of Seaweed Fibre in Textiles

Seaweed fibre is finding increasing use across diverse segments of the textile industry due to its unique combination of comfort, sustainability, and functionality:

1. **Fashion and Apparel** – Its soft, silky texture and breathable properties make it ideal for luxury clothing, lingerie, scarves, and eco-fashion collections.
2. **Sportswear and Activewear** – With natural UV protection, breathability, and antibacterial qualities, it is highly suitable for outdoor and performance-oriented apparel.
3. **Baby Clothing** – The hypoallergenic, skin-friendly, and soothing properties of seaweed fibre make it safe and comfortable for sensitive baby skin.
4. **Medical Textiles** – Used in wound dressings, bandages, and therapeutic garments due to its antibacterial and healing-promoting characteristics.
5. **Wellness and Home Textiles** – Seaweed fibre is incorporated in bedding, towels, and spa wear, enhancing comfort while providing skin-care benefits.

6. **Eco-Fashion and Blended Fabrics** – When blended with cotton, silk, or wool, it enhances softness, functionality, and sustainability while maintaining durability.

Properties of Seaweed Fibre

Seaweed fibre possesses a unique combination of physical, chemical, and functional properties that distinguish it from conventional textile fibres. Physically, it is soft, lightweight, and smooth with a silky luster, making it comfortable to wear and aesthetically appealing. The fibre has good breathability and excellent moisture absorption, allowing it to regulate body temperature and keep the wearer cool and dry. It also exhibits high drape and flexibility, comparable to natural luxury fibres such as silk and cashmere. Chemically, seaweed fibre retains valuable bioactive components from seaweed, including vitamins, minerals, amino acids, and antioxidants, which remain permanently embedded in the fibre structure even after repeated washing. These bioactive substances are gradually released in contact with the skin, providing therapeutic and skin-care benefits. Functionally, seaweed fibre offers antibacterial and anti-inflammatory properties, making it suitable for sensitive skin and medical textiles. It also provides natural UV protection, safeguarding the wearer against harmful sun radiation. Additionally, it is fully biodegradable and produced through eco-friendly processes like the Lyocell method, enhancing its environmental sustainability. However, the fibre has moderate tensile strength and requires blending with other fibres such as cotton, wool, or polyester to improve durability and extend its applications. Overall, seaweed fibre combines comfort, functionality, and ecological responsibility, making it a highly promising material for the future of sustainable textiles.

Challenges of Seaweed Fibre in Textiles

Despite its remarkable properties and sustainability, seaweed fibre faces several challenges that limit its widespread use in the textile industry. One of the primary issues is the high production cost, as extracting seaweed and processing it through advanced methods like the Lyocell technique requires specialized technology and significant investment. This makes seaweed fibre less competitive compared to conventional fibres such as cotton or polyester. Another challenge is the limited large-scale manufacturing capacity, as seaweed fibre production is still in its early stages and lacks widespread industrial infrastructure. Additionally, the fibre's moderate tensile strength can restrict its use in heavy-duty applications, often necessitating blending with stronger fibres to enhance durability. Consumer awareness is another barrier, since eco-friendly innovations like seaweed fibre are still relatively new and not widely recognized in the mass market.

There are also concerns related to the sustainable harvesting of seaweed, as overexploitation of marine resources could disrupt coastal ecosystems if not managed responsibly. Furthermore, the availability of seaweed fibre-based fabrics is currently restricted to niche markets and luxury segments, which limits its accessibility for mainstream consumers. Overcoming these challenges requires technological advancements, cost reduction strategies, and greater promotion of eco-friendly textiles to establish seaweed fibre as a viable and sustainable alternative in the global textile industry.

Future of Seaweed Fibre in Textiles

The future of seaweed fibre in textiles appears highly promising as the global fashion and textile industries shift towards sustainability and circular economy models. With increasing consumer demand for eco-friendly, biodegradable, and wellness-oriented fabrics, seaweed fibre stands out due to its unique combination of comfort, bioactivity, and environmental responsibility. Ongoing advancements in fibre extraction and processing technologies are expected to reduce production costs and enhance fibre strength, enabling large-scale commercialization. Future innovations may also focus on functional textiles, where seaweed's natural antibacterial, anti-inflammatory, and UV-protective properties can be harnessed for medical clothing, sportswear, and skincare-integrated apparel. Moreover, collaborations between marine biotechnologists, fibre engineers, and fashion designers could unlock new applications in luxury fashion, smart textiles, and home furnishings. However, the future success of seaweed fibre will depend on sustainable seaweed cultivation practices, government support, and investment in green technologies to avoid overexploitation of marine resources. If these challenges are addressed, seaweed fibre has the potential to revolutionize the textile sector, offering a balance between innovation, health benefits, and environmental sustainability for the next generation of fabrics.

Conclusion

Seaweed fibre represents a remarkable innovation in the pursuit of sustainable and functional textiles. Derived from renewable marine resources, it not only offers softness, breathability, and excellent moisture management but also provides added value through its bioactive properties, including antibacterial, anti-inflammatory, and UV-protective functions. These characteristics make it suitable for diverse applications ranging from fashion and baby clothing to sportswear, home textiles, and even medical fabrics.

However, its widespread adoption is still challenged by high production costs, limited large-scale availability, and the need for improved tensile strength. With ongoing research, technological advancements, and responsible resource management, seaweed fibre has the potential to become a mainstream sustainable material in the textile industry. As consumer demand for eco-friendly and wellness-oriented products continues to grow, seaweed fibre stands out as a promising solution that bridges environmental responsibility with innovation, paving the way for a greener and healthier future in textiles.

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ECO-WARRIOR FUNGI: COMPARATIVE BIOPESTICIDE PERFORMANCE OF BEAUVERIA, METARHIZIUM, AND LECANICILLIUM

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Abstract

Entomopathogenic fungi are an important category of biological control agents that have shown remarkable potential in managing a wide range of insect pests. Among them, *Beauveria bassiana*, *Metarhizium anisopliae*, and *Lecanicillium lecanii* are the most widely studied and commercially available fungal biopesticides. These fungi infect insects through direct cuticle penetration, making them effective against pests that are difficult to control using chemical insecticides. This review provides a comparative analysis of the biology, mode of action, host range, formulation methods, environmental adaptability, and field performance of these fungal agents. Challenges related to environmental sensitivity, inconsistent efficacy, and mass production are discussed, along with future directions for enhancing the use of entomopathogenic fungi in Integrated Pest Management (IPM). The review highlights the growing significance of fungal-based biopesticides as eco-friendly and sustainable alternatives to synthetic pesticides.

Keywords: Entomopathogenic fungi; *Beauveria bassiana*; *Metarhizium anisopliae*; *Lecanicillium lecanii*; Biopesticides; Biological control; Integrated Pest Management; Insect pathology; Sustainable agriculture.

Introduction

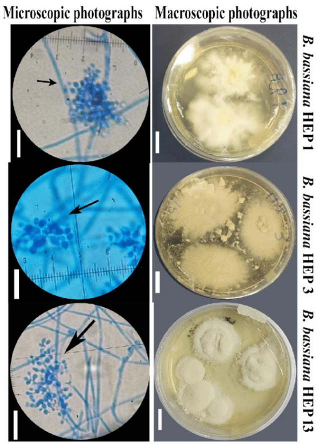
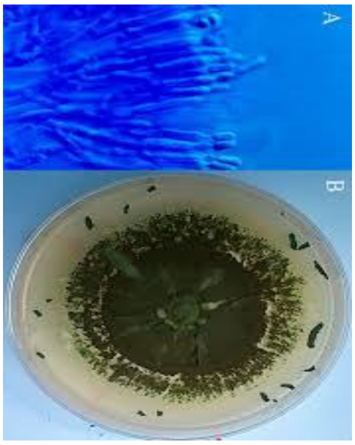
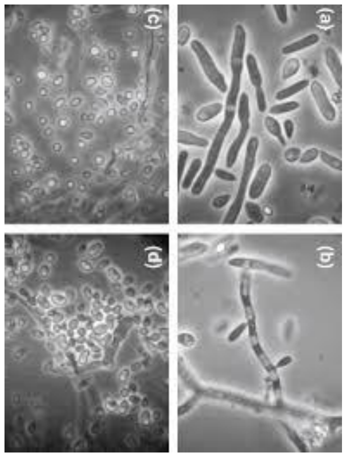
Biopesticides based on entomopathogenic fungi have become essential tools in modern pest management due to their eco-friendly nature, high specificity, and minimal risk to humans and non-target organisms. These fungi naturally occur in soil and plant surfaces and infect a variety of insects, providing effective and sustainable control. *Beauveria*, *Metarhizium*, and *Lecanicillium* are among the most influential genera, extensively used against agricultural, horticultural, and plantation crop pests. Their unique infection strategies and adaptability make them suitable for integration into IPM systems.

Biological Characteristics

The three entomopathogenic fungi differ in morphology, temperature requirements, and ecological preferences. *Beauveria bassiana* produces white cottony mycelia and thrives in moderate temperatures. It has a broad host range, infecting various insect orders. *Metarhizium anisopliae*, characterized by its green spores, prefers slightly higher temperatures and shows excellent activity against soil-dwelling pests. *Lecanicillium lecanii*, recognized for its slimy white colonies, grows best in humid environments and is particularly efficient against soft-bodied insects like aphids and whiteflies.

Table 1. Biological Characteristics

Fungal Species	Morphology	Optimum Temperature	Unique Traits
Beauveria bassiana	White, cottony growth	20–28°C	Wide host range; good foliar persistence
Metarhizium anisopliae	Green spores	25–30°C	Very effective against soil insects
Lecanicillium lecanii	Slimy white colonies	22–28°C	Strong activity on soft-bodied pests

		
Beauveria bassiana	*Metarhizium anisopliae*	*Lecanicillium lecanii*

Mode of Infection and Pathogenesis

Entomopathogenic fungi follow a similar infection cycle but differ in speed, enzyme production, and colonization patterns.

The infection begins with spore adhesion to the insect cuticle. *Beauveria* and *Metarhizium* attach using hydrophobic interactions, whereas *Lecanicillium* uses sticky mucilage. After adhesion, the fungi produce cuticle-degrading enzymes such as proteases, lipases, and chitinases. *Metarhizium* is particularly known for strong chitinase activity, enabling rapid penetration of harder exoskeletons. Once inside the hemocoel, the fungi multiply, secrete toxins, and disrupt physiological processes. Host death typically occurs within 3–8 days. The cadavers then serve as sites for sporulation, contributing to natural epizootics.

Table 2. Pathogenesis Overview

Stage	*Beauveria*	*Metarhizium*	*Lecanicillium*
Adhesion	Hydrophobic spores	Hydrophobic & electrostatic	Sticky mucilage
Penetration	Proteases & chitinases	Strong chitinase activity	Mild penetration for soft pests
Host Mortality	3–7 days	3–5 days	4–8 days
Sporulation	White coating	Green coating	White slimy covering

Beauveria bassiana

Biology

Beauveria bassiana is a widely used entomopathogenic fungus belonging to the family Clavicipitaceae. It produces white, cottony mycelia and dry powdery conidia. The infection begins when hydrophobic spores adhere to the insect cuticle. The fungus produces proteases, chitinases, and lipases, which dissolve the exoskeleton and allow it to enter the hemocoel. Once inside, the fungus multiplies rapidly, secretes toxins like beauvericin, and disrupts the insect's physiological processes. The insect typically dies within 3–7 days. Afterwards, white mycelia emerge from the cadaver and sporulate, contributing to natural epizootics.

Preparation of Mother Culture

The production process begins with creating a pure and active mother culture. *Beauveria bassiana* grows vigorously on Potato Dextrose Agar (PDA) medium, which supports dense mycelial and conidial formation.

Media Preparation (PDA)

To prepare the PDA medium, combine:

- Potato extract – 200 g
- Dextrose – 20 g
- Agar – 20 g
- Distilled water – 1000 ml

Mix thoroughly and sterilize in an autoclave at 121°C for 20 minutes to ensure complete microbial decontamination.

Slant Preparation

Once sterilized, the medium is allowed to cool slightly and is dispensed aseptically into sterile test tubes. Inside a Laminar Air Flow (LAF) chamber, the tubes are placed in a slanted position, creating an angled surface ideal for fungal colonization.

Inoculation

A 22–30-day-old pure culture disc of *Beauveria bassiana* is transferred aseptically onto the PDA slant.

Incubation

The inoculated slants are incubated at 25 ± 2°C for 10–15 days.

Fully grown cultures show:

- Thick white mycelial growth
- Powdery white conidial layer (typical of *Beauveria*)

This fully grown culture serves as the mother culture for further large-scale multiplication.

Mass Multiplication of Beauveria bassiana

To meet field-level application needs, large quantities of fungal biomass are produced through standardized mass multiplication methods.

Liquid Substrate Preparation

Sterile broth is dispensed at 300 ml per bottle and sterilized at 121°C for 20 minutes. After sterilization, the bottles are cooled aseptically to avoid contamination.

Inoculation with Mother Culture

A portion of the *Beauveria bassiana* mother culture is inoculated into each cooled broth bottle under aseptic conditions.

Incubation

The inoculated bottles are incubated at room temperature for 10–15 days.

During this period, *Beauveria bassiana* develops:

- Thick white mycelial mats
- High-density powdery white spores
- Strong sporulation suitable for agricultural formulations

Biomass Harvesting

Once the incubation period is complete, the fungal biomass along with the broth is collected. The entire mass is homogenized using a sterile blender to create a uniform suspension containing spores and mycelial fragments.

Formulation Preparation

The homogenized biomass is thoroughly mixed with a suitable carrier material such as:

- **Talc-based carrier** (most commonly used)
- **Oil-based carrier** (used for sprayable formulations)

The final mixture is standardized to achieve a spore concentration of 10^8–10^9 CFU/g, ensuring high field efficacy.

Packaging and Labelling

The formulated product is:

- Packed in airtight containers
- Sealed to maintain viability
- Labelled clearly with:
    - Fungal species and strain
    - Manufacturing date
    - Expiry date
    - Batch number
    - Spore count
    - Storage instructions.

Usefulness in Agriculture

Beauveria bassiana is effective against:

- ✔ Whiteflies
- ✔ Thrips
- ✔ Aphids
- ✔ Mealybugs
- ✔ Helicoverpa larvae
- ✔ Coffee berry borer

It is widely used in vegetables, cotton, pulses, fruit orchards, and spice crops. Being safe to beneficial organisms and residue-free, it is an excellent component in IPM programs. It is also compatible with many botanicals and microbial biopesticides.

Metarhizium anisopliae

Biology

Metarhizium anisopliae, known for its distinct green conidia, belongs to the family *Clavicipitaceae*. It thrives in soil environments and infects soil-dwelling pests efficiently. The infection process begins with conidia germination on the insect cuticle, followed by enzymatic penetration using serine proteases and strong chitinases. Once inside the hemocoel, fungal hyphae proliferate, leading to the insect's dehydration and death within 3–5 days. Green sporulation on the insect cadaver is a characteristic feature.

Preparation of Mother Culture

Mother culture preparation is the first and most essential step for producing a stable and contamination-free inoculum. *Metarhizium anisopliae* grows effectively on Potato Dextrose Agar (PDA), which supports rapid mycelial development and conidiation.

Media Preparation (PDA)

To prepare the PDA medium, mix:

- Potato extract – 200 g
- Dextrose – 20 g
- Agar – 20 g
- Distilled water – 1000 ml

The medium is thoroughly mixed and sterilized in an autoclave at 121°C for 20 minutes to eliminate microbial contaminants.

Slant Preparation

After sterilization, the medium is allowed to cool and is poured aseptically into sterile test tubes. Inside the Laminar Air Flow (LAF) chamber, the tubes are kept in a slanted position, creating an inclined surface for better fungal growth.

Inoculation

A 22–30-day-old pure culture disc of *Metarhizium anisopliae* is aseptically transferred onto the surface of the PDA slant.

Incubation

The inoculated slants are incubated at 25 ± 2°C for 10–15 days.

Fully grown cultures show:

- Dense mycelial growth
- Olive-green conidial layer (characteristic of *M. anisopliae*)

This slant now serves as the mother culture, used for all subsequent large-scale production.

Mass Multiplication of *Metarhizium anisopliae*

Mass multiplication ensures the production of sufficient fungal biomass for talc-based or oil-based formulations used in agriculture.

Liquid Substrate Preparation

Sterile broth is prepared and dispensed into culture bottles at 300 ml per bottle. Each bottle is sterilized at 121°C for 20 minutes in an autoclave and allowed to cool aseptically.

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Inoculation Using Mother Culture

A portion of the actively growing mother culture is transferred aseptically into the cooled broth medium.

Incubation Phase

The bottles are incubated at room temperature for about 10–15 days.

During this period, the fungus grows extensively, forming:

- Thick mycelial mats
- Abundant olive-green conidia
- High-density spores suitable for field formulations

Biomass Harvesting

At the end of incubation, the mycelial mass along with the broth is collected.

The biomass is homogenized using a sterile blender to create a uniform fungal suspension containing spores and mycelial fragments.

Formulation Preparation

The homogenized fungal biomass is blended thoroughly with a suitable carrier material:

- Talc-based formulation (most widely used in agriculture)
- Oil-based formulation (useful for spraying and better field adhesion)

The mixture is standardized to achieve a spore concentration of 10^8–10^9 CFU/g, ensuring effective field performance.

Packaging and Labelling

The final formulation is:

- Packed airtight
- Properly sealed
- Labelled with essential information, including:
  - Fungal species and strain
  - Batch number
  - Manufacturing and expiry date
  - Spore load
  - Storage conditions.

Usefulness in Agriculture

Metarhizium anisopliae is the most effective EPF for soil and subterranean pests, including:

✔ Termites
✔ White grubs
✔ Root weevils
✔ Root borers
✔ Spodoptera larvae (soil-pupating)
✔ Sugarcane early shoot borer (soil stage)

It is extensively used in sugarcane, groundnut, potato, coconut, arecanut, vegetables, turfgrass, and forest plantations. It survives well in the soil and persists longer than other EPFs, making it ideal for soil application and seed treatment.

Lecanicillium lecanii

Biology

Lecanicillium lecanii (formerly *Verticillium lecanii*) is a soft-bodied insect pathogen belonging to the family *Cordycipitaceae*. It produces sticky conidia and grows best in high humidity (75–90%). Its infection cycle is particularly suited for sap-sucking insects. The spores germinate on the insect body, penetrate the soft cuticle, and colonize the hemocoel. Host death occurs in 4–8 days. The fungus sporulates around the cadaver, often appearing as a white, cottony mass.

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1. Preparation of Mother Culture

The production of high-quality biopesticide formulations begins with a pure and actively growing mother culture. The Potato Dextrose Agar (PDA) medium is commonly used due to its nutritional richness, which supports robust fungal growth.

Media Preparation:

The PDA medium is formulated using 200 g of potato extract, 20 g dextrose, and 20 g agar, made up to 1000 ml with distilled water. After mixing, the medium is sterilized in an autoclave at 121°C for 20 minutes to ensure complete elimination of contaminants.

Slant Preparation:

Once sterilized, the medium is allowed to cool and is dispensed aseptically into sterile test tubes. The tubes are placed in a slanting position inside a Laminar Air Flow (LAF) chamber to increase the surface area for fungal growth.

Inoculation:

A 22–30-day-old pure fungal culture disc is carefully transferred onto the PDA slant. The inoculated tubes are incubated at room temperature (25±2°C) for 10–15 days, allowing the fungus to establish a uniform, dense mycelial mat.

This serves as the mother culture, which is later used for large-scale production.

Mass Multiplication of Entomopathogenic Fungi

Mass production aims to obtain sufficient fungal biomass required for field-ready biopesticide formulations such as talc-based or oil-based products.

Substrate Preparation:

Sterile broth is prepared and dispensed into culture bottles at 300 ml per bottle. Each bottle is again sterilized at 121°C for 20 minutes, then allowed to cool under aseptic conditions.

Inoculation with Mother Culture:

After cooling, each bottle is inoculated with a portion of the prepared mother culture. The bottles are incubated at room temperature for 10–15 days, enabling vigorous fungal colonization.

Biomass Harvesting:

Once the fungus has fully grown, the broth containing fungal biomass is collected. The mixture is homogenized using a sterile blender to achieve a uniform suspension of spores and mycelial fragments.

Formulation Preparation:

The homogenized fungal biomass is blended with the required carrier material—commonly sterilized talc powder or oil, depending on the desired formulation. The mixture is thoroughly combined to achieve optimal spore concentration.

Packaging:

The final formulation is packed, sealed, and properly labelled, indicating strain name, formulation type, spore load, date of manufacture, batch number, and expiry.

Usefulness in Agriculture

Lecanicillium lecanii excels in controlling:

- ✔ Aphids
- ✔ Whiteflies
- ✔ Mealybugs
- ✔ Soft scales
- ✔ Thrips (to some extent)

It is widely used in polyhouses, shade nets, vegetable crops, plantations, and orchards. Its activity is enhanced under humid conditions, making it especially effective in greenhouse IPM programs.

Comparative Table: Biology, Production & Agricultural Use

Feature	*Beauveria bassiana*	*Metarhizium anisopliae*	*Lecanicillium lecanii*
Conidial Color	White	Green	White
Main Target	Foliar pests	Soil pests	Soft-bodied sap feeders
Best Environment	Moderate humidity	Soil; high temp tolerant	High humidity
Mass Production	SSF, LF	SSF, LF	Primarily SSF
Field Use	Foliar spray	Soil drench & seed treatment	Foliar spray (humid)
Key Crops	Cotton, vegetables	Sugarcane, groundnut	Greenhouse crops
Persistence	7–14 days	10–20 days	4–10 days

Conclusion

Beauveria bassiana, *Metarhizium anisopliae*, and *Lecanicillium lecanii* are powerful fungal biopesticides with distinct biological traits and pest targets. Their mass production is economically feasible through solid-state and liquid fermentation methods. In agriculture, these fungi offer safe, eco-friendly alternatives to chemical insecticides and play a crucial role in IPM strategies. Choosing the right fungus based on pest biology (foliar, soil, or soft-bodied pests) and environmental conditions significantly enhances field performance. Their continued adoption in Indian agriculture will support sustainable crop protection and reduce pesticide load.

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Importance of Commercial Horticulture

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Large-scale cultivation of fruits, vegetables, flowers, plantation crops, and spices, includes production, processing, marketing, export, Integrates modern technologies for higher productivity is called as Commercial Horticulture

Status of India's Horticulture sector:

Indian horticulture sector contributes about 33% to the agriculture Gross Value Added (GVA) making very significant contribution to the Indian economy. Apart from ensuring nutritional security of the nation, it provides alternate rural employment opportunities, diversification in farm activities, and enhanced income to farmers. India is currently producing about 320.48 million tones of horticulture produce which has surpassed the food grain production, that too from much less area (25.66 million Ha. for horticulture against 127.6 M. ha. for food grains). Productivity of horticulture crops is much higher compared to productivity of food grains (12.49 tones/ha against 2.23 tones/ha.). India has emerged as world leader in the production of a variety of fruits like mango, banana, guava, papaya, sapota, pomegranate, Lime & aonla and is the second largest producer of fruits and vegetables. Besides, India has maintained its dominance in the production of spices, coconut and cashew nut. Among the new crops, kiwi, gherkins, kinnow, date palm and oil palm have been successfully introduced for commercial cultivation in the country.

1. Economic Growth

Commercial horticulture plays a crucial role in strengthening the agricultural economy. Horticultural products such as fruits, vegetables, spices, plantation crops, and flowers contribute significantly to the national income. These crops fetch higher market prices and have strong domestic as well as international demand. As a result, the horticulture sector becomes a major contributor to the GDP, particularly in developing countries like India.

2. Employment Generation

The horticulture sector is highly labour-intensive. It provides employment opportunities in multiple stages—from crop production, harvesting, grading, and packaging to processing and marketing. Additionally, it creates jobs in allied industries such as cold storage, transport, floriculture units, and food processing industries. This helps reduce rural unemployment and underemployment.

3. High Profitability

Compared to traditional field crops, horticultural crops often give higher economic returns per unit area. Many fruits and vegetables have shorter growing periods, allowing farmers to grow multiple crops annually. High-value crops like grapes, pomegranates, flowers, and exotic vegetables offer excellent profit margins, making horticulture a preferred choice for commercial farming.

4. Export Potential

Commercial horticulture contributes significantly to foreign exchange earnings. Countries export fresh fruits, vegetables, spices, nuts, plantation crops, and processed horticultural products to global markets. This enhances the country's reputation in international trade and provides better profitability to farmers who produce export-quality crops.

5. Nutritional Security

Horticultural crops are rich in essential nutrients such as vitamins, minerals, antioxidants, and dietary fiber. They are crucial for a balanced diet and help fight malnutrition and lifestyle diseases. Promoting commercial horticulture ensures the availability of fresh, high-quality, and nutritious food for the growing population.

6. Diversification of Agriculture

Commercial horticulture reduces the overdependence on traditional cereal crops. By diversifying into fruits, vegetables, floriculture, and plantation crops, farmers can reduce risks associated with climate change, price fluctuations, and crop failures. Agricultural diversification also leads to more efficient land use and better resource management.

7. Development of Agro-Industries

The growth of commercial horticulture promotes the establishment of various agro-based industries. These include fruit and vegetable processing units, cold storage facilities, floriculture industries, spice processing units, and packaging industries. Such industries add value to raw produce, reduce wastage, and provide additional income and employment.

8. Environmental Benefits

Horticulture helps maintain ecological balance. Fruit orchards, plantation crops, and tree-based horticulture systems contribute to soil conservation, reduce erosion, and increase green cover. Many horticultural plants act as carbon sinks, thus helping mitigate climate change. Biodiversity is enhanced as a wide variety of crops are cultivated.

9. Technological Advancement

Commercial horticulture encourages the adoption of innovative farming techniques such as:

- Greenhouse and polyhouse cultivation
- Drip and sprinkler irrigation
- Precision farming and hydroponics
- Tissue culture and micro-propagation

These advanced technologies improve productivity, quality and sustainability.

10. Improved Farmer Livelihoods

By providing higher income, improved market access, and opportunities for value addition, commercial horticulture significantly uplifts farmer livelihoods. It helps farmers move from subsistence agriculture to profitable enterprise-based farming. This improves their standard of living and contributes to rural development.

11. Sustainability & Climate Resilience

- Diverse crops reduce dependency on single-crop farming
- Supports climate-smart agriculture
- Perennial horticultural crops help in carbon sequestration

12. Post-Harvest & Value Addition

- Includes sorting, grading, packaging, storage, and transportation
- Improves shelf life and market value of produce
- Value addition increases farmer income and reduces wastage

13. Role in Rural Development

- Improves livelihoods of small and marginal farmers
- Promotes entrepreneurship through nurseries, cold storage, and processing units
- Supports self-help groups (SHGs) and rural women enterprises

14. Government Support & Policies

- Schemes for orchard establishment and modernization
- Subsidies for drip irrigation, greenhouses, cold storage
- National Horticulture Mission promoting growth and exports

Challenges in Commercial Horticulture

- ➢ High initial investment
- ➢ Need for skilled labor
- ➢ Post-harvest losses due to poor storage and handling
- ➢ Market fluctuations and limited cold-chain facilities

Conclusion

- ➢ Commercial horticulture is vital for economic growth and food security
- ➢ Provides income, employment, and export opportunities
- ➢ Supports sustainable agricultural development

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Conservation Agriculture in India: Pathway to Sustainable Farming

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Abstract

Conservation Agriculture (CA) is a sustainable farming system based on minimal soil disturbance, permanent soil cover, and crop diversification. In India, where agriculture is heavily dependent on monsoons and dryland farming covers nearly 60% of cultivated land, CA offers a pathway to resilience, food security, and climate-smart growth. This report examines the definition, importance, role, necessity in Indian agriculture, challenges, innovations, and prospects of CA in dryland farming.

Introduction

Agriculture in India faces multiple crises: soil degradation, water scarcity, climate variability, and declining profitability. Traditional practices such as intensive tillage and residue burning exacerbate these problems. Conservation Agriculture, promoted globally by FAO and adopted in parts of India, offers a holistic solution.

Definition of Conservation Agriculture

FAO Definition: A resource-efficient farming system that sustains productivity while conserving soil, water, and biodiversity.

Core Principles:

The core principles are interlinked and together aim to enhance biodiversity (above and below ground), soil health (structure, organic matter, biology), resource-use efficiency (water, nutrients) and resilience to climate and weather extremes

1. Minimum soil disturbance (zero/reduced tillage):

Rather than ploughing deeply, turning and inverting the soil (traditional tillage), conservation agriculture aims to disturb the soil as little as possible. In some cases, this means no-till (zero tillage) or direct seeding into the previous crop's residue. This includes minimizing mechanical operations, such as deep ploughing, extensive harrowing, ridging, etc. Direct seeding and fertiliser placement are preferred. Tillage disrupts soil structure, destroys soil aggregates, reduces soil organic matter and kills soil biota (worms, microbes), exposes soil to erosion and oxidation of organic carbon. By disturbing the soil less, you preserve soil structure, enhance infiltration of water, reduce runoff and erosion, slow the oxidation of organic matter, thereby carbon and nutrients are retained. It also saves labour, fuel, and time in many cases, improving cost efficiency.

Key practices:

- No-till or reduced till drills: planting directly into residue or soil without complete ploughing.
- Minimal soil inversion, minimal soil disturbance operations.
- Using specialized equipment (direct seeders) if needed to handle the crop residue.
- Keeping compaction in check (since less disturbance means roots and biota must "do the job").
- Careful placement of fertiliser/seeds to reduce the need for heavy tillage.

2. Permanent soil cover (mulching, crop residues):

The soil surface should ideally be covered at all times – either by the residue of the previous crop (dead plant material), by living cover crops or plants, or by mulch. The cover helps protect the soil from direct raindrop impact and wind erosion, while also maintaining a favourable microclimate and biological activity. Bare soil is vulnerable: raindrops can break aggregates, create crusts, accelerate runoff, erosion, reduce infiltration. A permanent cover moderates soil temperature (reduces extremes), retains moisture (reducing evaporation), improves infiltration, supports soil fauna (worms, microbes) under the cover. Over time, the plant residues add organic matter to the soil, contributing to fertility and carbon sequestration.

Key practices:

- Retain crop residues on the field after harvest rather than burning or removal.
- Plant cover crops (legumes, grasses) during fallow periods or between main crops.
- Apply mulch (organic materials) especially in fields or systems where crop residue is insufficient.
- Manage weeds under the cover crop or mulch so that the cover is maintained.
- Ensure that soil cover does not interfere with crop establishment (e.g., residue is not too thick, seed-bed contact is maintained).

3. Crop diversification (rotations, intercropping):

Rather than growing the same crop continuously (monoculture), CA encourages rotation of different crops, intercropping or associations of crops, and/or integration of cover crops/green manures. The cropping sequence should include species with different rooting depths, nutrient requirements, life-cycles to break pest/disease/weed cycles and better utilise soil resources. Crop diversification improves resilience: pests and diseases are less likely to build up in a single-crop system. Different crops utilise different layers of the soil and nutrients, reducing nutrient depletion and improving nutrient cycling. It supports biodiversity (above and below ground), improves soil structure (different root systems), and stabilises yields over time.

Key practices:

- Alternate crops: e.g., cereal → legume → cereal rather than cereal every year.
- Intercropping: growing two or more crops together (e.g., maize + legume) to utilise space and resources efficiently.
- Use of cover crops or green manures within the rotation to add nitrogen or organic matter.
- Avoid long continuous monoculture cycles; include fallow or restorative crops if needed.
- Monitor pest/disease/weed history and plan rotations accordingly.

Importance of Conservation Agriculture

i. Enhancing Soil Health and Fertility

By emphasising minimum soil disturbance, permanent soil cover and crop diversification, CA helps protect and rebuild soil structure, organic matter and biological activity. For example, CA practices enrich the soil with organic matter, enhancing soil structure and microbial life. Better soil health means improved nutrient cycling: organic matter decomposes slowly, nutrients are held and released more effectively, reducing losses. Healthier soils are more resilient to degradation (erosion, compaction, crusting), which helps ensure the land remains productive over the long term. This means farmers can maintain or gradually increase yields without depleting the resource base (soil), making agriculture more sustainable.

ii. Water-Use Efficiency and Soil Moisture Retention

Permanent soil cover (crop residues, mulches) reduces soil surface evaporation, shields the soil from direct sunlight and wind, and moderates soil temperature fluctuations. This helps retain moisture. Reduced tillage maintains soil structure and porosity, improving infiltration of rainwater (less runoff) and helping soils hold more water for crops. These benefits are especially important in regions prone to irregular rainfall, drought or heavy rainfall events (which can cause erosion or leaching). CA helps buffer those risks. For example: by retaining water better and lowering erosion, CA contributes directly to more efficient use of water resources.

iii. Reducing Soil Erosion and Protecting Land Resources

Exposed soil under conventional tillage is vulnerable to erosion by rain and wind. CA's permanent cover and minimal disturbance protect soil from detachment and loss. By reducing erosion, CA helps maintain topsoil -the most fertile layer -thereby preserving long-term productivity of the land and avoiding land degradation. In many areas where land is limited and population/food demand is rising, preventing land degradation is essential -we cannot afford to lose productive land. CA plays a key role.

iv. Climate Change Mitigation and Adaptation

CA contributes to climate mitigation: by reducing tillage and protecting soil organic matter, soils can act as a **carbon sink** (i.e., storing more carbon instead of releasing it) and reduce greenhouse gas emissions. CA also enhances adaptation: healthy soils with good structure, water retention capacity and biodiversity are better able to withstand climate extremes (droughts, heavy rainfall), thus reducing risk for farmers. In short, CA helps both sides of the climate equation: adaptation (resilience) and mitigation.

v. Biodiversity, Ecosystem Services and Environmental Protection

Through crop rotations, cover crops and reduced disturbance, CA supports a richer soil biota (earthworms, microbes, beneficial fungi) and above-ground biodiversity (plants, insects) that all contribute to ecosystem health. These increased ecosystem services include better pest and disease regulation, enhanced pollination, improved nutrient cycling, all indirectly supporting farm productivity. Reduced runoff and erosion also mean fewer nutrients/pesticides leaching into waterways, thereby protecting water quality. In this way, CA contributes not only to farm-level productivity but to the broader environmental health of landscapes, watersheds and communities.

vi. Economic and Social Benefits for Farmers

Less tillage means lower costs for fuel, labour, machinery wear and tear. Over time, this can lead to reduced production costs. Improved soil and water management reduces crop failure risk (e.g., from drought, erosion) and stabilise yields, which enhances livelihood security for farmers. In many cases, higher yields (or at least stable yields) *and* lower input costs together improve profitability and farm sustainability. For instance: some sources note CA can increase yields up to ~20% while drastically reducing soil erosion. Socially, as farms become more resilient and less dependent on intensive inputs/maintainable services, community well-being improves (food security, rural incomes, less degradation of communal resources).

vii. Meeting Rising Food Demand Sustainably

With the global population rising and pressure to produce more food from less land (and with less environmental impact), traditional intensive farming systems are reaching limits (soil degradation, water shortages, biodiversity loss). CA offers a pathway to produce more sustainably. By maintaining or increasing productivity while conserving natural resources, CA helps ensure that future generations will still have productive land. Especially relevant in places like India (and regions like the Indo-Gangetic plains) where land is under pressure, water is limited, and soils may already be degraded. Then CA becomes a strategic choice.

viii. Long-Term Sustainability and Intergenerational Equity

Because CA preserves soil, water, biodiversity and land productivity, it aligns with the idea of sustainable agriculture: meeting today's needs without compromising tomorrow's. Farmers adopting CA are investing in the long-term health of their land, which benefits their children, the community, and the environment. In many cases, conventional high-intensity practices lead to 'mining' of soil fertility, losses of topsoil, and declining yields.

Innovations in Conservation Agriculture

Over recent years, several innovations like technological, agronomic, input-based, system-level have emerged to enhance or enable CA practices

a. Machinery & Seeding Technology

Low-disturbance and direct-seeding planters: Innovations include hand planters, animal-drawn planters, and tractor-mounted equipment designed specifically for zero or minimum-tillage systems. Residue-management drills and coulters that can sow through crop residues without turning the soil. These allow the "minimal disturbance" principle to be more fully realised. Smart automation: Precision machines that adjust depth, spacing, residue cutting, and sowing to optimize plant establishment in conservation systems.

b. Digital & Precision Agriculture Tools

Soil-moisture sensors, remote sensing (drones/satellites), IoT devices: These allow real-time monitoring of soil condition, residue cover, crop stress, and enable optimized inputs (water, fertiliser) in CA systems. Artificial intelligence and machine learning to analyse farm-scale data and support decision-making. e.g., which areas of the field to minimise disturbance, where to increase residue cover, etc. Digital platforms for tracking changes in soil organic carbon (SOC), which is a key indicator under CA. Some novel "soil carbon copilots" are emerging that integrate multi-modal data.

c. Biological and Input Innovations

Use of **cover crops** and **green manures**: These serve as soil cover and organic matter sources, supporting the CA cover-and-diversity principle. Bio-based inputs: Microbial inoculants, mycorrhizae, plant growth promoting rhizobacteria (PGPR), biofertilisers that help build soil biology rather than just using synthetic fertiliser. Mulches and other soil-cover innovations: In arid regions, work on superhydrophobic sand mulches (a novel material innovation) to reduce evaporation and enhance yields has been reported.

d. Crop Rotations, Diversification & Agroecological Systems

Enhanced crop rotation schemes, intercropping, agroforestry integration: This help build biodiversity, interrupt pests/diseases, improve soil fertility and support the cover and diversity principle of CA. For example, the intercropping or "push–pull" strategy is used for pest and weed management within CA systems. Integration of trees/shrubs in cropping systems (agroforestry) also complements CA by providing permanent cover, organic matter, and rooting-depth diversity. Conservation agriculture innovation systems emphasise the mix of these practices rather than standalone adoption.

e. Water & Moisture Management

CA reduces evaporation and improves water infiltration, but innovations further enhance this: e.g., drip or micro-irrigation systems, smart irrigation scheduling in CA fields, rainwater harvesting in CA systems. Retaining crop residues on the surface in CA acts as mulch which reduces soil surface temperature and evaporation—innovation here lies in coupling residue management with water-savings strategies.

f. Carbon & Climate-Smart Agriculture

CA is increasingly framed as a climate-smart agriculture approach: building soil organic carbon, reducing emissions from tillage, reducing burning of residues. Monitoring and verification technologies emerging to quantify carbon sequestration benefits of CA. Soil sensors, remote sensing, modelling platforms. Innovations in incentive mechanisms: linking CA adoption to carbon credits or payments for ecosystem services is gaining traction (though more at policy level than purely technological).

Why These Innovations Matter -The Benefits

Improved soil health: By reducing disturbance, keeping cover, and integrating rotations/cover crops, soil structure improves, microbial activity increases, organic matter builds up.

Water efficiency & drought resilience: CA helps reduce evaporation, improve infiltration, retain moisture and thus increases resilience especially in dry regions.

Reduced greenhouse-gas emissions: Tillage releases CO_2; CA practices reduce fuel use, reduce emissions, and increase carbon storage.

Reduced input costs: Over time, less fuel for tillage, less erosion to repair, possibly lower fertiliser/pesticide use with better soil health and rotations.

Sustainability and resilience: With climate change, soil degradation and erosion threats increasing -CA innovations strengthen resilience.

Comparative Table: Conventional vs Conservation Agriculture

Aspect	Conventional Agriculture	Conservation Agriculture
Soil disturbance	Intensive tillage	Zero/reduced tillage
Soil cover	Residue burning	Mulching, Cover crops
Crop Diversity	Monocropping	Rotations, Intercropping
Water Use	High, inefficient	Efficient, Moisture conservation
Carbon emission	High (Burning, Fuel use)	Low, Carbon sequestration
Short term yield	Higher initially	Lower initially
Long term yield	Declining	Stable, Resilient

Major Constraints in Conservation Agriculture

High Initial Costs: Specialized equipment for zero tillage, residue management, and precision seeding can be expensive, making adoption difficult for smallholder farmers.

Knowledge & Awareness Gaps: Farmers often lack training or understanding of CA principles (minimal soil disturbance, permanent soil cover, crop rotation), leading to hesitation in adoption.

Residue Management Issues: Competing uses of crop residues (fodder, fuel) reduce availability for soil cover, which is a core CA practice.

Weed & Pest Pressure: Reduced tillage can increase weed infestation and pest problems, requiring effective integrated management strategies.

Institutional & Policy Barriers: Limited government support, weak extension services, and lack of incentives hinder scaling up CA practices.

Cultural Resistance: Traditional farming practices are deeply ingrained, and farmers may resist shifting to new methods without clear short-term benefits.

Site-Specific Limitations: In areas with heavy soils, poor drainage, or erratic rainfall, CA practices may not deliver expected results.

Summary:

Conservation Agriculture (CA) is a sustainable farming system built on three interlinked principles: minimal soil disturbance, permanent soil cover, and crop diversification. According to the Food and Agriculture Organization (FAO), it "promotes minimum soil disturbance, maintenance of a permanent soil cover, and diversification of plant species" in order to enhance biodiversity, natural processes, and resource-use efficiency. In India, where approximately 60% of cultivated land is rain-fed and farming heavily depends on the monsoons. CA offers a pathway to climate-smart growth, enhanced resilience, improved food security and long-term sustainability. The traditional paradigm of deep tillage, burning residues and monoculture cropping in India has led to soil degradation, water scarcity, yield instability and declining profitability, especially in dryland regions. By reducing soil disruption, maintaining a protective surface cover (via crop residues or cover crops), and rotating or intercropping crops to break pest/disease cycles and better exploit soil resources, CA helps rebuild soil health, conserve moisture, reduce erosion and sequester carbon. While significant challenges-such as equipment access, residue management and farmer awareness remain, the innovations emerging in equipment, digital monitoring, biological inputs and cropping system design make CA increasingly viable for India's dryland and marginal farming systems.

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Rural Development in India and the Critical Role of Agricultural Extension

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1. Introduction

Rural development is a cornerstone of India's overall progress because a large share of the country's people, workers and farmers still live in villages. According to the Economic Survey 2022–23, about 65% of India's population in 2021 lived in rural areas, and nearly 47% of the population depended on agriculture for their livelihood.

In this context, rural development is not only about building roads and houses; it also includes:

- improving agricultural productivity and incomes,
- creating non-farm employment,
- reducing poverty and hunger, and
- ensuring social inclusion and better quality of life.

Agriculture and agricultural extension are at the heart of this process, because they directly influence farm production, technology adoption, and rural livelihoods.

2. Agriculture as the Backbone of Rural Development

Agriculture continues to be the single largest source of employment in rural India. The Ministry of Agriculture and Farmers' Welfare notes that about 54.6% of the total workforce is engaged in agriculture and allied activities (Census 2011), and the sector contributed around 18.4% to India's Gross Value Added (GVA) in 2022–23.

Recent labour surveys also show that agriculture still employs a high share of workers:

- As per Periodic Labour Force Survey (PLFS) and related analyses, around 59–60% of the rural workforce has been engaged in agriculture in recent years.

This means that any improvement in agriculture—higher productivity, better prices, value addition, diversification—has a direct impact on rural incomes, food security and poverty reduction.

Thus, rural development in India is closely linked to strong and dynamic agriculture, supported by effective extension services.

3. What Is Agricultural Extension and Why Is It Important?

Agricultural extension refers to the system of education and advisory services that:

- transfers improved technologies (seeds, fertilisers, machinery, irrigation, digital tools) from research institutions to farmers,
- gives information on crop management, weather, pests and markets,
- trains farmers in sustainable and climate-resilient practices,
- and helps them connect with government schemes and credit.

The Economic Survey 2024–25 explicitly states that agricultural extension is vital for disseminating knowledge, enhancing productivity and promoting sustainable agriculture. It highlights the Government's Sub-Mission on Agricultural Extension (SMAE) to strengthen extension, entrepreneurship and productivity.

Research studies and meta-analyses on India's extension system show:

- Extension services have a positive and significant impact on farm productivity and output, especially for smallholders.
- Investments in agricultural research, education and extension generate very high returns, not only in yields but also in poverty reduction and better nutrition.

In simple words, without effective extension, new technologies remain on paper or in laboratories; with extension, they reach fields and change rural lives.

4. Government Initiatives Supporting Rural Development and Extension

The Government of India has launched several programmes that combine rural development goals with agricultural support and extension:

1. **Sub-Mission on Agricultural Extension (SMAE)**
   - Strengthens state extension systems, including Krishi Vigyan Kendras (KVKs), ATMA (Agricultural Technology Management Agencies), and use of ICT (mobile, apps, portals) for advisories.
2. **Krishi Vigyan Kendras (KVKs)**
   - KVKs conduct frontline demonstrations, on-farm trials, training and capacity building of farmers in almost every district.
   - A recent study on KVKs found that advisory and training programmes have direct and spillover effects on yields and incomes, benefiting even non-participating farmers in nearby villages.
3. **Digital and Modern Extension**
   - Use of Kisan Call Centres, mobile SMS, farmer portals and apps helps deliver timely information on weather, pests, prices and schemes.
   - Modern extension approaches promoted by the government emphasise climate-smart agriculture, integrated farming systems and resource conservation.
4. **Rural Employment and Asset Creation (MGNREGA)**
   - Under MGNREGA, rural workers are employed for creating farm ponds, check dams, land levelling, bunding and plantations, which directly strengthen the agricultural base and water resources in villages. Studies show that MGNREGA has helped reduce seasonal migration and improved food security in rural India.

Through these initiatives, rural development and agricultural extension work hand in hand: extension provides knowledge and skills, while rural development schemes create infrastructure, income and resilience.

5. How Agricultural Extension Drives Rural Development

The role of agricultural extension in rural development can be seen in several dimensions:

(a) Increasing Farm Productivity and Incomes

Extension agents and KVK scientists introduce high-yielding varieties, improved agronomic practices, balanced fertiliser use, integrated pest management and better water management.

Empirical evidence from multiple Indian studies shows that farmers who receive regular extension support generally achieve higher yields and net returns than those who do not.

Higher productivity means:

- more marketable surplus,
- higher farm incomes,
- and greater spending power in rural markets—leading to overall village development.

(b) Promoting Diversification and New Livelihoods

Extension also encourages crop diversification (towards fruits, vegetables, pulses, oilseeds), and promotes livestock, fisheries, beekeeping, agro-processing and value addition.

According to NITI Aayog's paper on the changing rural economy, diversification into non-farm and high-value activities is essential for better employment and incomes in rural areas.

By guiding farmers towards new enterprises, extension services help:

- reduce risk from single-crop dependence,
- create off-farm and on-farm jobs,
- and stimulate rural entrepreneurship (e.g., custom hiring centres, input shops, small processing units).

(c) Supporting Climate-Resilient and Sustainable Development

Climate change has increased the frequency of droughts, floods, heatwaves and pests, which hit rural communities hardest.

Extension plays a critical role in:

- promoting drought-tolerant and flood-tolerant varieties,
- training farmers in water harvesting, micro-irrigation and soil conservation,
- spreading awareness about crop insurance schemes (PM Fasal Bima Yojana) and risk management.

These measures protect both agriculture and rural livelihoods, making development more sustainable and resilient.

(d) Empowering Women and Youth in Rural Areas

Recent data from PLFS show that a very high proportion of rural women are engaged in agriculture, and their share in the agri workforce is rising.

Extension programmes that specifically target women farmers, Self Help Groups (SHGs) and rural youth:

- build their skills in improved farming, dairy, poultry, kitchen gardens and micro-enterprises,
- enhance their decision-making power and income,
- and contribute to social and gender equity in rural development.

6. Challenges and the Way Forward

Despite its importance, agricultural extension in India faces some well-recognised challenges:

- Limited number of extension workers compared to the huge number of farmers.
- Low public expenditure on agricultural research and extension—about 0.7% of agricultural GDP, which is below the recommended 2%.
- Need for better coordination among multiple agencies (state departments, KVKs, NGOs, private sector).
- Gaps in reaching marginal, tribal, women and remote-area farmers effectively.

Going forward, experts and policy documents suggest:

- Strengthening SMAE and KVK networks,
- Increasing investment in research–extension linkages,
- Using digital tools and farmer producer organisations (FPOs) to reach more farmers,
- and integrating extension closely with rural development schemes, credit, markets and infrastructure.

If these steps are taken, agricultural extension can become an even more powerful engine of inclusive rural development.

7. Conclusion

Rural development in India cannot be separated from the fortunes of agriculture and the well-being of farmers. With around two-thirds of the population still living in rural areas and a large share of workers depending on agriculture, policies that improve farming systems have a direct and immediate impact on rural poverty, employment and food security.

Agricultural extension acts as the bridge between science and society, between agricultural research and rural fields. By spreading knowledge, technologies and skills; by supporting diversification, climate resilience and women’s empowerment; and by linking farmers to schemes and markets, extension services play a central role in transforming rural economies.

Strengthening agricultural extension, along with well-designed rural development programmes, is therefore essential to achieving sustainable, inclusive and resilient rural development in India—where villages are not just places of survival, but centres of growth, innovation and dignity for millions of people.

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World Soil Day: How Soil Shapes the Postharvest Quality of Fruits and Vegetables

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Abstract

Postharvest quality determines how long fruits and vegetables stay fresh, nutritious, and marketable, yet this quality is shaped long before harvest—by the soil itself. Balanced nutrients, biologically active soils, and favourable physical and chemical conditions enhance both preharvest development and postharvest performance. Beneficial microbes act as natural quality managers, strengthening plant resilience and improving fruit composition, while organic matter boosts sweetness and antioxidant levels. Conversely, degraded or contaminated soils threaten food quality and safety, increasing susceptibility to spoilage and heavy-metal accumulation. Sustainable soil management practices, from composting and cover cropping to improving structure and drainage, emerge as powerful tools for reducing postharvest losses and elevating sensory and nutritional attributes. World Soil Day 2025, celebrated globally on 5 December, highlights the theme "Healthy Soils for Healthy Cities," reminding us that soil health underpins not only agricultural productivity but also safe food, resilient communities, and sustainable urban systems. Ultimately, good soil grows good food—and good food stays good for longer. This article explores how soil fertility, organic matter, microbial life, moisture, structure, pH, and contamination collectively influence key attributes such as firmness, flavour, colour, aroma, nutritional value, and shelf life.

Keywords: Postharvest, Soil, Fertility, Microbes, Moisture, pH, Health, Quality, Safety, Sustainable, Food system.

Introduction

Postharvest quality determines how fresh, nutritious, and appealing fruits and vegetables remain after harvest. High postharvest quality ensures that produce reaches consumers in good condition, minimises losses along the supply chain and supports food safety. With nearly one-third of horticultural produce lost between harvest and consumption, maintaining quality has become essential for reducing waste, improving profitability, and delivering healthier food to consumers. Postharvest attributes such as firmness, flavour, colour, nutritional value, and shelf life are often linked to storage conditions, packaging, and handling practices. Yet the story begins much earlier. Long before a tomato ripens or a mango is picked, the soil beneath the plant determines much of its final quality. Healthy soil is the hidden foundation of fresher, long-lasting and better-tasting produce. Let us explore how soil shapes these postharvest attributes and why the journey to quality truly begins underground.

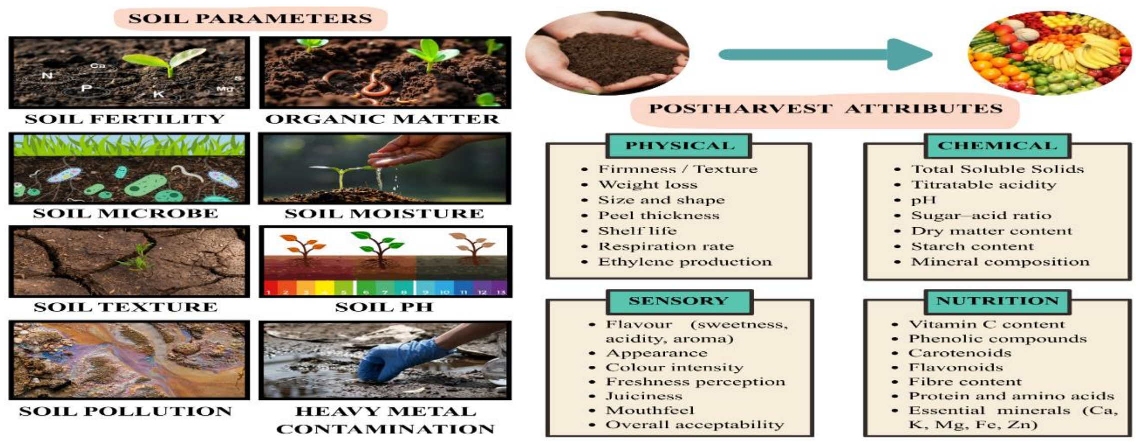

Figure 1. Soil Parameters Influencing Postharvest Quality Attributes

Soil Fertility: The First Step Towards Longer Shelf Life

Balanced soil fertility is fundamental to producing fruits that remain firm, flavourful, and stable during storage. Nutrient-rich soils supply essential elements that support optimal plant growth and directly influence postharvest performance. In temperate fruit trees, such as grapevines, apples, and pears, the availability of nutrients, particularly nitrogen (N), potassium (K), and calcium (Ca), plays a crucial role in determining fruit quality and longevity (Brunetto *et al*., 2015).

Nitrogen is critical for the synthesis of key compounds, including anthocyanins that define berry and wine colour in grapevines. However, both deficiency and excess can compromise postharvest traits. Low nitrogen can impair yeast activity during fermentation, while excessive nitrogen promotes vegetative growth, dilutes anthocyanins, reduces sugar concentration, and results in fruit with poorer storage behaviour. This illustrates how soil N levels must be carefully managed to sustain both fruit development and quality.

Potassium is equally important, contributing to sugar accumulation, colour formation, and flavour enhancement. In grape berries, K supports proper maturation and affects parameters such as pH and acidity, which influence wine quality. In apples and pears, achieving the right K: Ca balance is essential; although potassium is abundant in the fruit, the excess of potassium can suppress calcium uptake.

Calcium, supported by good soil fertility, strengthens cell walls and reduces physiological disorders. Adequate Ca availability improves firmness, reduces susceptibility to fruit cracking and postharvest rots. Ca enhances both pre- and postharvest health. Boron also contributes to cell wall stability, while magnesium supports chlorophyll formation and vitamin content, adding to overall nutritional quality. When these nutrients are lacking, fruits and vegetables break down more quickly, soften faster, and become more susceptible to disease.

Soil Organic Matter Boosts Flavour and Nutrition

High soil organic matter creates a fertile environment that enhances nutrient availability, water retention, and microbial activity. These factors collectively improve the flavour and nutritional profile of horticultural produce. Carrots grown in soils with higher organic matter show better carotenoid content and improved sweetness.

Reganold *et al.* (2010) showed evidence from commercial strawberry systems in California that demonstrates this clearly. Organic farms, which typically maintain higher levels of soil organic carbon and nitrogen, were shown to produce strawberries with superior nutritional attributes, including greater dry matter, higher antioxidant activity, and elevated concentrations of ascorbic acid and phenolic compounds (Reganold *et al.*, 2010).

The enriched organic soils also supported more active and diverse microbial communities, with increased microbial biomass, greater functional gene diversity, and enhanced capabilities for key biogeochemical processes such as nitrogen fixation and pesticide degradation. These soil conditions contribute to improved plant nutrition and metabolic activity, which translates into fruits with better flavour, sweetness, and overall sensory acceptance, as confirmed by consumer panels. In essence, soils rich in organic matter not only nourish plants effectively but also promote the production of fruits that are more flavourful, more nutritious, and more resilient during storage. This highlights how biological richness below ground can significantly elevate the eating quality and health benefits of fresh produce.

Soil Microbes: Nature's Quality Managers

Beneficial soil microorganisms play a pivotal role in enhancing plant health, nutrient uptake, and stress tolerance. They ultimately shape the quality of harvested produce. Healthy soils teem with beneficial microbes that enhance plant immunity and nutrient uptake. These microbes help plants develop stronger skins, richer pigments, and greater resistance to postharvest disorders. Mycorrhizal fungi improve calcium uptake, vital for preventing postharvest issues like blossom-end rot in tomatoes. Rhizobacteria improve firmness and vitamin content through better nutrient assimilation.

Todeschini *et al.* (2018) studied strawberry plants inoculated with arbuscular mycorrhizal fungi (AMF) and plant growth–promoting bacteria (PGPB), illustrating how these microbes act as natural managers of fruit quality. Different AMF species, such as *Rhizophagus irregularis*, *Funneliformis mosseae*, and *Septoglomus viscosum*, alongside selected *Pseudomonas* strains, were shown to improve root colonisation, stimulate vegetative growth, and influence plant physiological status.

While AMF predominantly enhanced root and shoot biomass, PGPB played a more prominent role in determining fruit yield and compositional traits. Inoculation, particularly with the Pf4 *Pseudomonas* strain, increased flower and fruit numbers, elevated soluble sugar and anthocyanin concentrations, and modified acidity, malic acid levels, volatile compounds, and elemental composition. These changes directly contribute to improved flavour, aroma, and nutritional value (Todeschini *et al.*, 2018).

The study demonstrates that soil microbes do far more than support plant growth. They actively modulate key quality attributes of fruit. By fostering healthier root systems, regulating nutrient flows, and stimulating the production of health-promoting compounds, beneficial microbes act as unseen quality managers within the soil. Selecting optimal plant–microbe combinations, therefore, offers a powerful tool for enhancing both fruit production and postharvest quality.

Soil Moisture and Structure Influence Textural Quality

The physical condition of soil, whether it is well-drained, compacted, or waterlogged, directly affects quality. Well-aerated soils promote root growth, leading to uniform size and better firmness. Waterlogged soils cause nutrient leaching and stress, producing watery, bland produce with poor keeping quality. Compacted soils restrict root activity, affecting size, flavour, and mineral content.

Soil moisture plays a decisive role in shaping the texture, appearance, and eating quality of horticultural produce. Mu *et al.* (2023) conducted research on 'Yanfu 3' Fuji apples demonstrating how carefully regulated soil water levels directly influence firmness, cracking susceptibility, surface smoothness, and sugar accumulation. Different irrigation regimes, ranging from moderate to light water stress, were compared across two treatment groups, with the physiological fruit-drop period separating early and late applications.

Moderate soil water stress, keeping the soil at around 65–75% moisture, proved particularly beneficial for apple quality. This level of controlled stress reduced fruit cracking, improved peel smoothness, and encouraged better colour development. Moreover, fruits grown under these conditions showed a noticeable increase in soluble solids, which translates into sweeter, more flavourful apples. Microscopic observations revealed why this happens. When soil moisture fluctuates too much, the fruit's outer cuticle becomes unstable and prone to cracking. In contrast, maintaining steady, moderate moisture helps the peel form a thicker, stronger cuticle, protecting the fruit from structural damage. This simple adjustment in irrigation can make a significant difference to both the appearance and the eating quality of apples.

Fruit water potential also emerged as a key factor: healthy, crack-resistant apples showed higher water potential and thicker cuticles, while cracked fruit exhibited lower water potential and weaker epidermal integrity. These findings highlight how soil moisture management not only affects physiological processes within the fruit but also determines external textural attributes such as smoothness and resistance to cracking. Selecting the right irrigation strategy can therefore optimise both the appearance and the postharvest performance of apples (Mu *et al.*, 2023).

Soil pH Shapes Colour, Taste, and Nutrient Availability

Soil pH regulates how well plants absorb nutrients. Slightly acidic soils (pH 6–6.8) support optimal nutrient uptake. Extreme pH levels (either too high or too low) result in deficiencies, poor pigmentation, and reduced shelf life. For example, blueberries thrive in acidic soils; if pH rises, berries become smaller, paler, and less firm. Therefore, soil pH plays a central role in determining how fruit develops its colour, flavour, and nutritional profile.

Research from major pomelo-growing regions in China provides strong evidence of this relationship. Higher soil pH, together with greater levels of exchangeable calcium and magnesium, was associated with increased yield. However, these conditions often came with a trade-off, slightly diminishing the intensity and balance of fruit flavour. In contrast, soils rich in organic matter enhanced the fruit's flavour quality, highlighting how biological activity and nutrient cycling contribute to sweetness, acidity, and aroma. Most soil properties, apart from organic matter and available phosphorus, also had positive effects on the nutritional composition of the fruit, underscoring the importance of balanced soil chemistry. Soil pH and organic matter are the most influential factors governing pomelo yield and quality. When growers combined practices that corrected soil acidity with strategies that increased organic matter, both production and fruit quality improved (Wu *et al.*, 2024). These findings show that managing soil pH is not just about achieving good growth. It directly shapes the taste, appearance, and nutrient richness of fruits and vegetables, and offers a sustainable pathway for improving quality as well.

Residues, Contaminants, and Heavy Metals Affect Safety

Poor soil management does more than reduce the freshness or shelf life of fruits and vegetables; it can threaten food safety itself. When soils are degraded, polluted, or poorly regulated, harmful contaminants such as heavy metals, pesticide residues, and industrial pollutants can accumulate. These substances may then be absorbed by plant roots and deposited in edible tissues, posing significant risks to human health.

Healthy, well-balanced soils act as a natural defence system. High organic matter binds heavy metals, reducing their mobility and limiting uptake by crops. Beneficial soil microbes also play a crucial detoxification role. They break down pesticide residues, degrade harmful compounds, and transform toxic metals into less available forms. In this way, biologically active soils protect our food from invisible contaminants long before harvest.

Contaminated soils, however, tell a different story. Fruits and vegetables grown in soils with excess lead, cadmium, arsenic, or nickel may look perfectly normal yet contain unsafe levels of these elements. Such contamination not only reduces marketability and export suitability but also increases the risk of chronic health effects for consumers. Moreover, produce grown in polluted soils often shows reduced firmness, uneven ripening, off-flavours, and shorter shelf life, which are indirect signs of stress caused by toxic soil conditions.

Ensuring food safety, therefore, begins underground. Regular soil testing, avoiding excessive agrochemical use, preventing wastewater irrigation, and building organic matter are essential steps. By maintaining clean and biologically active soils, farmers not only improve postharvest quality but also safeguard the health of consumers who rely on their produce every day.

Sustainable Soil Management = Better Postharvest Outcomes

Practices that build soil health ultimately lead to produce that lasts longer, tastes better, and withstands postharvest stress more effectively. Healthy soil acts like a quiet partner in the supply chain, working behind the scenes to strengthen plant structure, improve nutrient density, and reduce susceptibility to rapid deterioration.

- **Adding compost and green manure**: Regular organic amendments enrich the soil with stable organic matter, improving moisture-holding capacity and boosting microbial diversity. Produce grown in such soils develops firmer textures and stronger cell walls, which slows wilting and shrivelling after harvest.
- **Using crop rotations and cover crops**: Rotations break disease cycles, reduce soil-borne pathogen loads, and enhance nutrient availability. Cover crops protect the topsoil, promote root health, and support beneficial microbial communities, all of which reduce postharvest decay and extend storage life.
- **Reducing chemical overuse**: Over-reliance on synthetic fertilisers and pesticides can destabilise soil microbial balance. Sustainable nutrient management ensures plants absorb nutrients gradually and efficiently, resulting in produce with better flavour, colour, and shelf life. Lower chemical residues also mean safer produce with slower oxidative spoilage.
- **Improving soil drainage and structure**: Well-structured soils with good aeration encourage deeper root systems. Plants grown in such soils accumulate balanced minerals and develop resilient tissues, helping fruits and vegetables maintain firmness during storage and transport.
- **Minimising soil erosion**: Preventing erosion helps retain the nutrient-rich top layer essential for plant health. Stable soils ensure a continuous nutrient supply, improving the internal quality of produce, and postharvest attributes like sweetness, aroma, and texture can be significantly enhanced.

When farmers invest in soil health, the benefits travel all the way from the field to the consumer's plate. Sustainable practices create crops that are naturally robust, less prone to postharvest losses, and superior in sensory quality. These improvements not only support farmer livelihoods but also contribute to a more resilient and sustainable food system.

Conclusion

Good soil grows good food, and good food stays good for longer. On 5 December, World Soil Day is celebrated worldwide to highlight the vital role of healthy soils play in sustaining food systems, ecosystems, and resilient communities. It is worth remembering that postharvest success doesn't begin in the cold store; it begins in the soil itself. The 2025 theme of World Soil Day, *"Healthy Soils for Healthy Cities,"* reminds us that even beneath our busy streets lies a living system that shapes the quality of the food we eat and the resilience of the cities we inhabit. Healthy urban soils support fresh food production, filter and purify water, regulate temperature, and sustain rich biodiversity. Yet as urbanisation accelerates and more land becomes sealed or degraded, safeguarding soil health becomes essential, not only for today's harvests, but for future food security. As we celebrate World Soil Day 2025, let us honour the ground beneath our feet: a quiet, often overlooked resource that determines flavour, nutrition, shelf life, and ultimately the well-being of communities. By protecting and revitalising our soils, we invest in healthier cities, stronger food systems, and a more sustainable future for all. Warm wishes for a meaningful and inspiring World Soil Day 2025.

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From Kitchen to Cure: Unlocking the Health Benefits of Functional Foods

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For centuries, food has been at the heart of culture and nourishment. But a powerful shift is underway, transforming our view of the kitchen from a place of mere meal preparation to a hub of proactive wellness. This isn't about exotic super foods from distant mountains; it's about understanding the profound, science-backed healing potential of everyday ingredients already in your pantry, fridge, and spice rack.

What Are Functional Foods?

A functional food is any whole or fortified food that provides a health benefit beyond basic nutrition. In simple terms, it's a food that has a proven, positive effect on one or more body functions, helping to reduce the risk of disease or promote optimal health.

Some examples include foods fortified with vitamins, minerals, probiotics, or fiber. Nutrient-rich ingredients like fruits, vegetables, nuts, seeds, and grains are often considered functional foods as well.

Oats, for instance, contain a type of fiber called beta glucan, which has been shown to reduce inflammation, enhance immune function, and improve heart health. Similarly, fruits and vegetables are packed with antioxidants, which are beneficial compounds that help protect against disease.

Examples of functional foods

Functional foods are generally separated into two categories: conventional and modified.Conventional foods are natural, whole-food ingredients that are rich in important nutrients like vitamins, minerals, antioxidants, and heart-healthy fats.

Meanwhile, modified foods have been fortified with additional ingredients, such as vitamins, minerals, probiotics, or fiber, to increase a food's health benefits.

Here are some examples of conventional functional foods:

Fruits: berries, kiwi, pears, peaches, apples, oranges, bananas

Vegetables: broccoli, cauliflower, kale, spinach, zucchini

Nuts: almonds, cashews, pistachios, macadamia nuts, Brazil nuts

Seeds: chia seeds, flax seeds, hemp seeds, pumpkin seeds

Legumes: black beans, chickpeas, navy beans, lentils

Whole grains: oats, barley, buckwheat, brown rice, couscous

Seafood: salmon, sardines, anchovies, mackerel, cod

Fermented foods: tempeh, kombucha, kimchi, kefir, sauerkraut

Herbs and spices: turmeric, cinnamon, ginger, cayenne pepper

Beverages: coffee, green tea, black tea

Here are some examples of modified functional foods: fortified juices, fortified dairy products, such as milk and yogurt, fortified milk alternatives, such as almond, rice, coconut, and cashew milk, fortified grains, such as bread and pasta, fortified cereal and granola, fortified eggs.

Examples of some functional foods include:

Functional foods	***Health benefits***	
Moringa (drumstick leaves):	Packed with Vitamins A, C, and E, as well as essential minerals like calcium, iron, potassium, and zinc, this nutrient-rich food offers potent antioxidant and anti-inflammatory benefits. It also supports the immune system, helps regulate blood sugar levels, and promotes heart health.	
Turmeric	It contains curcumin which has strong anti-inflammatory, anti-cancerous & antioxidant properties. It also aids in digestion & improves gut health.	
Indian Gooseberry (Amla)	One of the rich sources of vitamin C, making it excellent for boosting immunity, improving skin health & supporting digestive health. It also helps in managing cholesterol levels.	
Fenugreek seeds (Methi seeds)	These are high in fiber, vitamins, protein, minerals & antioxidants. It helps in the regulation of blood sugar, boosts heart health, strengthens immunity, supports digestion and reduces inflammation. It also Enhance milk production in lactating women.	
Flaxseeds	Flaxseed is rich in Omega-3s, dietary fiber, protein, and antioxidants, supporting heart health, digestion, and immune function. It also contains vitamins, minerals, and phytochemicals that reduce inflammation, promote bone health, and enhance skin and hair health. Additionally, its prebiotic fiber supports a healthy gut microbiome	
Garlic	Garlic is a potent functional food containing phytochemicals like allicin. It supports immune function, heart health, and digestion while offering anti-inflammatory, antibacterial, and antiviral benefits. Regular consumption may help lower cholesterol, reduce cancer risk, and protect against infections.	

Yogurt	Yogurt is rich in protein, calcium, and probiotics, supporting digestive health, immune function, and bone health. It also contains vitamins, minerals, and antioxidants that aid in weight management, reduce inflammation, and improve muscle function and recovery.	
Green tea	It is rich in catechins, L-theanine, and antioxidants, which support heart health, weight loss, and brain function. It aids in digestion, boosts immunity, and reduces cancer risk.	
Nuts (almonds, cashews, walnuts, pistachios, etc)	Nuts, abundant in healthy fats, protein, and fiber, not only promote heart health, aid in digestion, and assist with weight management but also supply a range of antioxidants, vitamins, and minerals that bolster immune function, alleviate inflammation, and support cognitive and bone health	
Curry leaves	These are rich in vitamins, minerals, antioxidants, and essential oils, not only promoting digestive health, alleviating inflammation, and boosting immune function but also contributing to eye health, improving skin and hair growth, and potentially reducing the risk of chronic diseases and neurodegenerative conditions.	
Tomatoes	Tomatoes are packed with Vitamin C, lycopene, potassium, which collectively enhance immune function, support heart health, and promote digestion. Additionally, their high antioxidant and anti-inflammatory content helps reduce cancer risk, improve skin and eye health, and manage chronic diseases.	
Tamarind (emli)	Tamarind is rich in Vitamin C, Vitamin B6, magnesium, and potassium. It also contains antioxidants, anti-inflammatory compounds, and digestive enzymes, supporting immune function by protecting against oxidative stress, and also improves digestion, & cardiovascular health.	
Mustard seeds	Mustard seeds are rich in omega-3 fatty acids, protein, and fiber, promoting heart health, supporting digestion, and aiding in blood sugar control. They also contain vitamins, minerals, antioxidants, and phytochemicals that reduce inflammation, protect against cell damage, and support immune function.	

Functional foods are more than just a trend—they are an essential part of a health-promoting diet. By including a variety of these foods in your daily meals, you can take proactive steps to support your health. Functional foods offer a natural and effective way to achieve your wellness goals. **The journey from "Kitchen to Cure" begins with the food you put on your plate**.

Potential benefits

Functional foods are associated with several potential health benefits.

May prevent nutrient deficiencies

Functional foods are typically high in important nutrients, including vitamins, minerals, healthy fats, and fiber. Filling your diet with a variety of functional foods — including both conventional and fortified foods — can help ensure you get the nutrients you need and protect against nutrient deficiencies. In fact, since the introduction of fortified foods, the prevalence of nutrient deficiencies has significantly decreased around the globe. For instance, after iron-fortified wheat flour was introduced in Jordan, rates of iron deficiency anemia among children were nearly cut in half. Fortification has also been used to prevent other conditions caused by nutrient deficiencies, including rickets, goiter, and birth defects.

May protect against disease

Functional foods provide important nutrients that can help protect against disease. Many are especially rich in antioxidants. These molecules help neutralize harmful compounds known as free radicals, helping prevent cell damage and certain chronic conditions, including heart disease, cancer, and diabetes.

Some functional foods are also high in omega-3 fatty acids, a healthy type of fat shown to reduce inflammation, boost brain function, and promote heart health.

Other types are rich in fiber, which can promote better blood sugar control and protect against conditions like diabetes, obesity, heart disease, and stroke. Fiber may also help prevent digestive disorders, including diverticulitis, stomach ulcers, hemorrhoids, and acid reflux.

May promote proper growth and development

Certain nutrients are essential to proper growth and development in infants and children. Enjoying a wide range of nutrient-rich functional foods as part of a healthy diet can help ensure that nutritional needs are met. In addition, it can be beneficial to include foods that are fortified with specific nutrients that are important for growth and development.

For example, cereals, grains, and flours are often fortified with B vitamins like folic acid, which is essential for fetal health.

Low levels of folic acid can increase the risk of neural tube defects, which can affect the brain, spinal cord, or spine. It's estimated that increasing the consumption of folic acid could decrease the prevalence of neural tube defects by 50–70%.

Other nutrients commonly found in functional foods also play key roles in growth and development, including omega-3 fatty acids, iron, zinc, calcium, and vitamin B12.

Uses

A well-rounded, healthy diet should be rich in a variety of functional foods, including nutrient-rich whole foods like fruits, vegetables, whole grains, and legumes.

These foods not only supply your body with the vitamins and minerals it needs but also support overall health.

Modified, fortified functional foods can also fit into a balanced diet. In fact, they can help fill any gaps in your diet to prevent nutrient deficiencies, as well as enhance health by boosting your intake of important nutrients like vitamins, minerals, fiber, heart-healthy fats, or probiotics.

Conclusion

The path from kitchen to cure is a journey of empowerment. It's about rediscovering the inherent wisdom in nature's pantry and using it to nourish our bodies deeply and preventively. By making conscious choices about what we put on our plates, we can transform our daily meals into a powerful ritual of healing and health, one delicious bite at a time. Your kitchen was always a pharmacy; now you have the key to unlock it.

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Communicating Agriculture: The Structure, Style, and Practice of Agricultural News Writing

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Abstract
Agricultural journalism is a specialized branch of journalism dedicated to communicating scientific, economic, and social information related to agriculture and rural development. This article explores the meaning, definition, importance, nature, scope, characteristics, and challenges of agricultural journalism, with a special emphasis on agricultural news writing. It examines newspapers and magazines as communication media, the structure and content of agricultural publications, the types and composition of agricultural stories, and the methods of gathering agricultural information. Furthermore, it explains the processes involved in writing, illustrating, and editing agricultural news. The conclusion highlights the importance of agricultural journalism as a tool of development communication and emphasizes the need for accurate, accessible, and ethical reporting to serve rural communities effectively.

Keywords: Agricultural Journalism; Rural Communication; Agricultural News Writing; Media in Agriculture; Agricultural Stories; Information Sources; Editorial Practices; Agricultural Reporting; Communication Media; Science Communication

1. Journalism: Meaning, Definition, and Importance

Journalism is the systematic process of collecting, verifying, presenting, and distributing information for public consumption. It functions as the central mechanism through which societies understand political events, economic activities, cultural developments, and scientific progress. Journalism involves various forms of writing, including news reporting, feature stories, commentaries, editorials, and photojournalism. The American Press Institute (2020) describes journalism as the practice of providing citizens with accurate, fair, and relevant information necessary for making informed decisions in a democratic society. The importance of journalism lies in its ability to disseminate timely information, educate the public on complex issues, ensure accountability through critical inquiry, promote social change by highlighting injustices, and empower individuals by expanding their knowledge and awareness. Through these functions, journalism plays a critical role in sustaining informed citizenship and strengthening democratic processes.

2. Agricultural Journalism: Meaning and Definition

Agricultural journalism is a specialized branch of journalism that deals with the communication of information related to agriculture, rural development, farming practices, agricultural markets, and scientific advancements in the agri-sector. It focuses on transforming scientifically complex agricultural knowledge into simple, understandable messages for farmers and rural communities. Talbot (2015) defines agricultural journalism as the journalistic practice of interpreting and presenting scientific agricultural information in a form that rural audiences can easily understand and apply. Unlike general journalism, agricultural journalism serves a development-oriented purpose, linking research institutions, government agencies, and farmers through effective communication channels.

3. Agricultural Journalism in Rural Areas: Problems and Prospects

The practice of agricultural journalism in rural areas faces several challenges. Low literacy levels in many rural regions limit the accessibility and comprehension of written content. The digital divide remains a significant barrier, as unreliable internet connectivity restricts the use of online platforms for agricultural communication. Another major challenge is the inadequate training of journalists who report on agricultural issues; many lack scientific knowledge, resulting in incomplete or inaccurate reporting. Additionally, mainstream media often deprioritize agricultural news, focusing instead on political events or entertainment content. Language barriers further complicate communication, as scientific terms are often not translated adequately into regional languages, making information difficult for farmers to understand.

Despite these challenges, the prospects of agricultural journalism remain promising. There is a rapidly growing need for agricultural information due to climate change, fluctuating weather patterns, and the introduction of new technologies. The rise of digital media—such as YouTube channels, WhatsApp groups, podcasts, and community radio—expands the reach of agricultural content. Government initiatives in agriculture, including subsidies, support schemes, and farmer welfare programs, create a demand for effective communication. Agri-tech startups and private extension services are emerging as new employers of skilled agricultural communicators. Moreover, universities, agricultural institutions, and ICAR centers have begun offering specialized courses in agricultural journalism, enhancing professional capacity.

4. Nature and Scope of Agricultural Journalism

The nature of agricultural journalism is inherently scientific, as it requires journalists to convey scientifically accurate information drawn from research findings, field experiments, and expert insights. It is also development-oriented because its ultimate goal is to support rural progress, enhance agricultural productivity, and improve the socio-economic conditions of farming communities. The educational nature of agricultural journalism helps farmers adopt scientific practices, understand government policies, and respond to environmental changes. It further embodies a public-service character, acting as a vital link between agricultural laboratories and farmers' fields by translating technical knowledge into practical guidance.

The scope of agricultural journalism is broad and multidimensional. It includes comprehensive reporting on agricultural policies, schemes, and programs announced by the government and institutions. It covers detailed information on crop cultivation practices, livestock management, soil health, irrigation methods, and climate-related challenges. The scope also extends to reporting on agricultural markets, price trends, Minimum Support Prices, and supply chain issues, which help farmers make informed economic decisions. Agricultural journalism also plays a critical role in communicating scientific advancements such as new seed varieties, innovative machinery, biotechnology tools, and digital farming technologies. Furthermore, it addresses rural livelihood issues by covering women's empowerment, Self-Help Groups, cooperative activities, and rural entrepreneurship. The domain of agricultural journalism further includes coverage of agri-business, food processing, export opportunities, and value chain developments, linking farmers with broader markets and enhancing agricultural growth.

5. Characteristics and Training of an Agricultural Journalist

An agricultural journalist must possess a solid understanding of agricultural topics, including crops, climate, soil, livestock, and modern technologies. The ability to simplify complex scientific terms into everyday language is essential for effective communication with rural communities. Strong interviewing skills, keen observation abilities, and a genuine interest in rural life are crucial qualities. Accuracy, objectivity, and clarity are fundamental, as misinformation can negatively affect farmers' livelihoods. Proficiency in regional languages is equally important since much agricultural communication occurs in local dialects. Training for agricultural journalists typically includes formal courses in journalism, mass communication, and agricultural extension, along with internships in agricultural universities, Krishi Vigyan Kendras (KVKs), or media houses. Skills in photography, editing, digital media production, and data interpretation further enhance journalistic competence.

6. Similarities and Differences with Other Types of Journalism

Agricultural journalism shares many similarities with general journalism. Both require accuracy, fairness, relevance, and clear communication. They follow standard journalistic principles such as the 5Ws and 1H, use reporting and editing techniques, and operate across print, broadcast, and digital platforms. However, agricultural journalism differs from other types in several ways. Its audience primarily consists of farmers and rural communities, whereas general journalism targets urban or mixed audiences. The language used in agricultural journalism must be simple, practical, and often grounded in local culture. The content focuses on issues such as climate, crops, livestock, government schemes, and rural development, in contrast to general journalism, which may emphasize politics, crime, entertainment, or sports. Agricultural journalism is uniquely development-oriented, aiming to educate and empower farmers rather than merely inform or entertain.

7. Newspapers and Magazines as Communication Media

Newspapers and magazines play a vital role in agricultural communication. They offer credibility, permanence, and wide reach across diverse populations. Newspapers provide timely updates on day-to-day events, policy announcements, market prices, and weather forecasts, making them useful for immediate decision-making. Magazines offer detailed, researched articles and feature stories, making them ideal for in-depth agricultural analysis. Readers of newspapers typically seek quick and concise updates, while magazine readers prefer analytical content, case studies, and expert opinions. Both newspapers and magazines contribute substantially to agricultural journalism by providing platforms for news, features, interviews, visuals, and advertisements.

8. Form and Content of Newspapers and Magazines

The style and language of agricultural writing in newspapers and magazines must be simple, clear, and focused on reader comprehension. Complex terms should be avoided unless properly explained. Agricultural stories are typically written in active voice with short, direct sentences. Newspapers contain headlines, news stories, editorials, columns, advertisements, and photographs. Magazines feature cover stories, long-form articles, interviews, infographics, photo features, and opinion pieces. Both formats contribute distinctively to agricultural journalism by combining information with illustration to engage readers effectively.

9. The Agricultural Story: Types, Subject Matter, and Structure

Agricultural stories can take the form of news reports, features, market stories, research-based reports, or human-interest narratives. News stories typically focus on immediate issues such as rainfall patterns, crop losses, or government announcements. Feature stories highlight innovations, technologies, or farmers' success stories. Market stories cover price trends and economic factors, while research stories explain scientific advancements and new seed varieties. The subject matter of agricultural stories includes crop cultivation, soil health, climate conditions, irrigation practices, livestock, agri-markets, government schemes, and rural development efforts. The structure of an agricultural story generally begins with a clear and engaging headline followed by a lead that answers the essential 5Ws and 1H. The body contains elaboration, data, and quotes, while the background section provides context. The conclusion summarizes the significance or future implications.

10. Gathering Agricultural Information

Gathering information for agricultural journalism requires the use of diverse sources. Government reports, press releases, and policy documents provide official data. ICAR institutes, State Agricultural Universities (SAUs), and Krishi Vigyan Kendras (KVKs) offer scientific insights and research updates. Journals, research summaries, and conference papers help journalists understand emerging technologies. Field visits, interactions with farmers, and observations of crop conditions provide practical, ground-level knowledge. Interviews with farmers reveal real-life challenges, while discussions with scientists ensure technical accuracy. Coverage of agricultural fairs, field demonstrations, exhibitions, and farmer-scientist interactions adds depth to reporting. Abstracting scientific materials involves translating complex research into simple, understandable language. Wire services such as PTI, UNI, and Reuters, along with digital agricultural portals, serve as additional sources of timely information.

11. Writing the Agricultural Story

The process of writing an agricultural story begins with collecting reliable information and verifying facts. Once the material is organized logically, the journalist must present it clearly and neutrally, using examples and expert opinions to enrich the report. Effective treatment involves providing background information that helps readers understand the broader context. Writing a strong lead is essential; it may summarize the main point, incorporate a quotation, describe a scene, or pose a question. Readability is maintained through short sentences, active voice, and smooth transitions. Unnecessary jargon must be avoided to ensure comprehension. Agricultural stories should reflect the realities of rural life while maintaining professional journalistic standards.

12. Illustrating Agricultural Stories

Photographs play an important role in agricultural journalism by providing visual evidence of farming practices, field conditions, and rural environments. Clear, original, and relevant photographs enhance the credibility of a story. Artwork such as graphs, charts, and maps helps convey data more effectively, depicting trends in production, price fluctuations, rainfall levels, or soil types. Captions accompanying images must be concise, accurate, and informative, clearly describing what the picture shows, where it was taken, and when the event occurred.

13. Editorial Mechanics

Editorial mechanics ensure the accuracy and clarity of agricultural stories. Copy reading involves correcting grammatical, typographical, and factual errors, while ensuring that the story flows logically. Headline writing requires creativity and precision, capturing the essence of the story in a few words. Proofreading is the final stage of checking for mistakes before publication. Page layout involves arranging text, images, and headings in a balanced and visually appealing manner, maintaining readability and professional presentation.

Conclusion

Agricultural journalism plays a pivotal role in bridging the gap between scientific research and farming practice. In an era marked by climate uncertainties, technological advancements, and policy shifts, effective agricultural communication becomes essential for supporting rural communities. Agricultural journalists must combine scientific understanding with clear and ethical reporting to provide accurate information that farmers can trust. Strengthening agricultural journalism will contribute to rural development, empower farming communities, and promote sustainable and resilient agricultural systems.

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Underutilized Vegetables: A Power-Packed Source of Nutrition & Food Security

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Introduction:

One important strategy for adjusting agriculture to the changing climate is the use and promotion of appropriate crops. The future of Agriculture will increasingly center on adapting neglected and underutilized crops, which could be crucial to ensure food security and a balanced diet and nutrition, especially for rural populations in India's breadbasket regions. An increasing number of people are calling for a change in agricultural methods to investigate unconventional choices, such as these lesser-known crops, in light of the shifting climate. A more robust agricultural system might result from this shift (Massawe *et al.,* 2015). A rich and reasonably priced source of vitamins and minerals are vegetables. Along with proteins from peas, beans and leafy greens, several vegetables like leguminous vegetables, sweet potatoes, potatoes, onions, garlic and methi also offer significant amounts of carbohydrates. Vitamins A (carrots, tomatoes, drumsticks and leafy greens), B (peas, garlic and tomatoes), and C (green chilies, drumstick leaves, cole crops and radish leaves) are among the necessary vitamins included in vegetables. Drumstick pods and leafy greens are also great suppliers of minerals. As a primary source of vital nutrients and antioxidants, vegetables are an essential part of a balanced human diet and play a key role in ensuring national nutritional security (Debbarma *et al.,* 2020). Fruits and vegetables are rich in essential fibers, minerals and vitamins as well as disease-preventing phyto-nutrients that people need to maintain good health. While many vegetables are cooked before eating, some can be consumed raw. In essence, cooking vegetables at home is more about flavour preferences and enjoyment than it is about preserving the nutrients and health-promoting elements.

Because they have many traits and characteristics that will be essential to our future food supply, neglected and underutilized plants contribute significantly to agro-biodiversity. These species are either commonly used in traditional ways or are wild species that provide sustenance supplying a nutritious diet to the underprivileged section of the society. These plants might also possess a variety of other traits, such as the capacity to adjust to future climate change by withstanding heat or salt, medicinal properties and genes that fend off illnesses and pests, reducing the need for pesticides (Chibarabada *et al.,* 2017). Additionally, the majority of the underutilized and neglected species are rich in nutrients and may be able to help poor rural people manage micronutrient shortages and diversify their diets. Therefore, encouraging them in areas with poor agricultural yield could increase the availability and accessibility of nutrient-dense food for rural inhabitants. (Haq and Williams, 2000). **"Underutilized crops"** are a variety of agricultural species that have historically been used for their food, shelter, fiber, fodder, oil or medicinal properties but have not yet gained traction among commercial farmers.

What are Underutilized Vegetables?

Crops that have survived as life support species in harsh settings and endangered ecosystems possess the genetic resilience to endure in difficult situations and provide important industrial and/or nutritional qualities for a range of applications are considered underutilized. One description of underused foods is **"foods which are less available, less utilized or rarely used or region specific."** Underutilized vegetable crops are sometimes defined as those that are not widely traded or extensively grown on a commercial scale. Therefore, under used vegetables are those that are not farmed for commerce or widely sold. These, though underutilized, have high nutritional and therapeutic value and the ability to withstand adverse climatic conditions. Despite this, people continue to ignore these vegetables due to a lack of awareness and comprehensive knowledge. Diverse names are used to elaborate range of underutilized crops. Some of the titles are underdeveloped, lost, abandoned, minor, underused, alternative, traditional, local, forgotten, niche, neglected, promising and orphan (Peduruhewa *et al.,* 2021). Despite their local or territorial significance and excellent uses as fruit, oil, fodder, fiber, etc., these vegetables continue to lack general acceptance due to amplification. Vegetables that are underutilized are essential to rural residents. They can improve economic standing through job opportunities, income production and increased worker productivity and profitability in both rural and urban areas. The average way to reduce the likelihood of being overly dependent on a limited number of primary food crops is to use underutilized crops.

Only around one-fourth of vegetable species are currently acknowledged as significant crops, the others are known as minor, uncommon, bush edible or under used vegetables. These lesser-known vegetables are frequently indigenous to particular areas and are frequently associated with farming in rural areas. Because they are occasionally seen as food for the underprivileged, their eating bears a social stigma in some societies. However, potential of those species to contribute to economic development, nutrition, health, food security and environmental benefits is not fully harnessed.

Characteristics of Underutilized Vegetables:

- The food value of a crop must be demonstrated by scientific or ethno-botanical means.
- The crop needs to have been grown, either historically or exclusively in a certain region.
- The crop must have a poor or non-existent formal seed supply system, be less often grown than other conventional crops and have indigenous usage in specific regions.
- Research, extension services, farmers, policy and decision makers and technology providers must have paid little attention to it. It may be very nutrient-dense and/or possess therapeutic, medicinal or other multipurpose qualities.

Importance of Underutilized Vegetables:

The potential of underutilized vegetables to prevent hunger, lessen poverty and foster economic growth is becoming more widely acknowledged. These crops can greatly improve quality of life of millions of people, especially for tribal groups and are important biological resources for rural areas. These vegetables, which are high in vital vitamins, minerals and antioxidants, promote improved health and nutritional diversity by providing a sufficient and well-balanced intake of different micronutrients. Furthermore, many neglected vegetables are advantageous in difficult growing environments because they can tolerate a variety of biotic and abiotic challenges.

When compared to other vegetables like tomatoes and cabbage, several endemic or conventional vegetables are recognized for their high nutritional value. Native vegetables or under appreciated crops have the potential to achieve nutritional security because they are a significant source of protein, minerals, vitamins and other phyto-chemicals. In addition to essential vitamins, a lot of these backyard vegetables are generally nutritious. Additionally, because they lessen the impact on environmental manufacturing, their commercialized, traditional and culturally valued medicinal vegetables are recommended as essential for organic farming.

For rural populations, these crops are immensely valuable because they are not only staples of local meals but also provide long-standing medical and therapeutic advantages. These vegetables which are traditionally eaten raw or cooked are a mainstay of the regional cuisine and extra production frequently helps households make ends meet.

Rural low-income groups continue to experience high rates of food insecurity and malnutrition. In both rural and urban settings, underutilized vegetables provide a means of addressing these problems by increasing farm labour productivity per area and margin profit, as well as by producing money and jobs. Underutilized vegetables can contribute significantly to global food and nutrition security by increasing agricultural productivity, supporting sustainable livelihoods and meeting changing market demands by diversifying the spectrum of edible plant species.

Table 1: Underutilized vegetables, their nutritional value and disease prevention attributes

Underutilized Vegetable	Nutritional Value (Key Components)	Disease Prevention / Health Attributes
Amaranth leaves (*Amaranthus spp.*)	Iron, calcium, vitamin A, vitamin C, folate, dietary fiber	Prevents anaemia, boosts immunity, supports bone health, reduces oxidative stress
Drumstick leaves (*Moringa oleifera*)	Protein, vitamin A, vitamin C, calcium, potassium, antioxidants	Boosts immunity, anti-inflammatory, helps control blood sugar, prevents malnutrition
Pumpkin leaves (*Cucurbita spp.*)	Vitamin A, C, iron, calcium, dietary fiber	Improves vision, prevents anaemia, aids digestion, antioxidant effects
Water spinach (*Ipomoea aquatica*)	Iron, vitamin C, carotenoids, dietary fiber	Prevents anaemia, promotes heart health, protects against oxidative damage
Bitter gourd (*Momordica charantia*)	Vitamin C, iron, potassium, bioactive compounds (charantin, polypeptide-p)	Anti-diabetic, improves immunity, supports liver health
Pointed gourd (*Trichosanthes dioica*)	Vitamin A, C, dietary fiber, magnesium	Regulates blood sugar, supports digestion, antioxidant properties
Indian spinach (*Basella alba*)	Iron, vitamin A, vitamin C, calcium	Prevents anaemia, supports skin and eye health, boosts immunity
Winged bean (*Psophocarpus tetragonolobus*)	Protein, calcium, phosphorus, vitamin B-complex	Supports muscle growth, strengthens bones, prevents malnutrition
Snake gourd (*Trichosanthes cucumerina*)	Vitamin A, C, minerals, antioxidants	Supports digestion, prevents constipation, anti-inflammatory
Colocasia leaves (*Taro leaves*)	Vitamin A, C, calcium, iron	Improves vision, prevents anaemia, supports bone health
Kale (*Brassica oleracea var. acephala*)	Vitamin K, C, calcium, iron, antioxidants	Anti-cancer properties, supports bone health, heart protection
Ridge gourd (*Luffa acutangula*)	Vitamin A, C, dietary fiber, potassium	Improves digestion, helps weight management, detoxifies liver
Ivy gourd (*Coccinia grandis*)	Vitamin A, C, iron, fiber	Anti-diabetic, supports digestion, boosts immunity
Cluster bean (*Cyamopsis tetragonoloba*)	Fiber, protein, calcium, phosphorus	Controls cholesterol, aids digestion, prevents constipation
Chow-chow / Chayote (*Sechium edule*)	Vitamin C, folate, potassium, fiber	Heart protective, supports digestion, reduces hypertension
Broad beans (*Vicia faba*)	Protein, folate, iron, magnesium	Improves nerve health, prevents anaemia, supports growth
Yam (*Dioscorea spp.*)	Carbohydrates, vitamin B6, potassium	Improves energy, regulates blood sugar, supports brain health
Elephant foot yam (*Amorphophallus paeoniifolius*)	Carbohydrates, vitamin B6, potassium, fiber	Anti-inflammatory, digestive aid, weight management
Scarlet gourd (*Coccinia grandis var. scarlet*)	Vitamin C, carotenoids, iron	Supports immunity, antioxidant properties, prevents anaemia
Drumstick pods (*Moringa oleifera*)	Vitamin C, potassium, calcium, fiber	Improves bone health, boosts immunity, digestive health
Fenugreek leaves (*Trigonella foenum-graecum*)	Iron, vitamin K, calcium, folate	Lowers blood sugar, improves lactation, prevents anaemia

African eggplant (*Solanum aethiopicum*)	Vitamin C, iron, antioxidants	Prevents anaemia, supports liver health, reduces oxidative stress
Tree spinach (*Cnidoscolus aconitifolius*)	Protein, calcium, vitamin A, C	Improves digestion, supports bone health, antioxidant effects
Nightshade greens (*Solanum nigrum*)	Iron, vitamin C, calcium	Protects liver, prevents anaemia, antioxidant properties
Tindora / Ivy gourd (*Coccinia indica*)	Vitamin A, C, dietary fiber	Anti-diabetic, supports digestion, antioxidant effects
Ash gourd (*Benincasa hispida*)	Water-rich, vitamin C, calcium, fiber	Cooling effect, aids weight loss, supports kidney health
Sword bean (*Canavalia gladiata*)	Protein, calcium, phosphorus, vitamin B-complex	Strengthens muscles, supports growth, prevents malnutrition
Teasel gourd (*Momordica dioica*)	Vitamin C, carotenoids, fiber	Improves immunity, antioxidant-rich, supports digestion
Agathi leaves (*Sesbania grandiflora*)	Protein, calcium, vitamin A, vitamin C	Improves eyesight, boosts bone health, prevents malnutrition
Drumstick flowers (*Moringa oleifera*)	Protein, vitamin C, calcium, flavonoids	Boosts immunity, regulates blood sugar, supports heart health
Wild yam (*Dioscorea bulbifera*)	Carbohydrates, potassium, vitamin B6	Energy source, helps regulate blood pressure, supports brain function
Snake tomato (*Trichosanthes cucumerina var. anguina*)	Vitamin C, fiber, carotenoids	Improves digestion, reduces oxidative stress, immune protection
Chinese cabbage (*Brassica rapa subsp. pekinensis*)	Vitamin C, K, folate, calcium, fiber	Improves bone health, boosts immunity, antioxidant properties
Pokchoi / Bok choy (*Brassica rapa subsp. chinensis*)	Vitamin A, C, K, calcium, potassium	Supports eye health, strengthens bones, prevents hypertension
Rhubarb (*Rheum rhabarbarum*)	Vitamin K, calcium, fiber, antioxidants	Improves digestion, supports bone health, antioxidant effects
Chekurmanis (*Sauropus androgynus*)	Protein, calcium, vitamin A, iron	Promotes lactation, prevents anaemia, strengthens bones
Lima bean (*Phaseolus lunatus*)	Protein, fiber, iron, folate, potassium	Regulates blood sugar, supports digestion, prevents anaemia
Parsnip (*Pastinaca sativa*)	Carbohydrates, vitamin C, folate, potassium, fiber	Improves digestion, lowers cholesterol, supports heart health
Celery (*Apium graveolens*)	Vitamin K, C, potassium, fiber	Lowers blood pressure, aids weight management, anti-inflammatory

Parsley (*Petroselinum crispum*)	Vitamin C, K, folate, iron, antioxidants	Detoxifying, prevents anaemia, improves immunity
Lettuce (*Lactuca sativa*)	Vitamin A, K, folate, potassium, fiber	Supports eye health, aids weight management, antioxidant effects
Taro (*Colocasia esculenta*)	Carbohydrates, vitamin E, potassium, fiber	Provides energy, improves digestion, supports heart health
Tannia / Tanier (*Xanthosoma sagittifolium*)	Carbohydrates, vitamin C, calcium, iron	Energy source, prevents anaemia, supports bone health
Chinese potato (*Plectranthus rotundifolius*)	Carbohydrates, dietary fiber, calcium, iron	Provides energy, prevents anaemia, supports digestive health
Yam bean (*Pachyrhizus erosus*)	Vitamin C, potassium, dietary fiber	Cooling, supports digestion, aids weight management
Curry leaves (*Murraya koenigii*)	Iron, calcium, vitamin A, antioxidants	Improves hair and skin, prevents anaemia, supports digestion
Bathua (*Chenopodium album*)	Vitamin A, C, calcium, phosphorus, iron	Supports digestion, prevents anaemia, strengthens immunity
Kantola (Spiny gourd, *Momordica dioica*)	Vitamin C, fiber, antioxidants	Improves immunity, supports digestion, reduces blood sugar
Oriental pickling melon (*Cucumis melo var. conomon*)	Vitamin A, C, potassium, dietary fiber, antioxidants	Improves digestion, supports hydration, regulates blood pressure, antioxidant & anti-inflammatory effects
Kasarkaya (*Strychnos potatorum*)	Protein, iron, calcium, antioxidants	Traditionally used for liver health, improves digestion, antioxidant & detoxifying properties
Water spinach (*Ipomoea aquatica*)	Iron, vitamin C, carotenoids, dietary fiber	Prevents anaemia, promotes heart health, supports digestion, protects against oxidative damage
Turkey berry (*Solanum torvum*)	Iron, calcium, antioxidants, flavonoids	Prevents anaemia, strengthens bones, protects liver, anti-inflammatory
Chekurmanis (*Sauropus androgynus*)	Protein, calcium, vitamin A, iron	Promotes lactation, prevents anaemia, supports bone health, antioxidant effects

Scope of Underutilized Vegetables:

Numerous plant crops are used for a variety of purposes, including industrial and medical ones. Nowadays, the majority of crops grown to meet 60% of human energy needs are wheat, rice, maize and potatoes. Despite being a great source of many nutrients and health-promoting elements, underutilized crops also help to prevent chronic illnesses and malnutrition. As a result, adding these crops to the diet and upgrading food chains can help to improve nutrition and general health.

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Tannia

Rhubarb

Spine Gourd

Parsley

Chekurmanis

Celery

Fig 1: Some underutilized vegetables

Issues with the Growth of Underutilized Vegetable Crops:

1. Compared to other crops, these may have unique qualities that are uncommon.
2. These could be restricted to a specific area or not administered widely.
3. In contrast to other typical crops, these might not be cultivated on a large scale.
4. Farmers, researchers and other responsible parties pay very little attention to these.
5. These may possess numerous pharmacological, nutritional and therapeutic qualities.
6. These must worsen agricultural diversification and production.
7. Ignorance about how to produce, eat and use these crops contributes to their increased neglect and notoriety.
8. A lack of knowledge about the advantages and extent of trade.
9. The quality of raw materials and other resources has not improved and breeding and biotechnology have not advanced technologically.
10. Cultivators, researchers, scientists and extension agents are less interested in and focused on underutilized crops.
11. A lack of facilities like market chains and infrastructure for underused commodities results in a decline in commerce and transportation.
12. Proper policies and rules pertaining to trustworthiness, marketability and investment.
13. It is more conditional due to a lack of technological resources for handling different underused vegetables.

Strategies for Development of Underutilized Vegetables:

Farmers can be successfully informed about the nutritional and medicinal advantages of underutilized vegetable crops by putting focused advertising and educational efforts into action. Training courses, organized workshops and informational campaigns can all help achieve this. Strengthening research and development efforts is vital for advancing knowledge in areas such as agronomy, crop improvement and post-harvest processes, ultimately leading to the development of superior cultivars and more efficient production systems. Establishing seed banks and plant nurseries is essential to guaranteeing a steady flow of premium seeds and planting supplies, which will enable wider cultivation. Crop production and sustainability can be greatly increased by encouraging the use of contemporary agricultural advancements, such as precision agriculture, biotechnology and plasticulture.

Farmers are encouraged to grow underutilized crops by creating value chains, market connections and market information systems that facilitate market access. Underutilized crops might be included in agricultural development agendas by including them into existing horticulture promotion programmes and schemes. Last but not least, forming alliances between governmental bodies, educational institutions, nonprofits, business partners and farmers' associations may help promote the development of these crops in a way that promotes food availability, biodiversity preservation and sustainable agricultural growth.

Conclusion:

One clever strategy to create a more resilient, inclusive and nutrition-focused food system is to promote underutilized vegetables. Despite being frequently disregarded, these crops can help small farmers, enhance diets and safeguard the environment. They are helpful in addressing climatic and dietary concerns because of their innate capacity to thrive in challenging environments. We must increase awareness, establish markets, improve legislation and incorporate them in research if we are to maximize their advantages. Supporting these crops is a step toward a safer and healthier future, not just a way to uphold tradition.

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Bovine Ketosis in Dairy Cows

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Abstract

Bovine ketosis is a common metabolic disorder in high-producing dairy cows, primarily occurring during early lactation due to negative energy balance. It is characterized by elevated ketone bodies, reduced appetite, decreased milk yield, and in severe cases, neurological signs. Ketosis leads to significant economic losses through decreased production, treatment costs, and increased morbidity or mortality of cows and calves. Early detection through clinical assessment and ketone monitoring, along with preventive strategies such as balanced nutrition and energy supplementation, is essential for effective management. Proper herd management can minimize the incidence and impact of this disease ensuring optimal productivity and health in dairy operations.

Introduction:

Bovine ketosis is a common metabolic disorder in dairy cattle, particularly in high-producing cows during early lactation (first 6-8 weeks of lactation) period. Ketosis is a metabolic state characterized by elevated levels of ketone bodies in the blood or urine (Bradford, 1990). Ketone bodies consist of β-hydroxybutyric acid (βHBA), acetoacetic acid (ACAC), and acetone (AC) (Kumar, 2025).

During early lactation, the animal's energy output exceeds its dietary energy intake. This typically occurs because the cow's demand for glucose increases substantially to support lactose synthesis for milk production, while at the same time, dry matter intake remains insufficient to meet these high energy needs. To compensate for this energy deficit, the cow mobilizes stored fat from adipose tissue, breaking it down into non-esterified fatty acids (NEFAs) that are transported to the liver for energy production. However, excessive fat mobilization can overwhelm the liver's metabolic capacity, leading to the accumulation of ketone bodies and the development of ketosis. Therefore, managing NEB through proper nutrition and transition cow management is crucial to maintain metabolic health and sustain optimal milk production (Herdt, 2000).

The condition severely affects animal performance by reducing feed intake, milk yield and reproductive efficiency. In severe or prolonged cases, it can predispose the animal to other metabolic and infectious diseases, further compromising herd health. Consequently, ketosis has a major economic impact on dairy farms due to decreased productivity, increased veterinary costs, and extended calving intervals. Early diagnosis and proper nutritional management are therefore essential to prevent and control the disease, ensuring optimal health and profitability of the dairy herd.

Biochemical Aspects of Bovine Ketosis

1. **Negative Energy Balance (NEB)**

During early lactation, dairy cows experience Negative Energy Balance (NEB) when their energy output exceeds dietary intake. This occurs mainly because of the increased glucose demand for lactose synthesis in milk production, combined with inadequate dry matter intake immediately after calving. To meet this energy deficit, cows begin to mobilize fat reserves from adipose tissue, releasing stored lipids into the bloodstream to be used as an alternative energy source.

2. **Lipid Mobilization and Fatty Acid Oxidation**

As fat reserves are mobilized, non-esterified fatty acids (NEFAs) are released into the bloodstream from adipose tissue. The liver plays a key role in processing these NEFAs. Depending on the metabolic state of the cow, NEFAs are either completely oxidized in the mitochondria via the TCA cycle to produce carbon dioxide (CO_2) and energy

(ATP), or they undergo partial oxidation, leading to the formation of ketone bodies. Partial oxidation becomes dominant when the TCA cycle is overloaded or limited due to low oxaloacetate availability, which occurs during glucose deficiency.

3**. Ketogenesis in the Liver**

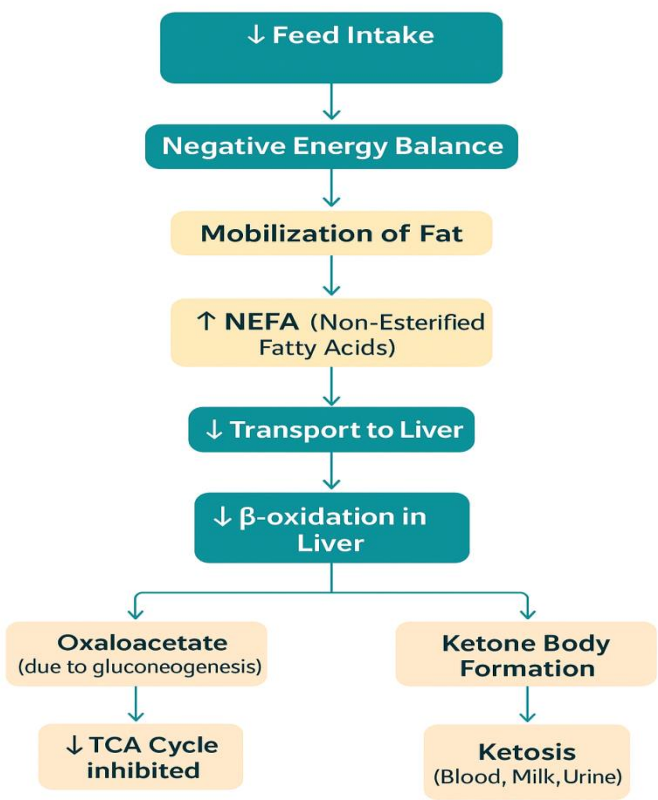
Under conditions of low glucose availability, acetyl-CoA derived from fatty acid oxidation cannot enter the TCA cycle because of insufficient oxaloacetate. As a result, acetyl-CoA is diverted into the ketogenesis pathway, forming ketone bodies such as acetoacetate, β-hydroxybutyrate (BHBA) and acetone. These compounds can serve as alternative energy sources for peripheral tissues; however, when produced in excess, they accumulate in the blood and tissues, leading to ketosis, a metabolic disorder that impairs health and productivity.

4. **Hypoglycemia**

During early lactation, much of the cow's glucose supply is directed toward lactose synthesis in the mammary gland. At the same time, dietary glucose intake is limited and gluconeogenesis, the liver's production of glucose from precursors like propionate may be insufficient due to reduced rumen fermentation. These factors contribute to low blood glucose levels (hypoglycemia), which further aggravates fat mobilization and ketone body formation.

5. **Altered Liver Metabolism**

As NEFAs flood the liver, not all can be oxidized or converted to ketone bodies. A significant portion is re-esterified into triglycerides. However, cows have a limited ability to export triglycerides in the form of very low-density lipoproteins (VLDL), leading to the accumulation of fat within the liver tissue. This condition, known as fatty liver syndrome, often occurs alongside ketosis and further compromise's hepatic function, reducing the animal's metabolic efficiency and overall performance.



Bovine Ketosis flowchart

Clinical Manifestations of Ketosis

Ketosis in dairy cows can occur in two forms- subclinical and clinical (Saradhi *et al.,* 2024 and Kumar, 2025)

1. **Subclinical Ketosis:** There is a mild elevation of ketone bodies in the blood, milk, or urine without any noticeable clinical signs. Although the animal appears normal, this condition can predispose cows to more severe metabolic disorders such as clinical ketosis, displaced abomasum or fatty liver.
2. **Clinical Ketosis**: In clinical ketosis, the signs become apparent and more severe. Affected cows show dullness with a marked reduction in appetite and milk yield, often exhibiting selective anorexia where they refuse concentrate feed but may still consume roughage. Neurological symptoms, known as nervous ketosis, may also be seen, including head pressing, ataxia, excessive licking, kicking and abnormal chewing movements. Additionally, a characteristic acetone-like odour is often detected in the breath, milk, or urine of affected animals.

Diagnosis of Bovine Ketosis

The standard diagnostic procedures of ketosis are:

i) Clinical history (early lactation and the last stage of pregnancy).
ii) Pathonomic clinical signs like low feed intake, the smell of ketone bodies in milk and urine.
iii) Urine/milk ketone strips: Ketone detection strips (Acetoacetate) and Milk BHB concentration > 0.15 mmol/L indicates subclinical ketosis
iv) Blood test
  a) β-hydroxy butyrate level (BHB) levels: Gold-standard test.
  Normal: < 1.2 mmol/L
  Subclinical ketosis: 1.2–2.9 mmol/L
  Clinical ketosis: > 3.0 mmol/L
  b) Non-esterified fatty acids (NEFA) levels: Indicates fat mobilization.
  Prepartum: > 0.4 mmol/L (risk factor)
  Postpartum: > 0.7 mmol/L (ketosis likely)
v)Liver function test: Aspartate aminotransferase and Glutamate dehydrogenase
vi) Glucose (< 2.2 mmol/L)

Advancements in Early Detection:

Early and accurate detection of subclinical ketosis is essential for effective herd management and prevention of economic losses. Recent advancements include the development of a graphene-based biosensor capable of detecting β-hydroxybutyrate (βHB) levels in dairy cows with high sensitivity and selectivity. This biosensor can accurately distinguish βHB even in the presence of interfering compounds such as glucose and urea and has shown consistent performance when tested with real milk samples, indicating its potential as a rapid and reliable field diagnostic tool. Furthermore, metabolomic profiling using advanced techniques such as Fourier transform infrared (FTIR) spectrometry, gas–liquid chromatography, nuclear magnetic resonance (NMR) spectroscopy, and gas chromatography–mass spectrometry (GC-MS) has improved the precision of ketosis diagnosis. Among these, serum βHB evaluation remains the gold standard, with concentrations exceeding 1.2 mmol/L serving as a threshold for identifying ketosis (Saradhi *et al.,* 2024).

Differential Diagnosis:

Ketosis in dairy cows must be carefully differentiated from several other conditions that present with similar clinical or neurological signs. Disorders such as lead poisoning, rabies, and listeriosis can resemble ketosis, particularly when neurological symptoms like excessive biting, licking, hyperesthesia, head pressing, and apparent blindness are observed (Bradford, 1990).

In addition, several metabolic and postpartum disorders occur during the same period and may mimic ketosis. These include hypomagnesemic tetany, downer cow syndrome, postpartum metritis, milk fever, grass tetany, and lameness.

Treatment of Bovine Ketosis

The treatment and management (Saradhi *et al.,* 2024)[5] principally depend on reducing the risk factors and immediate supply of dietary energy.

i) IV Dextrose (50% solution)

ii) Oral Propylene Glycol @690g per cow per day.
iii) Vitamin B_{12} Supplementation
iv) Corticosteroids like dexamethasone (less commonly used) (Kahn *et al.,* 2015).
v) Non-steroidal anti-inflammatory drugs (NSAIDs) (if there is inflammation).

Prevention and management:

Prevention of ketosis is more effective and economical than its treatment emphasising on proper nutrition, regular monitoring, stress minimization, and early diagnosis. The below mentioned preventive and managemental measures helps promote better productivity and overall health status of the cows.

i) Provide balanced diet with adequate energy and protein levels to milking cows as well as to the dry cows particularly during the transition period. Gradually adapting cows to higher energy intake before calving helps them cope better with the metabolic demands of early lactation (Grummer, 1995).
ii) Routine evaluation of body condition score (BCS). Cows with a BCS below 2.5 at calving are at greater risk of developing ketosis (Duffield *et al.,* 2009).
iii) Maintaining a low-stress environment with sufficient space, comfort, and gentle handling practices reduces the likelihood of metabolic disturbances (Murray *et al.,* 2006).
iv) Early detection through regular screening of blood or urine for ketone bodies allows for prompt intervention before the condition becomes severe (McArt *et al.,* 2012)[10].
v) Consistent veterinary supervision further supports herd health and helps refine feeding and management practices (Kahn *et al.,* 2015).

Conclusion

The dairy industry is one of the most profitable and rapidly growing sectors today, with high-yielding dairy cows serving as the cornerstone of successful farming operations. However, ketosis remains one of the most common and economically significant non-infectious diseases affecting these cows. This metabolic disorder can lead to substantial losses by reducing milk yield, increasing treatment costs, and in severe cases, causing the death of affected cows or their newborn calves. Therefore, it is essential for farmers to implement effective preventive measures, including proper nutritional management, adequate energy supplementation during early lactation, and regular monitoring of ketone levels to safeguard herd health and ensure sustained productivity and profitability in dairy farming.

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Tospo Viruses: Emerging Threats to Global Agriculture

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Introduction:

Tospo viruses are regarded as emerging plant viruses, not only due to their growing economic importance worldwide, but also because our understanding of their biological complexity has advanced only in recent decades. They belong to the family Bunyaviridae, which predominantly includes animal and insect infecting viruses. However, the plant infecting members of this family are unique and have been separated into a distinct genus named Tospo virus, after the type species Tomato spotted wilt virus (TSWV). These viruses are propagatively transmitted by thrips, meaning the virus replicates inside the vector, enabling efficient and persistent transmission. Diseases caused by TSWV were first identified in Australia around 1915, but significant expansion of the genus occurred only in the late 20th century as more viruses with similar biological properties were discovered. Today, at least twelve recognized species have been reported under the genus Tospo virus and several new isolates continue to be identified globally indicating the dynamic and evolving nature of this virus group. Tospo viruses exhibit a wide host range, infecting more than 1,000 plant species, including major vegetables, ornamentals and commercial crops. Infection typically results in systemic and localized symptoms depending on host susceptibility and developmental stage. Some characteristic symptoms include:

- **Tomato:** Bronzing of young leaves, upward curling, necrotic spots, plant wilting, and distinct concentric ring patterns on fruits.
- **Groundnut (peanut):** Chlorosis, mottling, necrosis of terminal buds, stunting, and yield reduction.
- **Muskmelon:** Leaf mottling, crinkling, yellow spotting and widespread systemic necrosis

These severe symptoms, coupled with the rapid multiplication of thrips vectors under favorable conditions, contribute to significant crop losses worldwide.

Furthermore, Tospo viruses possess a tripartite negative/ambisense RNA genome enclosed in membrane bound particles, an uncommon characteristic among plant viruses. Their genetic diversity and ability to adapt to multiple thrips species enhance their epidemiological success. Overall, the continuous emergence of new Tospo virus species, expanding geographical distribution, and increasing resistance breakdown in host cultivars highlight the urgent need for integrated management strategies, including vector control, resistant varieties, and strict quarantine measures.

Economic importance:

Tospo viruses are recognized as one of the top ten economically most destructive plant virus groups globally. Their impact on agriculture is enormous, with annual crop losses exceeding US $1 billion. Their economic significance is largely due to their extremely broad host range, infecting more than 800 plant species across over 80 botanical families, including vegetables, legumes, ornamentals, and oilseed crops. This wide host adaptability allows Tospo viruses to survive continuously in diverse cropping systems and weed reservoirs, making them major threats to global food security. Among the reported Tospo viruses, groundnut bud necrosis virus (GBNV) is one of the most devastating in South and South-east Asia. In India, GBNV alone can cause up to 80% reduction in groundnut yield, particularly under conditions favoring thrips population build up. Losses are further aggravated by the lack of highly resistant cultivars and difficulty in managing thrips vectors. It is also notified that even moderate levels of infection can severely impair productivity and profitability. Additionally, the timing of infection plays a crucial role in disease severity. Early infection by Tomato spotted wilt virus (TSWV) results in drastically higher yield loss than late infection, both under artificial sap inoculation and natural field conditions. Young plants, when infected during active growth phases, exhibit more severe systemic symptoms, stunted development, and significant reduction in final harvestable yield. Overall, the high damage potential, wide host range, increasing vector populations, and expanding geographical distribution collectively highlight Tospo viruses as one of the most serious viral concerns for modern agriculture. Effective management requires integrated strategies combining host resistance, vector control, cultural practices and surveillance to mitigate economic losses.

Status of tospo group:

For many years, Tomato spotted wilt virus (TSWV) was believed to be the only representative of a unique group of plant infecting viruses and was referred to as the "tomato spotted wilt virus group." However, advancements in molecular virology and serological techniques revealed that TSWV shares several biological and structural characteristics with members of the family Bunyaviridae, particularly with respect to its tripartite (L, M, S) negative/ambisense RNA genome, enveloped particles and propagative transmission by insect vectors. These findings led to a significant taxonomic revision and TSWV was established as the prototype species of a newly created genus within the Bunyaviridae, now known as genus Tospo virus. This taxon is unique because Tospo viruses are the only plant infecting viruses within the Bunyaviridae, whereas all other genera infect animals or insects. As research expanded globally, several distinct Tospo viruses were identified and characterized based on serology, genome sequencing, host range and vector specificity. Initially, they were classified broadly into three major groups:

- ❖ Tomato spotted wilt virus (TSWV)
- ❖ Impatiens necrotic spot virus (INSV)
- ❖ Watermelon silver mottle virus (WSMV)

Further refinement, driven by molecular characterization and phylogenetic studies, led to recognition of additional species within each group. Notable examples include:

- ❖ Groundnut ring spot virus (GRSV)
- ❖ Groundnut bud necrosis virus (GBNV)

Along with other emerging species such as Chrysanthemum stem necrosis virus (CSNV), Capsicum chlorosis virus (CaCV), etc. The continuous discovery of new Tospo virus species demonstrates their genetic diversity, rapid evolution, and ability to adapt to new hosts and vector species. Given their expanding distribution and severe economic impact, Tospo viruses remain one of the most important virus groups threatening global agriculture.

Taxonomical status:

Among plant viruses, Tospo viruses possess a distinctive virion morphology, genome architecture, and gene expression strategy, setting them apart from other plant infecting viruses. The virions are spherical, enveloped particles measuring approximately 80-110 nm in diameter, which is relatively large, compared to most plant viruses. Their envelope is derived from host cellular membranes and is embedded with two surface glycoproteins, Gn (≈78 kDa) and Gc (≈58 kDa). These glycoproteins form characteristic spike like projections on the virion surface, facilitating virus attachment and entry into both plant and thrips cells. Inside the viral envelope, the nucleocapsid consists of three pseudocircular ribonucleoprotein (RNP) complexes, each associated with the viral RNAs. These complexes are encapsidated by a nucleocapsid (N) protein of about 29 kDa, which plays a key role in RNA encapsidation, translation control, and replication. In addition, a small number of molecules of a large protein (L protein, ≈200 kDa) are present within the particle. This L protein functions as the RNA dependent RNA polymerase (RdRp), responsible for transcription and replication of the tripartite genome. This unique combination of enveloped morphology, ambisense RNA segments, and replication in both plants and thrips vectors makes Tospo viruses one of the most biologically complex groups of plant viruses studied to date.

Transmission:

Tospo viruses are exclusively transmitted by thrips, small insect pests belonging to the family Thripidae under the order Thysanoptera. Despite the presence of more than 5,000 thrips species worldwide, only a very limited number have been confirmed as propagative vectors of Tospo viruses. This propagative mode of transmission is highly significant, as the virus replicates inside the thrips and can be transmitted throughout the insect's life once acquired at the larval stage. The currently recognized vectors include:

- *Frankliniella occidentalis*- Western flower thrips
- *Frankliniella fusca*- Tobacco thrips
- *Frankliniella schultzei*- Common blossom or cotton bud thrips
- *Thrips tabaci*- Onion thrips
- *Thrips palmi*- Melon thrips
- *Scirtothrips dorsalis*- Chilli thrips
- *Thrips setosus*- A vector in East Asian cropping systems

Among these, *F. occidentalis* is considered the most efficient and globally significant vector, capable of transmitting at least four Tospo virus species. *F. schultzei* also transmits multiple viruses but notably fails to transmit Impatiens necrotic spot virus (INSV). The efficiency of transmission varies significantly among species. The restricted vector range, coupled with highly efficient transmission by specific thrips species, has major epidemiological implications. Thrips population dynamics, movement and host preference play a critical role in disease spread, outbreak severity and geographic expansion of Tospo viruses.

Symptoms:

The symptom expression of Tospo virus infection varies widely depending on the host plant species, the specific plant organ infected and the growth stage at which the infection occurs. Younger tissues generally exhibit more pronounced and systemic symptoms due to active cell division and virus movement. In general, plants infected with Tospo viruses may display a wide spectrum of localized and systemic symptoms, including:

- **Local lesions:** Necrotic or chlorotic spots at the initial infection site
- **Ring patterns:** Conspicuous ring spots, often forming concentric circular patterns on leaves or fruits
- **Green island effect**- Small areas of green tissue retained on otherwise chlorotic leaves
- Chlorotic and necrotic patches leading to tissue collapse
- Stem streaks or discoloration, sometimes accompanied by vein necrosis
- Systemic symptoms such as stunting, leaf bronzing, mottling, distortion, wilting and plant death

These symptoms collectively contribute to poor plant growth, reduced photosynthetic activity, and severe yield losses, especially when infection occurs at early developmental stages.

Host range:

The host range of Tospo viruses varies significantly depending on the virus species and the level of vector preference and distribution. Collectively, Tospo viruses possess one of the broadest host ranges among all known plant viruses, infecting more than 800 plant species belonging to over 80 botanical families, including both monocotyledonous and dicotyledonous plants. Economically important hosts span a wide spectrum of crops such as vegetables, oilseeds, pulses, ornamentals, fiber crops and fruit bearing plants. Among these, members of the solanaceae and asteraceae families comprise the largest number of susceptible species, making them highly vulnerable to Tospo virus outbreaks. Additionally, numerous weed species also act as important reservoir hosts, enabling virus survival between cropping seasons and facilitating epidemic development through thrips vectors. The extensive host adaptability of Tospo viruses not only intensifies disease spread but also complicates their management, emphasizing the need for integrated host vector control strategies in affected cropping systems.

Management:

Agronomic practices:

It is reported that closer plant spacing, resulted in a lower incidence of Peanut bud necrosis disease (PBND) compared to wider spacing. Reduced spacing partly suppresses thrips movement within the crop canopy by increasing shade, lowering temperature fluctuations and reducing the exposure of young plant tissues, which in turn limits vector feeding and virus spread. Similarly, sowing time has a significant influence on disease occurrence. It is also reported that early sown groundnut crops experienced a much higher PBND incidence than those sown later. Early season crops coincide with peak populations of *Thrips palmi* and other vector species, enhancing chances of early infection, which ultimately causes greater systemic damage and yield loss. Scientific reports emphasize the importance of cultural practices such as optimized sowing time and plant spacing in minimizing the spread and impact of PBND under field conditions.

Resistant varieties:

Host plant resistance remains one of the most effective and economical strategies to manage Peanut bud necrosis disease (PBND) and other Tospovirus infections. It was identified by scientific research that CSMG-12 and CSMG-15 as promising groundnut varieties, each showing only about 10% PBND incidence coupled with higher pod yield under field conditions. Such genotypes offer a valuable option for farmers in endemic regions. Further screening studies revealed that several groundnut genotypes, including ICGV-91187, TCGV-90267, ICG-90308, LGN-1, AK-107 and ICGS-11, displayed high levels of resistance with disease incidence ranging from 0-5%, making them excellent source for resistant varietal development and large scale cultivation in PBND prone areas. Similarly, host resistance has also been explored in other susceptible crops. During screening of tomato varieties for resistance against Tomato spotted wilt virus (TSWV), it was reported that HYT-1 showed the lowest TSWV infection along with significantly higher yield performance, indicating its potential as a resistant variety for commercial cultivation. Overall, these researches underscore the importance of resistant cultivar deployment as a cornerstone for Tospo virus disease management, especially in regions where vector control alone is insufficient due to persistent thrips activity.

Chemical control:

Integrated cultural and chemical management strategies can significantly reduce TSWV infection in tomato. Scientific studies showed that UV reflective mulch, when combined with Acibenzolar-S-Methyl (a systemic acquired resistance inducer) and methamidophos, remarkably lowered TSWV disease incidence in tomato compared to untreated plants grown on conventional black mulch. The reflective mulch works by repelling thrips vectors through light reflectance, thereby reducing feeding and virus transmission, while the chemical treatments further contribute to suppression of vector populations and enhancement of plant defenses. Integrated pest and disease management (IPDM) combining vector deterrent mulches with resistance inducing chemicals to achieve more effective and sustainable control of TSWV in tomato cultivation.

Conclusion:

Tospo viruses represent one of the most damaging and rapidly emerging groups of plant viruses worldwide. Their unique biological features including a tripartite negative/ambisense RNA genome, enveloped virions, and propagative transmission by a limited number of thrips vectors contribute to their exceptional epidemiological success. With an extremely wide host range exceeding hundreds of crop and ornamental species, these viruses continue to expand geographically and cause severe economic losses, particularly in systems where vector populations flourish. Continuous evolution, genetic diversification and frequent breakdown of host resistance further intensify the threat. Therefore, successful management of Tospo viruses must rely on an integrated approach that combines vector population suppression, optimized cultural practices, deployment of resistant cultivars and strict quarantine and surveillance. Strengthening research on virus host vector interactions and development of durable resistance is crucial to mitigate the growing impact of this destructive virus group on global agriculture.

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The Smart Crops: Powerhouse of Nutrition

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Introduction

A small course of grains belonging to the group of forage grass called as minor millets which belong to the family Poaceae. Minor millets comprise of proso millet or panivaragu (Panicum miliaceum), foxtail millet or thenai (Setariaitalica), little millet or samai (Panicum sumatrense), barnyard millet or sanwa millet (Echino chloacolona) and kodo millet or varagu (Paspalum scrobiculatum). Minor millets can grown well in adverse soil and climatic condition, shorter crop duration, suitable for contingency plan. Compare to major cereals, it is more nutritious. Finger millet is highly tolerant to alkalinity, even more than pH 11. Foxtail millet, proso millet and little millet is suitable for both drought and water logging condition. Kodo millet and proso millet is highly drought resistant.

Importance of small millets Newly acquired life-styles has now given us diabetes, hypertension and cardiovascular disease running rampant. For the above diseases millets have returned as a viable option to live healthy life without consuming loads of anti-diabetic and anti-hypertension medicines that are not only very expansive but also have serious side effects in the long run. Minor millets also act as a prebiotic feeding micro-flora in our inner ecosystem. Minor millets will hydrate human colon to keep us from being constipated. The high levels of tryptophan in minor millet produce serotonin, which is calming to our moods. Magnesium in minor millet can help reduce the effects of migraines and heart attacks. Niacin (vitamin B3) in millet can help lower cholesterol. Minor millet consumption decreases Triglycerides and C-reactive protein, thereby preventing cardiovascular disease. All millet varieties show high antioxidant activity. Millet is gluten free and non allergenic. Millets contribute towards balanced diet, and can hence ensure nutritional security more easily through regular consumption along with keeping the environment safe as they are low input crops mostly adapted to marginal lands. Declining small millets cultivation has resulted in reduced availability of these nutritious grains to needy population and also the traditional consumers have gradually switched over to more easily available fine cereals due to Government policies. This is a disturbing trend and needs urgent focus by the agricultural experts and policy makers. Immediate policy and market support, value addition and promotional activity are necessary for arresting the further decline not only in cultivation but also consumption. Improving productivity and enhancing demand should be the twin approaches Finger millet – Eleusine coracana (2n=36)•Finger milltet/African millet/Keppai/Mutthair/Thamid a/Nacheni/Crow footed millet. The genus Elusine consists of eleven species Finger millet is an important staple food in parts of East and Central Africa and India particularly in Karnataka. • It is a gluten free variant of Millet, rich in proteins and amino acids. In growing children, finger millet is intended to facilitate brain growth. It is also high in calcium and has healthy concentrations of iron and other minerals as well. Foxtail millet – Setariaitalica (2n =18) • Dwarf Setaria/Foxtail bristle grass/Giant Setaria/Green foxtail/Italian millet/German millet/Hungaraian millet • Second most widely planted species of millet and the most important in East Asia. Place of origin is China. It can tolerate water logging • It is rich in carbohydrates that help in balancing blood sugar levels in the body. These millets have a high Iron content. Foxtail Millet can improve overall immunity. Proso millet – Panicum miliaceum (2n=36) • Boom corn millet/ Common millet/Broom tail millet/Hog millet/Kashfi millet/ Red millet/ White millet Barnyard millet – Echinochloa frumentacea (2n=54) • Kuthiravaali/Udalu and Kodisama (telgu), Shamul (marathi), Sama (gujarati), Shamula (bengali) and Swank (punjabi) • In India, barnyard millet is developed in the Himalayan area from the north to the Deccan region in the south. • It is ideal foods for the patient suffer from diabetes mellitus. • Barnyard millet is recommended to patient who suffers from Cardiovascular diseases and diabetes. They are also most effective to reduce the blood glucose level and lipid level.

Little millet or samai – Panicum sumatrense (2n=36) • It is native to India and is called as Indian millet. The species name is based on a specimen collected from Sumatra (Indonesia). • It is mainly cultivated I Caucasus, China, east Asia, India and Malaysia. It is adapted to both temperate and tropical climates. It can withstand both drought and water logging. • It is loaded with vitamin B and essential minerals such as Calcium, Iron, Zinc, and Potassium. Little Millet is largely used in Southern states of India in numerous traditional dishes. It is a healthier alternative to rice and does not cause weight gain. Kodo millet or varagu – Paspalum scorbiculatum (2n=40) • It is an annual grain that is grown primarily in Nepal and also in India, Philippines, Indonesia, Vietnam, Thailand and in West Africa from where it originated. • It has large potential to provide nourishing food to subsistence farmers in Africa and elsewhere. • Kodo is a fantastic source of B vitamins, especially niacin, B6, and folic acid, among other vitamins and minerals. It contains calcium, iron, potassium, magnesium, and zinc minerals. Being gluten-free millet, it is great for gluten-intolerant individuals. It can relieve cardiovascular disorders such as high blood pressure and cholesterol levels when eaten regularly by postmenopausal women.

Promotion of small millets for better nutrition Cultivation and consumption of small millets can be promoted by

(1) supporting production and improving productivity (through research and developments to enhance yield and nutritional qualities, cultivation as pure crops as well as intercrop with other main crops, cultivation as fail-safe crops – late sowing when monsoon fails, particularly early-maturing cultivars that yield considerably even under constrained environments);

(2) providing on-farm support and linking farmers to value chains;

(3) undertaking campaigns to build consumer awareness;

(4) ensuring products in demand are available and accessible;

(5) supporting processors, food service, health/medical and industrial sectors to incorporate millets (for example, development of modern ready to-eat and ready-to-cook products, post-harvest processing technology development, nutrition investigation, methods for extending shelf life, etc.); and

(6) policy support (including small millets and value-added products in the public distribution systems, minimum support price and mid-day meal/school feeding schemes, etc.).

Future challenges and prospects

Small millets have the potential to serve as an alternate/ supplement to major cereal staples because of their ability to be used/cooked in similar ways, diverse adaptation to adverse conditions and nutritional qualities. Small millets can fit very well into multiple cropping systems both under irrigated and rainfed conditions. Their storability under normal storage conditions has made them 'famine reserves'. They can provide nutritious grains as well as valuable fodder in a short span of time. Therefore, there is an urgent need for Indian policy makers to refocus their attention towards millet farming systems and enact policies that create an enabling environment for millet farmers.

What are the Health Benefits of Millets?

Millets are anti acidic and gluten free, it helps to prevent type 2 diabetes. Its effective in reducing blood pressure. Reduces risk of gastrointestinal conditions like gastric ulcers or colon cancer. Eliminate problems like constipation, excess gas, bloating and cramping. Millet act as a probiotic feeding micro flora in our inner ecosystem.5 fact important related to millet.

Powerhouse of nutrition: Millet's rich in minerals and plant-built nutrients type phyto-nutrients. Essential phytonutrient as lignans present in millets which helps lessen the peril of heart diseases. Pearl millets are rich in insoluble fibre and aid in better digestion, and are also known for their anti-cancer properties. Foxtail millets are not just rich in magnesium that assists to regulate blood pressure levels, they are also high in iron and calcium that help boost immunity levels. Sorghum, on the other hand, is a gluten-free variant of millets that is beneficial for those suffering from celiac disease. Overall, millets are tiny power-packed nutrient foods and are a must for a healthy lifestyle.

Defences as of Diseases

By swelling cases of obesity, diabetes and early heart strokes, there is a sudden rise in health consciousness among people. There is a need to make healthy diet choices, and for those who are aware, millets are making quite an impact Millets are gaining ground as healthy options for those suffering from lifestyle diseases, be it diabetes, cardiovascular diseases, intestinal disorders or allergies towards gluten.

Resilience towards climate change

Millets are also resistant to the cold, drought and salinity and thus, are suitable for cultivation on dry and arid land. The prevalence of stress conditions and their consequences are circumvented by several traits such as short stature, small leaf area, thickened cell walls, and the capability to form dense root system Also, the C4 photosynthetic trait is highly advantageous to millets. In the C4 system, carbon dioxide (CO_2) is concentrated around ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO), which in turn suppresses ribulose 1,5-bisphosphate (RuBP) oxygenous (RuBisCO), which in turn suppresses ribulose 1,5-bisphosphate (RuBP) oxygenation and photorespiration.

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Extrusion Technology in Aquafeed Industry

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INTRODUCTION

Despite significant progress made in these recent decades, the world is falling short of its goal of eliminating all forms of hunger and malnutrition. Degraded ecosystems, an intensifying climate crisis, and increased biodiversity loss pose global threats to jobs, economies, the environment, and food security, all of which are exacerbated by the COVID-19 pandemic, crises, and other humanitarian emergencies. It is a well-known fact that protein from animal foods is deficient in the average human diet. This deficiency is responsible for a great deal of illness and death in almost every country around the world, but especially in Africa (Ogello *et al.,* 2014). Protein deficiency causes poor growth, muscular weakness, and an increased susceptibility to many diseases even in the absence of illness (Das *et al.,* 1996). Feed, as one of the major inputs in aquaculture production, is facing fundamental development challenges, resulting in poor aquaculture growth. Fish feed development and management are critical to aquaculture growth and expansion, as well as a major factor in determining the profitability of an aquaculture venture. The development of aquaculture industries with innovative technologies cage culture, pen culture, recirculatory aquaculture etc have been increased the production of fishes and shell fishes in many folds. Increase in production trend pose pressure on commercial feed industries to develop feeds not only with improved nutritional benefits but also in a reasonable price. In 2017 the aquafeed market in India was valued at USD 1.20 billion (Ambasankar *et al.,* 2017). Among the state,s Andhra Pradesh is the leading one in aquafeed consumption, consuming 22% followed by West Bengal consuming 10% of total feed consumption of the country.

Aquafeed industry

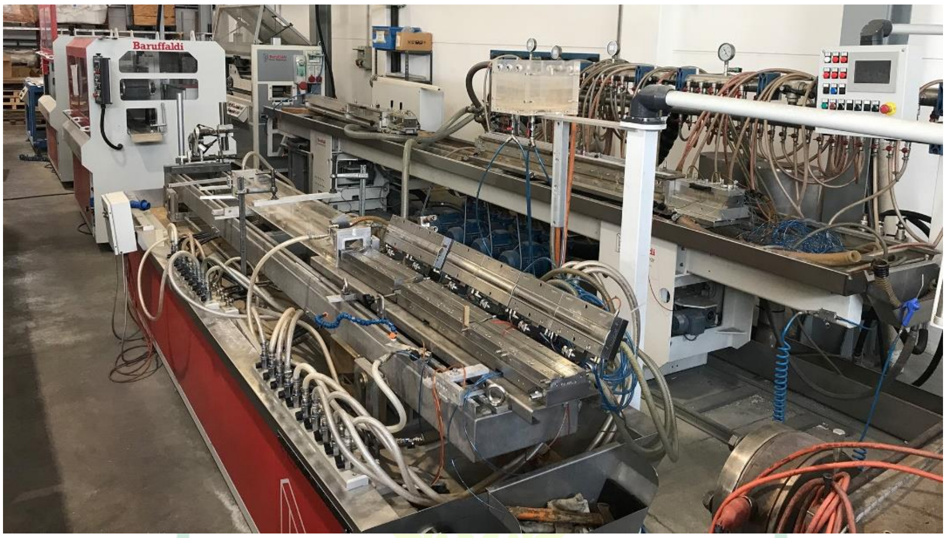
A variety of feed stuffs are utilized for aquafeed preparation depending upon their availabilities such as fish meal, crustacean meal, SBOC, mustard oil cake, GNOC, fish oil, maida, rice bran, wheat flour etc. Researcher try to evolve new technologies that can satisfy the need of different fish species according to their feeding habit. Invention of extrusion process has been created a new chapter in aquafeed industries. Different types of feeds are developed to meet the need of fishes such as – pigmented feed (to improve colouration in fish), floating feed (for surface feed fish), micro-encapsulated feed (to prevent nutrient leaching), micro-bound feed (to increase water stability), powered feed (according to the mouth size of fish) etc.

Why the need of extruder

Affordability of high-quality feeds limits smallholder participation and threatens aquaculture profitability and sustainability (Munguti *et al*., 2014). Aquafeeds that are ready-to-use or manufactured are not widely available (Ngugi *et al.,* 2007). Some small-scale farmers create low-cost feeds on their farms using locally available ingredients. The feeds are insufficient to meet the needs of expanding semi-intensive aquaculture systems; they have poor functional quality, particularly in terms of physicochemical properties (Munguti *et al.,* 2014; Ogello *et al*., 2014). As a result, the pursuit of alternative processing methods with optimised operating conditions for the production of high-quality feeds has become critical (Cocker, 2014). Smallholder farmers should ideally combine locally sourced ingredients into a mash, which they then moisten and press with simple mechanical tools to produce pellets. While this method meets some short-term needs, it is incapable of producing consistently high-quality feeds in commercial quantities. Extrusion cooking is a more versatile processing technique (Kazamzadeh, 1989). To fill the demand for high-quality fish feed, small-scale feed manufacturers are increasingly turning to low-cost extruders.

Extrusion technology

Extruders are essentially screw pumps; the screw(s) rotate within a tightly fitting stationary barrel. A feeding mechanism is used to introduce semi-moist feed or dry powder/grit into the extruder at a constant rate of mass or volume. As a result of the rotation of the flighted screw, the material advances (s). Heat is typically supplied externally to the extruder barrel and is produced in part by viscous mechanical energy dissipation. Temperature control is required at various sections of the extruder and at the die end. Inside the extruder, the material goes through several unit operations such as mixing, compression, shearing, and cooking before being shaped in the die and forced to exit under pressure.



Extrusion machinery

Procedure of extruded fish feed

The combined mash is pushed through a heated closed barrel by screw(s) and pressed through a die at the barrel's end (Levic & Sredanovic, 2010). Carbohydrate, protein, fibre, and fat components of the mash are heated, mixed, and sheared under high pressure, resulting in cooked molten dough that is shaped into pellets as it exits the die. As a result of the thermal and shear modification of the mash ingredients, the nutritional and functional properties of the pellets are improved. Extrusion has also been shown to destroy anti-nutritional factors such as trypsin inhibitors and lectins (Moscicki, 2011; Nikmaram *et al*., 2015), increase the solubility of nitrogen and dietary fibre, and reduce lipid oxidation by denaturing deteriorative enzymes (Alam, *et al*., 2015).

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The Stay-Green Trait: How Crops Keep Their Leaves Alive to Produce More

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Introduction

Across many agricultural regions, farmers often watch their crops turn yellow before the grains fully mature. This premature drying limit the plant's ability to fill grains, ultimately reducing yield. Yet some plants stay green, fresh, and physiologically active for much longer. Their leaves continue functioning, their stems remain healthy, and their grain-filling lasts longer. This remarkable capacity is known as the stay-green trait, and it is emerging as one of the most important physiological adaptations for modern, climate-resilient agriculture.

Stay-Green Trait

At its core, the stay-green trait refers to a plant's ability to remain green, healthy, and photosynthetically active even after flowering (anthesis), a stage when many crops begin to lose vigor. Some plants display cosmetic stay-green, where leaves retain their green color but no longer contribute meaningfully to growth or grain filling. In contrast, functional stay-green is far more valuable, as leaves continue to carry out active photosynthesis, producing sugars and energy that support grain development. This prolonged activity is especially important in drylands, heat-prone regions, and nutrient-poor soils, where early senescence limits grain filling and sharply reduces crop productivity.

Why Stay-Green Is Vital in Today's Agriculture

Climate change has intensified conditions like heatwaves, drought, nutrient stress, and erratic rainfall. Under such conditions, many crops quickly enter senescence, shutting down their metabolism earlier than they should. Stay-green varieties, however, retain productivity for longer. They support extended grain filling, preserve biomass quality, maintain stronger stems, and generally show far better resilience in stress environments. As a result, the stay-green trait has become one of the key targets in breeding programs aimed at climate-smart farming.

Slower Chlorophyll Breakdown

It is the foundation of staying green. One of the key reasons stay-green crops remain productive is their ability to slow the breakdown of chlorophyll, the pigment essential for capturing sunlight. Normally, stress accelerates chlorophyll degradation through enzymes like chlorophyllase and PAO. But stay-green plants suppress or delay these enzymes, allowing their chloroplasts to remain intact. As a result, photosynthesis continues long after other plants have stopped producing energy. This extended activity provides more assimilates for grain filling, improving yield and grain quality.

Sustained Photosynthesis

In stay-green crops, the photosynthetic machinery remains functional for a longer period. The leaves maintain active chloroplasts, stable thylakoid structures, and robust activity of photosynthetic enzymes such as Rubisco. Even under water stress or high temperatures, these plants continue to fix carbon efficiently. A longer photosynthesis period naturally leads to more biomass accumulation and better grain filling, which is why stay-green traits often correlate with higher yield stability.

Better Water Management and Delayed Stress Signals

Water availability is a major trigger for early senescence. Stay-green crops often possess deeper or more efficient root systems, enabling them to access deeper soil moisture. Their leaves maintain higher relative water content and avoid rapid declines in leaf water potential. Because these plants delay the buildup of drought-induced hormones such as ABA, they postpone the internal signals that tell the plant to begin aging. This helps them remain physiologically young and functional even during dry spells.

Hormonal Balance

Plant hormones play a powerful role in regulating aging and senescence. Stay-green plants often maintain a higher level of cytokinins, which promote cell longevity and delay leaf yellowing. Meanwhile, they suppress or regulate hormones like ethylene and ABA that accelerate senescence during stress. By mastering this internal hormonal balance, stay-green plants keep their tissues active and productive long after non-stay-green varieties have shut down.

Nitrogen Retention and Nutrient Use Efficiency

Nitrogen is a core component of chlorophyll and many proteins involved in photosynthesis. Crops with strong stay-green traits often show better nitrogen uptake or more efficient nitrogen remobilization. Their leaves do not lose nitrogen early, enabling chlorophyll and essential enzymes to remain active for a longer time. This nitrogen use efficiency aspect is especially important in cereal crops like sorghum and maize grown in low-input systems.

Protection Against Oxidative Stress

Stress conditions such as drought and heat lead to the formation of reactive oxygen species (ROS), which damage cell structures and accelerate aging. Stay-green varieties possess stronger antioxidant systems, including high activity of enzymes like superoxide dismutase, catalase, and peroxidase. These defenses slow down cellular damage and preserve leaf integrity, enabling plants to stay green longer and maintain metabolic function under stress conditions.

Where Stay-Green Makes the Biggest Impact

The stay-green trait is widely recognized in sorghum, where several major QTLs (Stg1–Stg4) have been identified and incorporated into drought-tolerant cultivars. In maize, stay-green hybrids are known for better stalk strength, improved grain filling, and superior stress tolerance. Pearl millet benefits from stay-green through improved grain yield and fodder quality. In wheat, delayed senescence helps maintain grain weight and protein content. Even in rice and pulses such as pigeon pea and chickpea, stay-green behavior contributes to yield stability under terminal drought.

Sorghum: The crop most famously associated with functional stay-green. Vital for dryland farming in India and Africa.

Maize: Stay-green hybrids show stronger stalks, higher grain filling, and better drought resilience.

Pearl Millet: Stay-green lines maintain green fodder quality and grain yield under heat and moisture stress.

Wheat: In wheat, delayed senescence improves grain protein and kernel weight.

Rice: Some improved lines exhibit slow senescence linked with nitrogen efficiency and heat tolerance.

Pulses: Pigeon pea and chickpea varieties with stay-green show better pod filling during terminal drought.

Genetic Basis and Its Physiological Meaning

The stay-green trait is controlled by complex genetic networks involving chlorophyll metabolism, nitrogen remobilization, water-use efficiency, hormonal regulation, and antioxidant activity. Breeding programs worldwide now use stay-green as a marker trait for drought tolerance and grain-filling efficiency. The genetic foundation aligns closely with the physiological mechanisms, making it a powerful selection tool for developing climate-resilient cultivars.

Conclusion: The Future Belongs to Stay-Green Crops

In a world where crops frequently experience stress before they complete grain development, the stay-green trait offers a major advantage. It allows plants to stay physiologically active when it matters most, supporting stronger yield, better grain quality, and higher resilience. The plants that stay green longer truly are the ones that keep feeding us, even under scarce rainfall or high temperature conditions. As agriculture evolves to meet climate challenges, stay-green trait will remain as the key component of the sustainable crop improvement.

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Applications of Artificial Intelligence Technology for Efficient Farm Management in North-Eastern India: Its Status, Scope, and Limitations

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Abstract:

Globally, farming is gradually changing due to new digital instruments that make it possible to monitor crops more carefully, anticipate issues before they arise, and perform regular chores more accurately. These technologies are especially promising in India's northeastern states, which have small farms, difficult terrain, and restricted access to machinery. Drones, weather-based warnings, remote-sensing surveys, and automated irrigation units are examples of early initiatives that demonstrate how these technologies might alleviate persistent problems. These initiatives are primarily funded by ICAR institutions, state agricultural universities, and proactive farmer groups. They are being used by farmers to monitor cattle, detect nutrient stress, detect diseases early, and enhance aquaculture techniques. Additional help is being provided by policies under the Agri-Stack and Digital Agriculture Mission. However, limited digital knowledge, poor connectivity, expensive technology, and the lack of local data required for trustworthy model building continue to limit wider application. In order to ensure that these tools actually improve food security and climate resilience in North-East (NE) India, this article examines the current progress, future opportunities, and enduring gaps. It emphasizes the critical need for region-specific datasets, straightforward user interfaces, focused financial support, and skill-building.

Key words: Remote Sensing, Digital Farm Management, Artificial Intelligence, Precision Agriculture

1. Introduction

The artificial intelligence (AI) tools that once remained in experimental stages are now slowly adopted in farm worldwide, helping farmers plan and manage their fields with better knowledge. In India, where most rural families rely on agriculture, these tools provide support against familiar difficulties such as inconsistent weather, declining resources, labour shortages and rising production risks. These challenges further worse in the North-Eastern (NE) India, where steep terrain, small cluster of land holdings, spatially varied microclimates and aged old traditional practices shape everyday farming. With limited technical know-how and guidance, fragile soils, unpredictable rainfall, and frequent pest problems keep productivity low and increase climate vulnerability. In this context, an information and decision-support systems can help farmers use available resources more efficiently (Chen & Hengjinda, 2019).

The rich biodiversity of NE region with diverse crops varieties such as large cardamom, rice, fruits, spices, and vegetables adds value but makes farm planning and implementation more intricate. The differences in elevation, soils and regional weather pattern mean that farm advisories often fail to apprehend local requirements. While extension services remain important, they face difficulty in such variation. New farming approaches based on remote sensing and automated advisories offer ways to interpret these differences more precisely (Adewusi et al. 2024; Gupta et al. 2021).

The advancement in drone imaging and satellite-based monitoring systems now offers early detection of disease, moisture & nutrient stress, and weed growth, which is effective in hilly areas where frequent field visits are difficult. Various agri-institutions such as ICAR-NEH, CAU Imphal, Assam Agricultural University and state agriculture departments have initiated testing these methods, marking a gradual move from manual to more systematic, technology-supported crop management systems (Arora et al. 2025). North-East is very vulnerable to floods, cloudbursts, landslides, and dry spells that vary greatly in space, making information and communication technologies (ICT) tools equally crucial for climate-smart farming. Farmers are unsure of when to take action because standard estimation techniques frequently overestimate or underestimate these. This gap is filled in part by the enhanced weather advisories that combine real-time updates with long-term history. IMD and ATMA's previous initiatives demonstrate how prompt advice on crop protection, irrigation, and sowing can provide farmers more assurance when the weather changes (Saxena et al. 2020).

Water management in farm is another area where technology is making a difference. Automated irrigation systems using soil-moisture sensors and weather-linked controls help regulate water use, a major concern in states like Nagaland, Meghalaya and Manipur. Likewise, predictive models based on temperature, humidity and pest behaviour can warn of outbreaks of various diseases such as rice blast, fall armyworm, citrus canker and other threats common to the region. Image-based health checks, early warning systems, and predictive tools for feed and water planning techniques that have proven successful globally and have great potential in locations like Mizoram and Nagaland are also beneficial to livestock and fisheries, which are the foundation of many rural livelihoods. Despite these advantages, adoption is still sluggish. There are few region-specific datasets on crops, soils, pests, and climate; digital literacy is low; connectivity is still erratic in many hill districts; and the price of sophisticated tools is still relatively high for small and marginal farmers. Additionally, cultural preferences for traditional methods may impede the transition to digital farming, and the terrain makes it challenging to deploy some tools (Mohamed et al. 2021; Eli-Chukwu, 2019).

Nevertheless, the area is entering a new stage of technological advancement. State governments are supporting digital solutions through programs like the Digital Agriculture Mission, Soil Health Digitization, and Agri-Stack; smartphone use is increasing; and young people are becoming interested in agribusiness. Data-enabled agriculture may significantly contribute to enhancing food security, boosting climate resilience, and modernizing farming throughout Northeastern India with improved connection, focused training, and the creation of localized datasets.

2. Current Status of AI Adoption in North-Eastern India

In the Northeast, the use of digital technologies is still in its infancy and is primarily limited to pilot programs run by ICAR institutions, state agricultural universities, and a few farmer groups eager to try out novel strategies. Small-scale digital platforms, localized weather advisories based on analytical models, and drone-based crop surveys are progressively emerging throughout the region. Although these initiatives are producing valuable field data and showcasing the usefulness of contemporary techniques, their reach is still much too narrow to have a significant impact on the region's diverse landscapes (Kumar et al. 2020).

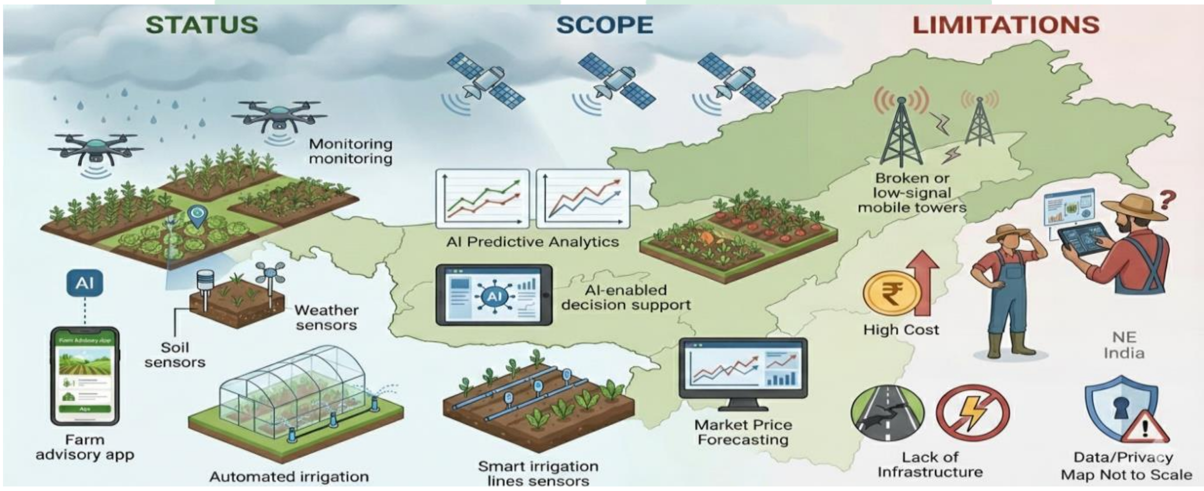

Fig. 1 AI technology in farm management (Generated with Google Gemini)

3. Major Applications of AI in Efficient Farm Management

Newer digital tools are beginning to take over tasks that previously required repeated field visits. Remote-sensing images and simple diagnostic apps help farmers spot nutrient stress, early signs of pests or diseases, water shortage and weed growth much earlier than they normally would. Forecast-based advisories also give farmers a better sense of when to irrigate, how to prepare for sudden weather changes and when pest outbreaks are likely (Fig. 1). In a region known for sharp climatic variations and fragile ecosystems, these early signals can guide timely decisions and reduce losses during sensitive stages of crop growth (Chouhan et al. 2024).

4. Scope for AI in North-Eastern India

The NE India has an enormous scope for intensifying AI supported farming. The region's diverse cropping, age old organic farming traditions and increasing digital exposure among young people offer a strong base. The ongoing programmes on digital agriculture, soil mapping and transparent market platforms add further support. These developments create opportunities for locally tailored advisory services that can raise productivity, strengthen ecological practices and encourage value-chain development and rural employment (Saxena et al. 2020).

5. Limitations and Challenges

Despite of these potentials, several constraints remain. Many rural and high-altitude areas still struggle with frail connectivity, and the lack of local datasets affects the reliability of digital recommendations. Drones, sensors and automated units remain costly for most smallholders, and the terrain itself often makes installation difficult. The limited digital skills and the continued dependence on traditional methods also slow down the adoption, preventing wider use of monitoring tools and simple decision-support systems.

6. Conclusion

The AI based tools can help farmers in the NE steer unpredictable weather, uneven terrain and a wide range of crops. An early effort with drones, pest alerts and controlled irrigation show that these technologies can support quicker and more assured decisions. Young farmers are increasingly open to such tools, and government support for digital agriculture is pushing adoption way forward.

Even so, broader use is still held back by poor connectivity, limited local data, high equipment costs and low digital literacy. Improving internet access, investing in region-specific datasets and offering practical training will be essential. With sustained support, AI can work alongside traditional knowledge and help build a more resilient and productive farming system in the NE India.

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From Subsidy-Driven Farming to Enterprise-Driven Agriculture: A Cultural Shift in Rural India

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Abstract

Agriculture is undergoing a paradigm shift from a subsidy-centric production system to an enterprise-oriented market ecosystem India. The transformation is driven by structured reforms, disruptive innovations, digitalization, agri-preneurship and fostering of Farmer Producer Organizations (FPOs). This article analyses the socio and economic changes that define this change over, emphasizing how FPOs are reshaping farmer participation and also accelerating the revolution of agriculture into a competitive enterprise through new amendments.

Key Words: Rural, FPO, Subsidy, Agri-preneurship, Innovation

1. Introduction: The End of a Dependency Era

For decades, agricultural development in India was realized mostly by input subsidies, Minimum Support Price (MSP) procurement, power support, interest subvention, crop insurance and various input incentives. Though these interventions stabilized production sector, they unintentionally reinforced farmer mindset to subsidy reliant, reducing sovereignty and delimiting innovation.

In mid 2010s, agri-sector pace was mainly driven by market integration, technology adoption, agri-startups and incubators, digital extension platforms, cluster-based production, professionalized community institutions

This represents not only an economic restructuring but also a socio-cultural transformation in rural India.

2. Defining Enterprise-Driven Agriculture

Enterprise-driven agriculture is characterized by:

2.1 Market-Linked Production

Farmers choose crops based on consumer preferences laterally demand analysis, price trends, export signals and processing needs of those crops.

2.2 Collective Action for Scaling Economies

Agglomeration of inputs, services and marketing reduces costs and improves bargaining power.

2.3 Post Harvest Value Addition and Processing

Farmers to capture higher value, move beyond initial production to further grading, sorting, packaging and processing management.

2.4 Knowledge on Financial and Business Management

Mainstream documentation, record-keeping, Management Information Systems (MIS), Capex, Opex, and financial utilization.

2.5 Technology Integration and Adoption

Utilization of digital advisories, automation with IoT sensors, drone technology, GPS, GIS, autonomous crop monitoring, digital payments and e-commerce. This aligns agriculture with modern enterprise orientation.

3. Catalyst role of FPOs

Farmer Producer Organizations (FPOs) are the institutional drivers that bridge the gap between traditional farming and agri-preneur models.

Their multifaceted functions include:

3.1 Boosting Market Power

FPOs enable farmers to secure better prices and stable markets through produce aggregation, quality standardization and collective sales.

3.2 Reduced Cost of Cultivation

Bulk procurement of chemical and biological inputs, machinery services reduce production costs by 10-20%.

3.3 Introducing Corporate Management

FPOs adopt corporate management practices at the grassroots levels with elected board members, skilled CEOs, accountants and market coordinators.

3.4 Financial Accessibility

Banking and Non-Banking financial companies prefer lending to organized farmer collectives, improving access to Capex, Opex and post-harvest credits.

3.5 Developing Local Community Value Chains

FPO-owned micro and small-scale processing units create rural employment, localized value retention and different opportunities for local community-enterprises.

3.6 Socio-Cultural Behavioural Transformation

FPOs cultivate a shift from:

- "beneficiary mindset" → "entrepreneurial mindset"
- "individual action" → "collective action"
- "distress sale" → "market negotiation"
- "production focus" → "market orientation"

This is decisive for the long-term sustainability.

4. Dimensions of Cultural and Behavioural Transition

The output metrics alone cannot make the transition understood; it must be analysed through the lenses of behavioural science:

Section	Transformation Title	Description of Change
4.1	Identity	Farmers begin identifying themselves as active business owners, shareholders, producers, marketers and entrepreneurs, shifting their perception as passive producers.
4.2	Risk Perception	Organized structures encourage farmers to adopt moderate-risk and reduce individual exposure to disruptive innovations.
4.3	Learning and Knowledge	knowledge shared and peer learning through FPOs enhances the adoption of best practices and digital tools, facilitating faster and more effective transition
4.4	Subsidy Dependence	Uncertain subsidy disbursement from the government causes farmers to prefer the reliable services provided by FPOs, indicating a move towards market-based solutions.

5. Formalized Drivers of Agri-enterprises

5.1 Government Initiatives

- Central Sector Scheme on Formation & Promotion of 10,000 FPOs
- PM Formalisation of Micro-Food Processing Enterprises (PM-FME)
- Digital agriculture mission
- Agricultural Infrastructure Fund (AIF)

Those enables the ecosystem creation for rural enterprises.

5.2 Incubation Ecosystem

Agri-innovation and business incubators (R-ABIs, ACICs, State Universities, DST-supported incubators) are nurturing rural startups, agri-tech innovations, FPO product branding, micro-food processing, supply chain and community centered enterprises.

5.3 Corporates and NGOs

Corporates, NGOs and other market players are integrating with FPOs for contract farming, traceability, input partnerships and buy-back agreements.

6. Shifting Value Chains

Enterprise-driven agriculture pushes farmers to move upward in the value chain rather being a sole bottom level producer.

6.1 From Raw Produce to Market-Specific Outputs

Standardized grading, packaging and branding align produce with consumer and industry market requirements.

6.2 From Local Mandis to Diverse Markets

FPOs diversify market channels via institutional buyers, processors, exporters, online platforms (ONDC, e-NAM) and modern retail chains.

6.3 Block Chain Traceability

With advent of block chain technology, digital receipts, QR codes and transaction records, transparency improves and credibility increases across the supply and value chains.

7. The Way Forward

To reinforce enterprise-driven agriculture, the following strategic actions are essential:

- **Focus on Business and Governance:** Strengthen FPO capacity through training in leadership, financial discipline and mandatory market-driven production and business planning.
- **Scale and Synergy:** Achieve economies of scale by integrating FPOs with SHGs/Cooperatives and developing cluster-level agri-processing infrastructure for high-value market participation.
- **Future-Proofing:** Actively engage rural youth as FPO associates, agri-preneurs and value chain coordinators to ensure long-term sustainability and digital integration.

8. Conclusion: The Rise of Agriculture as Enterprise Culture

Indian agriculture is gradually moving away from a subsidy-dependent system to an enterprise-oriented value chain. FPOs represent the most transformative institutional innovation in this journey. By encouraging collective action, management, market orientation and value addition, FPOs are reshaping the cultural and economic status of rural India.

The future of Indian agriculture lies in entrepreneurship, organization and integrative value chain and FPOs will remain at the vanguard of this transformation.

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Drink Plenty of Water and Take Beverages in Moderation

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Introduction

"*Thousands have lived without love, not one without water.*" - W. H. Auden

Water is often called the *elixir of life*, and rightly so, it forms the essence of human existence. Nearly two-thirds of the human body is composed of water, emphasizing its indispensable role in maintaining life and health (Jéquier & Constant, 2010). From regulating body temperature to transporting nutrients and removing waste products, water is vital for every physiological function (Popkin, D'Anci, & Rosenberg, 2010). As the saying goes, *"You never miss the water till the well runs dry,"* reminding us of its irreplaceable value in our daily lives. Beverages, too, quench thirst and help meet our body's fluid requirements. However, not all beverages are created equal. Some are nourishing such as milk and fresh fruit juices while others, particularly sugar-sweetened and caffeinated drinks, can be harmful when consumed excessively (Santos et al., 2022; Temple et al., 2017). *"Too much of anything is bad,"* and this holds true even for beverages that provide temporary refreshment but long-term health risks when taken in excess. Studies indicate that excessive intake of sugary drinks is linked with obesity, type 2 diabetes, and cardiovascular diseases (WHO, 2015; CDC, 2024).

Among nourishing beverages, milk remains a "*complete food*," suitable for all age groups. It provides high-quality proteins, calcium, phosphorus, and B vitamins essential for bone health and growth (FAO, 2020; Drewnowski, 2020). Similarly, natural beverages like coconut water, herbal teas, and unsweetened fruit juices can be consumed in moderation for hydration and nutritional benefits (EFSA, 2023).

In modern lifestyles dominated by fast food and ready-to-drink beverages, maintaining hydration through plain water is both a *simple yet powerful health habit*. Drinking sufficient water daily not only supports metabolism and detoxification but also enhances cognitive and physical performance (Hakam et al., 2024). On the other hand, moderation in beverage intake reflects a balanced approach to health *"balance is not something you find; it's something you create."*

Thus, cultivating mindful drinking habits prioritizing water and limiting high-calorie, sweetened, or stimulant beverages is a cornerstone of good nutrition and preventive health. In short, *"pure water is the world's first and foremost medicine."*

Why Do We Need Water?

"*Pure water is the world's first and foremost medicine.*" - Slovak Proverb

Water is essential for life, constituting 60-70% of body weight and forming the primary component of blood, lymph, and other body fluids (Jéquier & Constant, 2010). It regulates body temperature, supports nutrient transport, and facilitates waste elimination. An adult requires approximately 2 litres/day, increasing to 3-4 litres/day during hot weather or intense physical activity (Mayo Clinic, 2024; Popkin et al., 2010). Water loss of just 2% of body weight can impair cognitive and physical performance (EFSA, 2023).

Safe and Wholesome Water

"Prevention is better than cure."

Water must be free from microorganisms (E. coli, Vibrio cholerae) and harmful chemicals (lead, arsenic, nitrates, excess fluoride). Excess fluoride (>1.5 mg/L) causes dental and skeletal fluorosis, whereas 0.5-0.8 mg/L is optimal (Susheela, 2020; WHO, 2017). Contaminated water causes over 3 million deaths annually due to diarrheal diseases (UNICEF, 2023).

How to Render Water Safe

1. Boiling: 10-15 min at 100°C destroys bacteria, viruses, and protozoa; removes temporary hardness (WHO, 2017).
2. Chlorination: 0.5 g chlorine tablet disinfects 20 L of water; residual chlorine (0.2-0.5 mg/L) prevents recontamination (EPA, 2021).
3. Modern Devices: UV, RO, and activated carbon filtration remove microbes, heavy metals, fluoride, and nitrates while improving taste (UNICEF, 2023).

Safe water ensures osmotic balance, enzymatic activity, and toxin-free hydration.

Milk: Nature's Perfect Beverage

"*There is no finer investment for any community than putting milk into babies.*" - Winston Churchill

Milk contains 3.3% protein, 3.9% fat, 4.8% lactose, and 0.7% minerals, with water constituting 87% (FAO, 2023). Casein and whey proteins are high biological value (HBV 84-90%), supplying all essential amino acids (Górska et al., 2022). A daily intake of 250-300 mL provides 300-350 mg of calcium, supporting bone mineralization (Weaver & Peacock, 2019). Milk fat carries vitamins A, D, and E, while low-fat milk provides nutrients with reduced calories (50 kcal/100 mL). Milk is also a key source of vitamin B_{12} for vegetarians. Pasteurization at 72°C for 15 sec ensures safety without nutrient loss (WHO, 2020).

Soft Drinks

Soft drinks are classified as natural (fruit juices) or synthetic/carbonated drinks. Natural juices provide 30-50 mg vitamin C/100 mL and 150-200 mg potassium/100 ml, supporting immunity and cardiovascular health (FAO, 2023). Carbonated drinks often contain 8-12 g sugar/100 mL and phosphoric acid, which can erode dental enamel and reduce appetite. Fruit-based beverages like buttermilk, lassi, and coconut water are healthier alternatives.

Soft Drinks: Nutritional and Health Implications

Soft drinks are widely consumed beverages, classified broadly into natural and artificial types. Natural soft drinks, such as fruit juices and sugarcane juice, provide energy primarily from natural sugars (5–15 g/100 mL), essential vitamins like vitamin C (12–60 mg/100 mL) and β-carotene, and minerals such as potassium (200–400 mg/100 mL) and calcium (10–50 mg/100 mL), supporting cardiovascular and bone health (Slavin & Lloyd, 2012; Basu

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et al., 2020). Potassium-rich juices, for instance, can aid in blood pressure regulation. However, fruit juices lack dietary fiber and cannot fully replace whole fruits.

Artificial or synthetic soft drinks generally contain carbonated water, sucrose or high-fructose corn syrup (10–12%), preservatives, and artificial flavors. Excessive intake is linked to dental erosion, suppressed appetite, obesity, insulin resistance, type 2 diabetes, and metabolic syndrome (Malik et al., 2019). For example, long-term consumption of sugar-sweetened beverages (>1 serving/day) is associated with a 26% higher risk of developing type 2 diabetes (Malik et al., 2019).

Safe preparation of beverages requires pathogen-free water to prevent gastrointestinal infections (WHO, 2022). Healthier alternatives include fermented dairy drinks (lassi, buttermilk), fresh fruit juices, and coconut water, which provide hydration, electrolytes, and probiotics while limiting added sugars and metabolic risk.

Physiological and Scientific Significance:

- Maintains hydration and electrolyte balance, particularly potassium (200–400 mg/100 mL) and sodium (20-40 mg/100 mL).
- Supplies vitamins (e.g., vitamin C 12-60 mg/100 mL) and minerals essential for cardiovascular and bone health.
- Supports gut microbiota through fermented drinks rich in lactic acid bacteria.
- Reduces risk of obesity and metabolic disorders when natural beverages replace sugar-laden carbonated drinks.

Tender Coconut Water (TCW)

TCW provides 17 kcal/100 g, with sugars ranging 1.5-5.5% depending on maturity. Mineral content per 100 mL includes: K 290 mg, Na 42 mg, Ca 44 mg, Mg 10 mg, P 9.2 mg, Fe 106 µg, Cu 26 µg (Raghavendra & Basavaraj, 2018). It is an excellent oral rehydration medium, restoring electrolytes lost through sweating. Caution is required in hyperkalemia or renal impairment.

Alcohol

Alcoholic beverages contain ethyl alcohol: beer 2-5%, wine 8-10%, spirits 30-40%. Ethanol provides 7 kcal/g, contributing to obesity when consumed in excess. Regular intake >2 drinks/day increases hypertension, stroke, liver cirrhosis, cardiomyopathy, and cancer risk (Boffetta & Hashibe, 2006; Rehm et al., 2017). Alcohol also impairs nutrient absorption, leading to deficiencies in vitamins and minerals.

Understanding Lactose Intolerance: Why Milk Can Be Troublesome for Some

"The dose makes the poison." - Paracelsus (1493-1541)

This timeless wisdom perfectly applies to lactose intolerance, a condition where even a nutritious food like milk can cause discomfort when the body lacks the enzyme to digest it properly. Lactose intolerance is a common digestive disorder caused by insufficient activity of lactase (β-galactosidase), an enzyme produced in the small intestine that breaks down lactose, the main sugar in milk, into glucose and galactose for absorption (Misselwitz et al., 2019). When lactase is deficient, undigested lactose reaches the large intestine and is fermented by gut bacteria, producing lactic acid, hydrogen, and carbon dioxide, which lead to bloating, gas, abdominal cramps, and diarrhea.

Lactose intolerance can occur in three main forms. Primary lactase deficiency, or adult hypolactasia, is genetically programmed and typically develops after weaning, particularly in Asian and African populations. Secondary lactase deficiency arises from intestinal damage due to infections, celiac disease, or inflammatory bowel disease and is often temporary, especially in children after diarrhea. The rare congenital form involves complete absence of lactase from birth (Suchy et al., 2019).

Interestingly, lactose is not just a potential irritant—it also plays a beneficial role in gut health. It promotes the growth of beneficial lactic acid bacteria, supporting a balanced intestinal microbiota. Many people with mild intolerance can still enjoy small amounts of milk, especially when consumed with other foods that slow gastric emptying. Fermented dairy products like yogurt, curd, and buttermilk are usually well-tolerated because lactic acid bacteria partially break down lactose (Heyman, 2022).

Lactose malabsorption affects approximately 65% of adults globally, with the highest prevalence in South and East Asia, including India, where 60–70% of adults are affected (NIH, 2023; Swallow, 2021). Complete avoidance of milk is rarely necessary. Instead, management strategies such as consuming small, frequent servings, choosing lactose-free or fermented dairy products, and using lactase enzyme supplements allow individuals to continue reaping milk's nutritional benefits, including calcium, protein, and vitamins.

Lactose intolerance highlights the importance of enzyme-mediated digestion and individual variability in nutrient absorption. Understanding this condition not only helps in dietary planning but also reflects how human populations have evolved different adaptations to dairy consumption over time.

Tea and Coffee

Tea and coffee contain caffeine (tea: 30-65 mg/cup; coffee: 80-120 mg/cup), which stimulates the central nervous system (Nehlig, 2016). Moderate intake (≤200 mg/day) improves alertness, while excessive intake (>400 mg/day) causes nervousness, anxiety, and increased blood pressure. Tea also contains flavonoids (100-200 mg/cup), which reduce cardiovascular risk (Krittanawong et al., 2021). Tannins in both beverages can reduce iron absorption, so consumption should be spaced from meals.

Tea and Coffee: Nutritional and Health Implications

Tea and coffee are among the most widely consumed beverages globally, primarily valued for their caffeine content, which acts as a central nervous system stimulant. A standard cup (150 mL) of brewed coffee contains approximately 80–120 mg of caffeine, while instant coffee provides 50–65 mg. Tea contains slightly lower caffeine levels, around 30–65 mg per cup (Temple et al., 2017). Low to moderate caffeine intake (20–200 mg) enhances alertness, reduces fatigue, and improves cognitive performance, whereas higher doses (>200 mg) may induce anxiety, restlessness, insomnia, and palpitations, particularly in sensitive individuals (Nehlig, 2016).

Beyond caffeine, tea contains theobromine and theophylline, which can promote coronary artery relaxation and improve circulation. Both tea and coffee are rich in tannins, which can inhibit non-heme iron absorption, warranting avoidance around meals to prevent nutritional interference (Hurrell & Egli, 2010). Excessive coffee consumption is associated with increased blood pressure, irregular heartbeats, and elevated LDL cholesterol and triglycerides, particularly in individuals with pre-existing cardiovascular conditions (Mostofsky et al., 2016).

Antioxidant Benefits:

Tea, particularly green and black varieties, contains flavonoids and polyphenols that reduce oxidative stress, lower inflammation, decrease coronary heart disease risk, and offer protective effects against certain cancers, such as gastric cancer (Yang & Landau, 2000). Coffee also provides polyphenols with modest antioxidant effects, but benefits are dose-dependent and may be offset by excessive caffeine intake.

Decaffeinated Options:

Decaffeinated coffee and tea retain most bioactive compounds with substantially lower caffeine, making them suitable for individuals with cardiovascular risk or caffeine sensitivity.

Physiological Significance:

- Enhances mental alertness and reduces perceived fatigue.
- Supports cardiovascular health through antioxidant polyphenols.

- Moderates digestive function; excessive tannin and caffeine intake may impair nutrient absorption.
- Emphasizes moderation to balance stimulatory benefits with potential cardiovascular and neurological risks.

Water and Beverage Management

Proper hydration and healthy beverage choices are essential for physiological homeostasis. Daily intake of safe water meets fluid requirements, and boiling is recommended when water safety is uncertain to eliminate pathogens. Consuming ≥250 mL of boiled or pasteurized milk daily provides calcium, protein, and essential vitamins, supporting growth and bone health. Preference for fresh fruit juices over carbonated drinks reduces added sugar intake and cardiovascular risk. Tea is generally favored over coffee due to antioxidant content and lower caffeine-related adverse effects. Alcohol intake should be minimized, as excessive consumption disrupts nutrient metabolism and increases risk of liver and cardiovascular disease. Adhering to these guidelines optimizes hydration, nutrient status, and overall health.

Dietary water and fluid management

- Water is the major constituent of the human body. Drink 2-3 litres of safe water daily; boil if safety is uncertain.
- Beverages are useful to relieve thirst and to meet fluid requirements of the body. Consume 250-300 ml of pasteurized milk daily.
- Some beverages provide nutrients while others act as stimulants. Prefer natural fruit juices and coconut water over carbonated drinks.
- Limit caffeine intake; tea is preferred over coffee.

Conclusion

Water and beverages play a pivotal role in maintaining hydration, nutrient balance, and overall health. Safe and adequate water intake, along with moderate consumption of nutrient-rich drinks like milk, natural fruit juices, and coconut water, supports physiological functions, bone health, and cardiovascular well-being. While tea and coffee provide stimulatory and antioxidant benefits, their intake should be moderated to avoid adverse neurological or cardiovascular effects. Conversely, excessive consumption of sugar-sweetened and alcoholic beverages poses significant health risks. Adopting mindful drinking habits prioritizing water, choosing wholesome beverages, and limiting high-calorie, caffeinated, or alcoholic drinks forms a cornerstone of preventive nutrition and long-term wellness. Ultimately, moderation, safety, and nutrient quality are key to optimizing hydration and supporting a healthy lifestyle.

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Ensure the Use of Safe and Clean Foods

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Introduction

Food safety is a cornerstone of human health, yet unsafe or contaminated foods remain a major global concern. According to the World Health Organization (WHO, 2024), approximately 600 million people fall ill annually due to foodborne diseases, resulting in 420,000 deaths, with children under five accounting for 40% of the burden. In the United States, while food recalls slightly decreased from 313 in 2023 to 296 in 2024, hospitalizations from foodborne illnesses more than doubled, from 230 to 487 cases, and deaths increased from 8 to 19 (CIDRAP, 2024). Similarly, in India, the Food and Drug Control Administration (FDCA) seized 351 tonnes of suspicious or unsafe food items in 2024-25, and 1.45% of food samples tested were found unsafe (Times of India, 2025).

These data highlight the urgent need for awareness and implementation of food safety practices, including proper handling, storage, and hygiene, to prevent contamination, reduce disease burden, and safeguard nutritional quality. Safe and clean foods not only protect against acute foodborne illnesses but also contribute to long-term health, growth, and development, emphasizing their essential role in public health nutrition.

Safe and high-quality foods are essential for maintaining optimal health and preventing nutrition-related disorders. Foods can be contaminated with naturally occurring toxins, environmental pollutants, or adulterants, all of which pose significant health risks (FAO & WHO, 2022). Consumption of such unsafe foods can lead to foodborne illnesses, ranging from mild gastroenteritis to severe systemic infections, contributing to morbidity and mortality worldwide (WHO, 2024). Ensuring food safety is therefore critical not only to protect public health but also to support overall well-being and sustainable nutrition.

What Makes Food Unsafe?

Food safety is compromised by various biological, chemical, and physical factors. Microorganisms, including bacteria, yeasts, and molds, along with their metabolic by-products, are major contributors to food spoilage and food-borne illnesses (Tarladgis, 2021). Naturally occurring enzymes in foods can also lead to deterioration, affecting texture, flavor, and nutritional quality (Gould, 2020). Contamination from insects, rodents, and intentional or accidental adulterants, as well as the presence of natural toxins or chemical residues exceeding permissible limits, further renders food unsafe (FAO & WHO, 2022). Environmental conditions such as temperature, moisture, and storage duration significantly influence the extent of food spoilage and microbial growth (Jay et al., 2020).

How Do We Select Safe Food?

Selecting safe and high-quality foods is the first step toward a nutritious and hygienic diet. Purchasing food items from reliable sources with high turnover ensures freshness and reduces the risk of spoilage (FAO & WHO, 2022). Certification marks serve as indicators of quality assurance. For example, AGMARK certifies honey and ghee; FPO (Fruit Products Order) ensures the quality of fruit and vegetable products like jams and squashes; and ISI (Bureau of Indian Standards) certifies food colors and essences (BIS, 2023). Packaged foods should always be checked for expiration dates or "best before" labels to ensure safety.

Grains should be free from infestation, foreign matter, and mold. Uniform size and the absence of shriveled or discolored grains indicate good quality (Jay et al., 2020). Loose fats and oils pose a higher risk of adulteration; thus, sealed branded products are preferred. Milk and dairy products, such as butter, ghee, and khoa, should be obtained from reputable dairies or reliable vendors to prevent contamination and adulteration (Drewnowski, 2020).

Whole spices with uniform color, size, and shape are safer than powdered spices, which are more prone to adulteration; certified products are recommended (FAO, 2020). Fruits and vegetables should be free from bruises, decay, insect damage, and mold. Eggs must be fresh and intact, while meat and poultry should have proper color, texture, and odor. Freshwater fish can be assessed for safety by its stiff body, clear bulging eyes, reddish gills, tight scales, and absence of off-odor or pitting upon finger pressure (Tarladgis, 2021).

Adhering to these guidelines helps prevent food-borne illnesses and ensures the nutritional quality of the diet.

Best Practices for Food Storage

Proper storage of agricultural commodities is essential to maintain food quality, prevent spoilage, and reduce the risk of food-borne illnesses. Grains and other produce should be adequately dried before storage to lower moisture content, which inhibits the growth of bacteria, molds, and toxin-producing fungi such as *Aspergillus* species responsible for aflatoxin contamination (FAO, 2020; Sharma et al., 2022).

Storage structures must be safe, clean, and designed to prevent exposure to environmental factors such as humidity, extreme temperature, and pests. Rodent and insect infestations can cause significant nutrient loss and render food unsafe for consumption. Regular disinfestation of storage areas using approved rodenticides such as aluminium phosphide is recommended to control rodent populations and protect stored grains (BIS, 2023).

In addition to chemical control, traditional household methods have proven effective in preventing pest infestations. For example, applying small amounts of edible oils to grains can form a protective layer, while dried neem (*Azadirachta indica*) leaves placed in storage bins act as a natural insect repellent (Singh & Singh, 2021). These practices, when combined with proper ventilation, hygiene, and periodic inspection, help maintain the safety and nutritional quality of stored foods.

Why Do Foodborne Diseases Occur?

Foodborne diseases result from the consumption of contaminated or improperly handled foods. Commonly affected items include milk and milk products (e.g., khoa, paneer), meat, poultry, seafood, and even cooked foods like rice and pulses (World Health Organization [WHO], 2022; Scallan et al., 2011).

These illnesses arise due to bacterial infections (e.g., *Salmonella*, *Listeria monocytogenes*), viral infections (e.g., norovirus, hepatitis A), and toxins produced by microorganisms (e.g., aflatoxins, staphylococcal enterotoxins) (Centers for Disease Control and Prevention (CDC), 2023). Improper food processing, inadequate cooking, unhygienic handling, and storing cooked foods at warm temperatures for extended periods create ideal conditions for microbial proliferation and toxin production (EFSA, 2023).

For example, keeping cooked rice at room temperature for several hours allows *Bacillus cereus* spores to germinate and produce toxins, which are resistant to reheating and can cause vomiting and diarrhea (Bintsis, 2018). Similarly, unpasteurized milk and inadequately cooked meat can harbor pathogenic bacteria leading to severe infections (FAO, 2020).

Thus, foodborne diseases are largely preventable through proper processing, hygienic handling, adequate cooking, and safe storage practices.

How Should Perishable Foods Be Handled?

Perishable foods, including milk, meat, seafood, vegetables, and cooked dishes, are highly susceptible to microbial spoilage due to bacteria, yeasts, and molds (World Health Organization (WHO), 2022). To prevent foodborne illnesses, proper storage and handling are critical.

These foods should be stored under refrigeration at temperatures of **≤10°C**, which slows microbial growth, or frozen for longer-term preservation (Centers for Disease Control and Prevention [CDC], 2023). However, even refrigerated items can spoil if stored beyond recommended durations.

Cross-contamination must be avoided by separating raw and cooked foods, and by using clean utensils and cutting boards (Food and Agriculture Organization [FAO], 2020). Cooked foods that are not consumed immediately should either be kept hot (≥60°C) or cooled rapidly to ≤10°C to minimize bacterial proliferation, as most pathogens multiply rapidly between 10°C and 60°C (Bintsis, 2018).

Refrigerated cooked foods should always be reheated to safe temperatures before consumption, though repeated reheating should be minimized to preserve both safety and nutritional quality (European Food Safety Authority (EFSA), 2023).

Following these handling practices helps maintain food safety, prevent microbial growth, and reduce the risk of foodborne illnesses.

Personal Hygiene for Food Safety

Maintaining personal hygiene is a fundamental aspect of food safety, as food handlers can transmit pathogens through direct contact (WHO, 2022). Individuals involved in food preparation and service should be free from obvious signs of illness, open wounds, or skin infections, which may serve as sources of contamination (Centers for Disease Control and Prevention (CDC), 2023).

In traditional practices, especially in India, cooked food is often handled with bare hands during preparation, serving, or eating. To minimize microbial contamination, the use of utensils such as spoons, ladles, and tongs should be encouraged (FAO, 2020). Hand hygiene is critical: hands should be washed thoroughly with soap and running water before starting food preparation, after handling raw foods, and after any interruption such as using the restroom or touching the face (EFSA, 2023). Household pets, including cats and dogs, can harbor pathogens like *Salmonella* and *Campylobacter* and should be kept away from areas where food is cooked, stored, or served (Bintsis, 2018).

Adherence to these personal hygiene practices significantly reduces the risk of foodborne infections and ensures safe, wholesome food for consumers.

Common Food Adulterants

Food adulteration is a serious public health concern, where non-food materials or inferior quality products are added to food, often to increase quantity or enhance appearance. Spoiled, stale, or poor-quality foods are sometimes made visually appealing by adding harmful colors, chemicals, or non-edible substances (Benson et al., 2021). Frequently adulterated food items include milk and milk products, cereals, pulses, edible oils, and spices (Kumar & Singh, 2022). Common classes of adulterants are:

- **Non-permitted synthetic colors:** e.g., metanil yellow in turmeric or turmeric powder (Gupta et al., 2020).
- **Non-edible oils:** e.g., castor or mineral oils added to edible oils (Bintsis, 2018).
- **Cheaper fillers or substitutes:** e.g., starches or chalk in milk powder (FAO, 2020).
- **Extraneous matter:** e.g., husk, sand, or sawdust in grains and spices (WHO, 2022).
- **Metal contaminants:** e.g., aluminum or iron filings due to improper processing or deliberate addition (Kumar & Singh, 2022).

Consumption of adulterated foods may lead to acute or chronic health issues, including foodborne illnesses, heavy metal toxicity, and in severe cases, epidemics (Benson et al., 2021). To minimize risk, it is essential to purchase from reliable sources, check foods carefully before buying, and prefer certified brands with regulatory marks such as AGMARK, FPO, or ISI (FAO, 2020).

Minimizing the Effects of Pesticide Residues

Pesticides are commonly used during crop cultivation to control pests and enhance yields, but residues can persist on fruits, vegetables, and other foodstuffs, posing potential health risks such as endocrine disruption, neurotoxicity, and carcinogenicity (Mostafalou & Abdollahi, 2017).

The risk of exposure can be significantly reduced through simple household practices:

1. **Thorough Washing:** Rinsing fruits and vegetables under running water removes surface residues. Washing with mild solutions like diluted vinegar or baking soda can further reduce pesticide residues (Chiesa et al., 2020).
2. **Peeling:** Removing outer skins of vegetables and fruits (where feasible) eliminates most pesticide residues.
3. **Cooking and Processing:** Boiling, steaming, blanching, and frying can degrade or reduce pesticide levels in many food items (Kumar et al., 2021).
4. **Safe Storage and Handling:** Foods should be protected from secondary contamination by kitchen insecticides or household sprays. Eatables must be properly covered and stored away from areas treated with chemical agents (WHO, 2022).

Adopting these strategies helps minimize dietary exposure to pesticides while maintaining the nutritional quality of the foods.

Practical Guidelines for Safe Food Handling

1. **Purchase from Reliable Sources:** Always buy food items from trusted vendors or brands. Check for certification marks such as AGMARK for honey and ghee, FPO for fruit products, and ISI for food additives, and ensure the products are free from visible defects, infestation, or contamination (FAO, 2020).
2. **Thorough Washing of Produce:** Vegetables and fruits should be washed carefully under running water to remove soil, pesticide residues, and surface microbes. Peeling or scrubbing tougher-skinned produce can further reduce contamination (Chiesa et al., 2020).
3. **Proper Storage:** Store raw and cooked foods in clean, dry, and airtight containers. Protect them from moisture, rodents, insects, and microbial contamination. Use traditional methods such as dried neem leaves or edible oils in storage bins when appropriate (EFSA, 2023).
4. **Refrigeration of Perishables:** Perishable foods such as milk, meat, and cooked meals should be kept at ≤10°C to slow microbial growth. Cooked foods should be either kept hot (>60°C) or cooled quickly (<10°C) and reheated before consumption (WHO, 2022).
5. **Personal Hygiene:** Food handlers should maintain clean hands, hair, and clothing, and avoid preparing food when ill or having open wounds. Hands should be washed thoroughly with soap before and during food preparation, and utensils and surfaces should be kept sanitized (Jéquier & Constant, 2010).
6. **Clean Utensils:** Use well-cleaned cooking and eating utensils to prevent cross-contamination. Avoid using the same utensils for raw and cooked foods without proper washing in between (Popkin et al., 2010).

By following these simple yet effective practices, the risk of **foodborne illnesses, contamination, and nutrient loss** can be minimized, ensuring a safe and wholesome diet.

Conclusion

Ensuring the use of safe and clean foods is fundamental to protecting public health, preventing foodborne illnesses, and sustaining nutritional well-being. The evidence presented underscores that food safety is not merely a technical or regulatory issue but a shared responsibility involving producers, handlers, and consumers. Contamination can occur at multiple stages from production and processing to storage and consumption highlighting the need for comprehensive preventive measures guided by scientific principles and hygienic practices.

Proper selection of food items from reliable sources, adherence to certification marks such as AGMARK, FPO, and ISI, and awareness about common adulterants are crucial first steps toward safe food consumption. Equally important are correct handling and storage techniques that prevent microbial growth, chemical contamination, and nutrient degradation. Maintaining personal hygiene, especially among food handlers, and adopting household-level interventions such as thorough washing, refrigeration, and traditional pest control methods further enhance food safety.

Minimizing pesticide residues through washing, peeling, and cooking also plays a vital role in reducing chronic health risks linked to chemical exposure. Collectively, these practices ensure that food retains its nutritional integrity and safety from farm to fork.

In conclusion, promoting food safety requires continuous public education, enforcement of regulatory standards, and integration of traditional knowledge with modern food science. Strengthening awareness and accountability at every level of the food system will help ensure that the food we consume is not only nutritious but also safe, wholesome, and conducive to long-term health and sustainability.

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Importance of Safety Consideration and Operator's Protective Gadgets in Farm Operations

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ABSTRACT

Agriculture remains one of the most hazardous occupations in India, accounting for a large number of fatalities, injuries, and disabilities each year due to extensive reliance on farm machinery. National data show that tractors, threshers, sugarcane crushers, and chaff cutters contribute significantly to farm accidents, resulting in severe economic and social losses. Despite the availability of safety standards established by the Bureau of Indian Standards (BIS) and regulations such as the Dangerous Machines (Regulation) Act, 1983, non-adherence to safety guidelines and lack of awareness continue to escalate accident rates. This article highlights the distribution, causes, and severity of agricultural accidents, emphasizing the need for strict safety measures, proper machine design, and effective accident compensation norms. Furthermore, the importance of Personal Protective Equipment (PPE)—including helmets, goggles, ear protection, coveralls, gloves, and safety footwear—is discussed as a crucial strategy for minimizing risk. By integrating engineering controls, regulatory measures, and operator-level protective practices, a safer agricultural work environment can be achieved, reducing both human suffering and economic losses.

INTRODUCTION

Agriculture is one of the most hazardous occupations in India, with thousands of accidents reported annually due to the extensive use of farm machinery. National studies consistently identify tractors, threshers, sugarcane crushers, chaff cutters, and tractor-trailers as the most accident-prone equipment. Reports from the WHO Collaborating Centre indicate that major states such as Haryana, Punjab, and Uttar Pradesh alone account for 5,000–10,000 deaths, 15,000–20,000 amputations, and up to 2 lakh serious injuries every year (Nag, P. K., and Nag A.,2004). Investigations across different regions further show that machinery-related accidents dominate farm injuries, with fatality rates varying from 4.3% to 22% depending on the state, and an estimated national economic loss of over ₹1100 crore annually (Nag, P. K. and Nag A.,2004).

These statistics highlight the urgent need for strong safety measures in machinery design, operation, and maintenance. In response, the Bureau of Indian Standards (BIS) has introduced several safety standards for tractors, threshers, power tillers, and crop protection equipment, while the Government of India enforced the Dangerous Machines (Regulation) Act, 1983, mandating essential protective devices. Along with engineering controls, the proper use of Personal Protective Equipment (PPE) such as helmets, gloves, goggles, ear protection and sturdy footwear plays a vital role in reducing injury severity.

Safety Standards in Agriculture: Considering the high accident rate, the Indian Standards Institute has developed numerous safety standards for commonly used farm machines. The Dangerous Machines Act provides guidelines for hazardous equipment, and safe feeding systems on threshers have been made compulsory. However, operators must strictly adhere to these safety provisions for maximum protection. To highlight the need for such safety standards, the category-wise and severity-wise distribution of agricultural accidents is shown in Table 1.

Table 1. Category wise and severity wise distribution of agricultural accidents

Sl. No.	Source	No. of accidents			% of total accident
		Fatal	Non fatal	Total	
1.	Farm machinery	39	659	698	30.5
2.	Hand tools	1	782	783	34.2
3.	Other sources (snake bites, animal bites, fallin well/pond, lightening, heat stroke etc.)	84	725	809	35.3
4.	Total	124	2166	2290	100

(Ajay *et al*., 2023)

In addition to knowing which machines cause the most accidents, understanding how and why these incidents occur is equally important. Factors such as slipping, loose garments, lack of safety covers, electrical shocks, and operator negligence play a major role in injury severity. Identifying these underlying causes helps in developing preventive strategies, improving safety awareness, and promoting the proper use of protective gadgets. The type-wise and cause-wise percentage of agricultural accidents is explained in Table 2.

Table 2. Type and Cause -wise percentage of accidents

Sl. No.	Type	Percentage of total accidents
1.	Cut slip	45.0
2.	Shock	3.5
3.	Burns	1.1
4.	Slippery ground	5.7
5.	Loose garments	5.1
6.	Lack of protective covers	1.2
7.	Lack of safety devices	4.3
8.	Ignorance	25.5
9.	Any other	12.6

(Ajay *et al.*, 2023)

Beyond safety analysis, it is important to consider the social and economic impact of agricultural accidents on the affected families. Compensation norms play a crucial role in ensuring timely support to victims who suffer injuries, amputations, or loss of life. Establishing fair and uniform compensation guidelines also encourages better reporting and accountability in agricultural workplaces. The proposed compensation structure for different types of agricultural accidents is outlined in Table 3.

Table 3. Proposed compensation norms for victims of agricultural accidents

Sl. No.	Details of accidents	Compensation proposed
1.	In case of death	₹. 1,00,000/
2.	Amputation of one body part/one body part rendered useless *viz*. hand, arm, leg, eye, foot/any other serious injury	₹. 30,000/-
3.	Amputation two body parts/two body parts rendered useless *viz*. hand, arm, leg, eye, foot etc./any other serious injury	₹. 45,000/-
4.	Amputation of finger, finger parts will be equivalent to amputation of complete finger	₹. 7,500/-
5.	Amputation of two fingers	₹. 15,000/-
6.	Amputation of four fingers/amputation of one body part	₹. 30,000/-

(Ajay *et al.*, 2023)

Preventing injuries in agricultural operations requires the proper use of personal protective equipment (PPE). The choice of PPE should be guided by a clear understanding of the hazards associated with each task and the protective options available. For agricultural chemicals, both product labels and Material Safety Data Sheets (MSDS) provide essential guidance on the recommended PPE to minimize risks. Additionally, consulting reputable suppliers can help ensure the selection of equipment that matches the specific protective needs of workers, as these suppliers are well-informed about the capabilities and variations of different PPE.

HEAD PROTECTION

Head protection is recommended in situations where there is a risk of falling objects or accidental contact with equipment, beams, or piping. Hard hats or safety helmets with chin straps should be used in such cases and must comply with ANSI Z89standards.

There are two types of hard hats:

- **Type 1:** Protection from impact to the top of the head.
- **Type 2:** Protection from impact to the top and sides of the head

Types of Head Protection:

- **Hard Hats and Safety Helmets** – Standard hard hats, including newer helmets with chin straps, are designed to protect against impact.

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- **Sun Protection Hats** – Wide-brimmed hats can reduce the risk of heat stress and protect the skin from UV exposure, lowering the likelihood of skin damage or skin cancer.

Fig. 1. Hard Hats, Safety Helmets and Sun Protection Hats

Best Practices: On farms, hard hats are rarely needed and should only be used when overhead hazards are present. For sun protection, workers should wear hats with wide brims to reduce heat stress and UV exposure.

EYE PROTECTION

Eye protection is vital for preventing serious injuries caused by flying particles, sharp objects, or chemical splashes, which can lead to permanent blindness.

Types of Eye Protection:

- **Safety glasses** – Designed for impact protection, available in wraparound or side-shield styles, including prescription versions.
- **Goggles** – Provide impact resistance and can fit over glasses. Chemical goggles are designed with indirect vents to block liquid splashes while allowing airflow.
- **Face shields** – Protect the entire face from impact or chemical hazards, but should always be worn with goggles for complete protection.

Fig. 2. Safety glasses, Goggles and Face shields

Standards: Safety glasses should meet the American National Standards Institute (ANSI) standard for eye protection (ANSI Z87.1-2003).

Best Practices: For handling chemicals, chemical goggles or face shields are required for splash protection. When working with hazardous substances such as anhydrous ammonia, non-vented goggles are essential to guard against both splash and vapor exposure. Even with a face shield, goggles must still be worn.

HEARING PROTECTION

Agricultural machinery and equipment often expose workers to harmful noise levels that can cause permanent hearing damage if not controlled.

Types of Hearing Protection:

- **Earplugs** – Typically made of foam that expands inside the ear canal; available as disposable or reusable. Some are made of soft plastic for comfort.
- **Earmuffs** – Fit over the ears and are specifically designed for hearing protection (not music headphones). Some models come with built-in radios.

Standards: The effectiveness of hearing protectors is measured using theNoise Reduction Rating (NRR), expressed in decibels (dB). For example, NRR 28 means noise can be reduced by 28 dB under ideal conditions.

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However, OSHA derates this value by half for real-life application, while NIOSH recommends other correction factors depending on device type.

Fig. 3. Earplugs and Earmuffs

Best Practices: Workers should choose hearing protection suited to the level of noise exposure and ensure correct fit and usage. Damaged or worn-out earplugs/earmuffs should be replaced to maintain effectiveness.

COVERALLS AND APRONS

Protective clothing such as coveralls and aprons is essential when handling agricultural chemicals, as it reduces the risk of exposure through splashes or contact.

Types of Protective Clothing:

- **Coveralls** – Worn as outer garments to protect against chemicals. Disposable coveralls are widely used, with protection levels varying by material. Tyvek, a common fabric, protects against dry chemicals but is not waterproof. For hazardous chemicals, coated or laminated Tyvek, polyvinyl chloride (PVC), or complete suits with hoods and gloves may be required.
- **Aprons** – Typically used when mixing concentrated chemicals to shield the torso from direct splashes. They are often made of nitrile, PVC, or other resistant materials. Unlike coveralls, aprons are usually reusable, though disposable options are also available.

Fig. 4. Coveralls and Aprons

Standards: The chemical label or Material Safety Data Sheet (MSDS) should always be consulted to determine the proper type of coverall or apron required for specific tasks.

Best Practices: It is important to distinguish between **liquid-resistant** and **liquid-proof**coveralls. Liquid-resistant materials may allow penetration through seams, whereas liquid-proof coveralls have sealed seams that prevent entry. Workers should always select garments appropriate to the level of chemical hazard they are handling.

GLOVES, SHOES AND BOOTS

The hands and feet are among the most exposed body parts in agricultural work and require proper protection against hazards such as chemicals, cuts, abrasions, heavy objects, and prolonged exposure to water.

Types of Protection:

- **Gloves** - Available in a wide range of materials to suit different hazards. Nitrile gloves are commonly recommended for pesticide handling. For most chemicals, unlined gloves are preferred to prevent absorption into soft linings. An exception is when handling **anhydrous ammonia**, where lined gloves are needed to provide insulation against extremely cold temperatures. Gloves also offer protection against cuts, abrasions, water immersion, and can improve grip or sanitation when handling food products.

- **Shoes and Boots** – Protective footwear includes **steel-toed shoes**to guard against heavy falling objects, and**chemical-resistant boots** made from suitable materials depending on the hazard. Disposable booties are also available for various applications.

Fig. 5. Gloves and Boots

Standards: As with other PPE, the chemical label or Material Safety Data Sheet (MSDS) should be consulted to determine the correct glove or boot material for use with specific chemicals.

Best Practices: Leather shoes should never be worn when handling chemical concentrates, as leather absorbs chemicals and cannot be properly cleaned. Boots or disposable booties should always be used in situations where chemical splashes are likely.

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TURNING SMOKE INTO SOIL: THE NEW STORY OF STUBBLE MANAGEMENT IN PUNJAB AND HARYANA

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Introduction

Punjab and Haryana, India's grain bowl, grow vast stretches of paddy each year. After the harvest, farmers are left with nearly 25 million tonnes of paddy straw. With only 15–20 days between rice harvest and wheat sowing, they often have little time to clear the fields. Burning is fast and cheap but the cost to the environment is staggering. The smoke adds to air pollution, reduces visibility, and causes respiratory problems. It also destroys soil fertility, killing beneficial microbes and depleting nutrients. Today, growing awareness, new technologies, and government initiatives are promoting sustainable stubble management, turning what was once waste into a valuable resource for cleaner air and healthier soil. Both farmers and policymakers are realizing that stubble isn't waste — it's wealth.

In the past few years, the two states have become testing grounds for innovative stubble management practices. Supported by the central government's Crop Residue Management Scheme, farmers now have access to modern machines that help handle straw responsibly.

What is Stubble Management?

Stubble management refers to the proper handling and utilization of the leftover crop residue mainly the stems and straw that remain in the field after harvesting crops like paddy (rice) or wheat.

Instead of burning this residue to clear fields quickly, stubble management promotes **eco-friendly methods** to either reuse, recycle, or naturally decompose it. The goal is to maintain soil health, reduce air pollution, and make productive use of agricultural waste.

New Green Revolution: Managing Stubble Smartly

1. In-situ Management – Handling Straw on the Field

Machines like the **Happy Seeder**, **Super Seeder**, and **Mulcher** allow farmers to sow wheat directly into the field without removing or burning the paddy straw. The straw acts as mulch, retaining moisture and enriching the soil.

2. Ex-situ Management – Giving Straw a New Life

In many areas, stubble is collected, baled, and used in **biomass power plants**, **brick kilns**, and **compressed biogas units**. Some companies are even turning straw into **packaging material, paper, and biofuels** creating jobs and a circular economy

Government initiatives and Farmer Participation

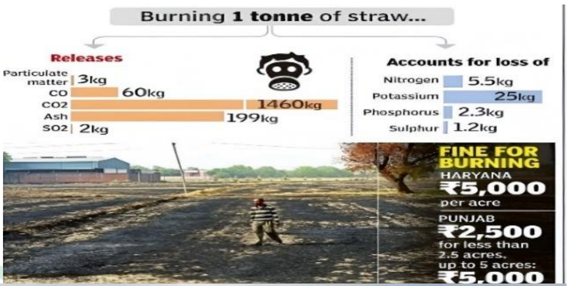
The governments of Punjab and Haryana, along with the **Commission for Air Quality Management (CAQM)**, have been working hard to promote alternatives to burning. Over ₹3,600 crore has been spent to subsidize crop residue management machinery and establish **Custom Hiring Centres** so that even small farmers can access the equipment. Satellite monitoring, "Parali Protection Forces," and awareness drives are helping identify hotspots and prevent fires before they start.

Advantages of Stubble Management

- ✓ **Reduces Air Pollution**
- ✓ **Improves Soil Health**
- ✓ **Conserves Moisture**
- ✓ **Saves Nutrients**
- ✓ **Supports Sustainable Agriculture**
- ✓ **Economic Opportunities**

Limitations of Stubble Management

- ✓ **High Initial Cost**
- ✓ **Limited Time Between Crops**
- ✓ **Lack of Infrastructure**
- ✓ **Awareness and Training Gaps**
- ✓ **Operational Challenges**
- ✓ **Weak Market Linkages**



Challenges on the Ground

Despite progress, hurdles remain. Many small farmers still find it expensive or inconvenient to use machines. Transporting and storing straw for industrial use can be difficult. And in the short harvesting window, burning remains the quickest option for some.

Moreover, real change requires behavioural shifts convincing farmers that stubble management pays off in the long run through better soil health, reduced fertilizer costs, and cleaner air for all.

From Smoke to Sustainability

Stubble burning is not just an agricultural problem — it's an environmental and social one. Yet, it also offers an opportunity to rethink farming in the 21st century. When managed properly, crop residue can improve soil fertility, generate renewable energy, and support rural livelihoods. Punjab and Haryana are now showing that the battle against the burning fields can be won — not with blame or bans, but with innovation, awareness, and collective action. The hope is clear: one day soon, the winter air of North India will carry the scent of ripe harvests — not smoke.

Conclusion

Stubble management offers major environmental and agricultural benefits but needs strong policy support, affordable technology, and farmer awareness to overcome its challenges. When implemented effectively, it can transform a major pollution problem into an opportunity for sustainable growth.

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Advances in Supercritical Fluid Extraction of Marine Bioresources

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Abstract

Although seaweeds and marine microalgae are abundant sources of useful bioactive compounds, conventional extraction techniques can damage these delicate molecules or utilise hazardous solvents. Supercritical Fluid Extraction (SFE) offers a safer, more effective, and cleaner alternative, particularly when utilising CO_2. SFE produces clean, solvent-free extracts while preserving delicate chemicals at moderate temperatures and adjustable pressure. The development of SFE, its guiding principles, and its growing application in the extraction of pigments, fatty acids, antioxidants, and other functional compounds from marine biomass are all covered in this article. SFE is emerging as a revolutionary tool for contemporary marine biotechnology due to its accuracy and sustainability.

Keywords: Supercritical fluid extraction (SFE), marine bioresources, bioactive compounds, seaweeds and microalgae, green extraction technology

Introduction

The world's seas contain enormous repositories of marine bioresources, especially microalgae and macroalgae (seaweeds), which are abundant in valuable bioactive substances such as pigments, polysaccharides, phenolics, and polyunsaturated fatty acids. Due to their health-promoting properties, these compounds are increasingly sought after for use in medications, cosmetics, and functional foods. However, common extraction techniques often employ hazardous chemical solvents, such as dichloromethane and hexane, which are detrimental to the environment and require energy-intensive separation procedures. Furthermore, the high temperatures employed in conventional processes may destroy thermolabile bioactive components, reducing their efficacy (Budisa & Schulze-Makuch, 2014).

Carbon dioxide (CO_2)-based Supercritical Fluid Extraction (SFE) has emerged as a leading "green" method in response to these challenges. The solvent exhibits the density of a liquid and the diffusivity of a gas by maintaining CO_2 above its critical temperature (31.1 °C) and pressure (73.8 bar), allowing for effective penetration of the algal matrix (Budisa & Schulze-Makuch, 2014).

This method operates at low temperatures, preserving the biological activity of heat-sensitive compounds while yielding pure, solvent-free extracts. This article reviews the advancements in SFE as a sustainable solution for harvesting the full potential of marine biomass.

A short history of the development of Supercritical Fluid Extraction

Supercritical fluid extraction (SFE) was developed as a result of early studies on fluid behaviour in hostile conditions. The first scientific observation of supercritical occurrences was made in 1822 when Baron Charles Cagniard de la Tour noted that the liquid-vapour border disappeared at high temperatures and pressures (Cagniard de la Tour, 1822). The "critical point," which describes how carbon dioxide changes into a homogeneous supercritical phase when heated above 31°C and squeezed beyond 73.8 atm, was first proposed by Thomas Andrews almost fifty years later (Andrews, 1876). The theoretical groundwork for contemporary SFE was established by his work.

The earliest documented industrial use of practical applications dates back to 1879, although commercial interest didn't really take off until the late 20th century. SFE attracted interest in the chemical, food, and petroleum industries during the 1970s and early 1980s as a potential "clean" technique for separation and purification (McHugh & Krukonis, 1990). Kurt Zosel at the Max Planck Institute made a significant discovery in 1976 when he developed a supercritical CO_2 process for decaffeinating coffee. Two years later, the first large-scale SFE plant was built. The 1980s marked a significant expansion of European interest in hops, spices, and herbal extracts, signalling the start of extensive industrial applications (Phelps et al., 1996; Ghosh & Pradhan, 2021).

What is Supercritical Fluid?

Substances that are forced beyond both their critical temperature and critical pressure, and into a phase that behaves differently from a liquid or a gas, are known as supercritical fluids (Table 2). This state, which is frequently referred to as a "fourth state of matter," combines beneficial characteristics of the two well-known phases. In this supercritical region, the fluid spreads and diffuses much like a gas, yet it retains the strong dissolving power typically associated with liquids (Fig. 1). Because there is no distinct boundary between gas and liquid in this state, the fluid also shows essentially zero surface tension. These combined characteristics make supercritical fluids extremely effective at dissolving a wide range of compounds and penetrating materials (Banerjee et al., 2008).

Table 2. Supercritical parameters for various chemical substances

Chemical compound	Critical temperature (°C)	Critical pressure (atm)
H_2O	374.1	217.7
NH_3	132.5	112.5
N_2O	36.5	72.5
CCl_2F_2	111.8	40.7

(Ghosh & Pradhan, 2021)

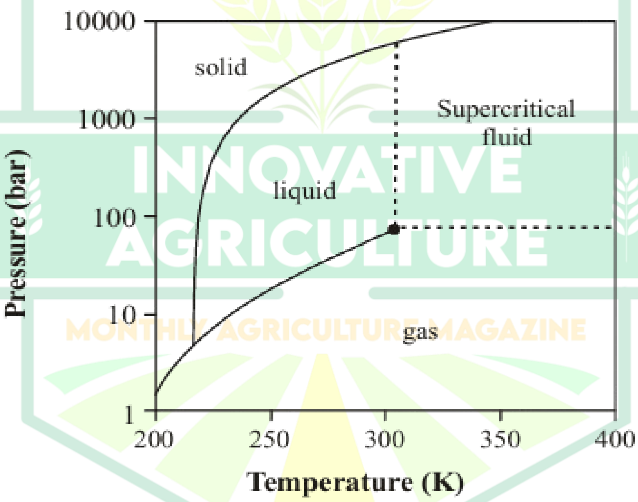

Figure. 1: Carbon dioxide pressure-temperature phase diagram

Properties of Supercritical Fluids

(i) Supercritical fluids behave like highly compressed gases that merge the characteristics of both liquids and vapours in a unique way. They flow easily like gases but can dissolve substances more effectively, similar to liquids.

(ii) Their solvent strength is generally comparable to that of light hydrocarbons for many solutes. Interestingly, fluorinated materials tend to dissolve even better in supercritical carbon dioxide than they do in hydrocarbon solvents, a feature that plays a valuable role in certain polymerisation processes.

(iii) As the pressure increases, the density of a supercritical fluid rises, and so does its ability to dissolve compounds. When these dense solutions are rapidly depressurised, the dissolved material precipitates as extremely fine particles—an important principle behind several supercritical flow-based reactor designs.

(iv) Supercritical fluids also mix readily with permanent gases such as nitrogen or hydrogen. Because of this, they can hold far higher concentrations of dissolved gases than conventional liquids, opening the door to enhanced reaction environments and specialised processing applications.

(v) Because of their unusual combination of density and diffusivity, supercritical fluids can facilitate chemical reactions that are difficult—or sometimes impossible—to carry out in ordinary liquid solvents.

Supercritical Fluid Extraction Process

Supercritical fluid extraction (SFE) is built on the distinctive behaviour of fluids that exceed their critical temperature and pressure, enabling them to function as exceptionally efficient and selective solvents. Although a range of fluids can be used, carbon dioxide remains the preferred choice due to its non-toxicity, moderate critical conditions, and ease of removal from the final extract (Figure 2).

Transition to the Supercritical State

To provide a consistent, energy-efficient flow, the pump's procedure begins by chilling carbon dioxide into a liquid. Once pressurised, the fluid is passed through a controlled heating zone. As the temperature rises above the critical point, the liquid transforms into a supercritical phase—a state that merges the dissolving capacity of liquids with the rapid diffusion and low viscosity of gases.

(i) **Extraction Within the Vessel**

The extraction chamber, which holds the raw material, is subsequently filled with supercritical CO_2. During this stage, the fluid enters areas that are inaccessible to regular solvents by passing through the sample's tiny pores. Due to its high diffusivity and absence of surface tension, it can effectively mobilise target molecules and transport them out of the matrix without causing thermal deterioration.

(ii) Separation and Depressurisation

The mixture of CO_2 and solute enters a separator where the pressure is purposefully lowered. The fluid's density is drastically reduced by even a slight drop in pressure, which reduces the fluid's solvating power and causes the dissolved chemicals to precipitate. Using multiple separators set at descending pressures allows the operator to collect different fractions individually, improving purity and selectivity.

(iii) Recovery and Recycling of the Solvent

Once the solutes are isolated, the CO_2 is either vented safely or recompressed, cooled, and cycled back into the system. This near-closed loop design minimises waste and avoids the contamination risks associated with traditional organic solvents.

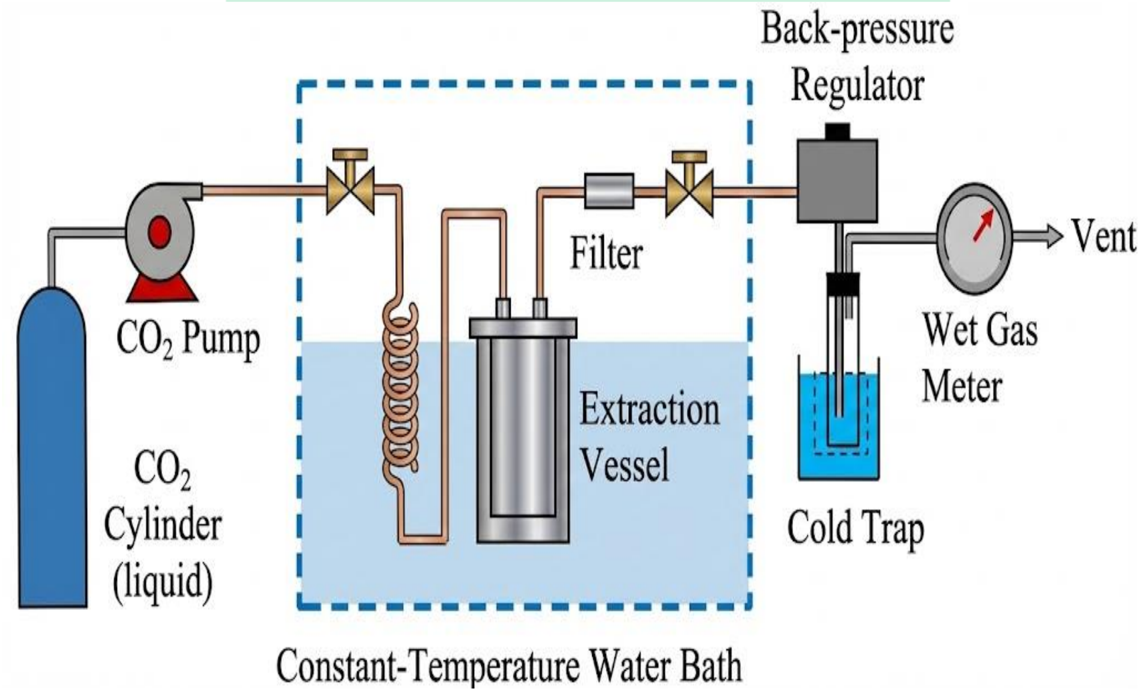

Figure. 2: Schematic diagram of supercritical fluid extraction apparatus (Markom et al., 2001)

Extracted Valuable Compounds from Microalgae and Seaweeds Using Supercritical CO_2

Seaweeds are emerging as one of the most promising natural sources of functional bioactive compounds. Because they include polysaccharides, including fucoidan, alginate, and laminarin, which are recognised for their exceptional health-supporting qualities, their distinct chemistry distinguishes them from other seaweed families (Table 2). Fucoidan's ability to reduce inflammation, combat oxidative stress, and even inhibit the growth of certain cancer cells has garnered special attention. Another common ingredient, alginate, has a high water-holding capacity and calms wounded tissues, making it useful in wound dressings as well as serving as a natural thickener in meals.

Brown seaweeds also contain phenolic compounds, especially phlorotannins, which are powerful natural antioxidants capable of protecting cells against free-radical damage. Along with these, they offer valuable omega-3 and omega-6 fatty acids that support brain development and help regulate inflammation. Their signature pigment, fucoxanthin, shows strong anticancer and antidiabetic potential, making it one of the most exciting marine-derived compounds under study today.

With this rich mix of nutrients and therapeutic molecules, brown seaweeds are increasingly seen as a sustainable source for developing functional foods, natural supplements, cosmetics, and pharmaceutical ingredients. Their bioactives represent a growing frontier in marine biotechnology and human health.

Table 2.

Sample sources	**Operating conditions**	**Extracted bioactive compounds**	**Reference**
Haematococcus pluvialis	40–90°C; 30.0–64.0 MPa	Astaxanthin	Yothipitak et al., 2008
Spirulina maxima	20–70°C; 10.0–180 MPa	Fatty acids and carotenoids	Canela et al., 2002
Nannochloropsis sp.	40–55°C; 40.0–70.0 MPa	Polyunsaturated fatty acids	Andrich et al., 2005
Nannochloropsis gaditana	40–60°C; 10.0–50.0 MPa	Carotenoids	Macıas-Sánchez et al., 2005
Chlorella vulgaris	40°C; 30.0 MPa	Antioxidants, carotenoids, fatty acids	Gouveia et al., 2007
Spirulina maxima	50–60°C; 30.0 MPa	γ–linolenic acid	Mendes et al., 2003
Crypthecodinium cohnii	40–50°C; 20.0–30.0 MPa	Omega–3 fatty acid	Couto et al., 2010
Scenedesmus almeriensis	32–60°C; 20.0–60.0 MPa	β-carotene, Lutein	Macıas-Sánchez et al., 2010
Dunaliella salina	40–60°C; 10.0–50.0 MPa	Carotenoids, Chlorophyll	Macıas-Sánchez et al., 2009

Advantages of Supercritical Fluid Extraction (SFE)

1. **Fast and efficient extraction:**
   The unique low-viscosity and high-diffusion behaviour of supercritical fluids allows them to move quickly through plant tissues, drastically reducing extraction time compared to traditional solvent methods.
2. **Highly selective:**
   By simply adjusting temperature or pressure, the solvating power of the fluid can be controlled. This allows the extraction of specific compounds with remarkable precision.
3. **Ideal for heat-sensitive materials:**
   Since SFE operates near ambient temperatures, delicate compounds—like essential oils, pigments, and nutraceuticals—are preserved without risk of degradation.
4. **Cleaner and safer extracts:**
   Supercritical CO_2 leaves no toxic solvent residues, ensuring pure extracts and eliminating the need for additional purification or solvent-removal steps.

5. **Enhanced flavour and aroma retention:**
   Volatile components often lost during distillation are retained in SFE, resulting in extracts with a richer sensory quality—especially valuable for the food, spice, and fragrance industries (Gopaliya et al., 2014).
6. **Environment-friendly technology:**
   Using CO_2 replaces hazardous organic solvents, reducing environmental load and making the process safer for workers and consumers.
7. **Complete separation and easy recovery:**
   When pressure is removed, CO_2 simply reverts to a gas, making it easy to separate the solvent from the extract and reuse the solvent.
8. **Compatible with analytical tools:**
   SFE's smooth integration with instruments like mass spectroscopy (MS) and gas chromatography (GC), which allow direct analysis in addition to extraction, can be advantageous for research, quality assurance, and product development.

Conclusion

Supercritical fluid extraction is one of the most promising environmentally friendly methods for obtaining valuable compounds from marine bioresources. Because it can operate at moderate temperatures, protect sensitive molecules, and produce clean, solvent-free extracts, it is significantly superior to conventional methods. As research advances, SFE is becoming increasingly important for unlocking the industrial, therapeutic, and nutritional potential of seaweeds and algae. Because of its precision, effectiveness, and sustainability, SFE has the potential to play a significant role in modern marine bioprocessing.

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Cultivation practices of Gac fruit

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Momordica cochinchinensis commonly known as Gac fruit belongs to the family Cucurbitaceae and it was originally discovered in Vietnam. The Gac plant is a perennial vine, and dioecious in nature where males and females flower on separate plants. Gac fruit is indigenous to temperate Asia (China, Japan, and Taiwan), the Indian subcontinent (Bangladesh and India in the specific areas such as Assam, Nagaland, Tamil Nadu, Uttar Pradesh, and West Bengal), Indochina (Thailand, Cambodia, Laos, Vietnam, Myanmar), Malesia (Philippines, Malaysia, and Indonesia), and Northeastern Australia (Queensland). Currently, Gac fruit is grown as a commercial crop on a limited scale in Vietnam and Thailand. The ripe fruits comes to harvest from August to February in open field conditions. In recent times, Gac fruit has emerged as one of the richest source of carotenoids when compared to other well-known fruits and vegetables due to presence of high levels of lycopene and β-carotene in its oily seed membrane (Chuyen et al., 2015).

Gac fruit has functional components such as carotenoids, α tocopherol, omega-3 fatty acids, polyphenol compounds and flavonoids which have significant health benefits for humans (Abdulqader et al., 2018) because of this high phyto nutrient value in all its fractions (i.e. aril, seeds, pulp and, peel) and medicinal and pharmaceutical properties, Gac fruit has gained the name “super fruit” or “heaven’s fruit” (Parks et al., 2013)

Morphology:

Gac plants have vine behaviour which produce flowers about 5–10cm in length and the vines can extend to 20m long. Gac fruit is typically oblong and almost round or ovoid in shape (John et al., 2018). The fruit is covered with short spines on the top. There is variation among different fruits with respect to their spines and fruit tips. In some fruits the spines are smooth and dense whereas in others they are hard and widely spaced. The fruit is composed of a peel covered in sparse or dense spines (exocarp), an orange spongy mesocarp (pulp), a red membrane (aril), and brown or black seeds. Each fruit has an average of between 15 and 20 seeds. Gac seeds are round, compressed, and sculptured. The color of the fruit changes from green to yellow, orange and finally red when ripening. The highest weight contributing anatomical component of the fruit is the pulp in the range of 49–75% of total weight. The aril in range of 6–31% and the peel is about 17% (Osman et al., 2017). Gac fruit contains carotenoids and other bioactive compounds such as phenolics, flavonoids, and vitamin C. Carotenoids and bioactive compounds provide health benefits such as anti-inflammation, anti-oxidant effects, cancer prevention, the main tenance of vision, embryonic development and reproduction, immune modulation, and neuroprotective effects (Chen et al., 2019).

Propagation:

Seed propagation is the main propagation method for Gac fruit in Asian countries, though cutting and grafting methods were also used. The plant can be propagated from root tubers as well. Seed germination is a simple process and it is not affected by prolonged dormancy and also it does not require deshelling of seeds. Selecting seeds to grow seed sprouts is important in the germination step of propagation. Robust seeds for germination should be extracted from large and fully ripe fruit, then selecting only seeds that sink in water. Good seed will sink because of increased density which indicates they are matured enough to germinate successfully. The selected seeds are laid in seed raising mix (2:1:1 pine bark: sand: peat moss) in trays then covered with mix. Trays are placed in open space with enough sunlight in the morning and should be protected from excessive exposure throughout the day, or can be placed in a greenhouse with average temperature of 25°C and relative humidity of 80%. Seed germination time is around 3 weeks, then the plants are transplanted into 150mm pots with potting mix (1:1 coir: perlite) and/or grown on land.

Nutrient management:

For Gac fruit fertilizers can be applied at two specific growth stages. The first stage from planting to flowering requires the ratio of NPK per hectare per week as follows: 25kg N, 5kg P and 18kg K. The second stage from fruit initiation onwards needs 2kg N, 5kg P, 18kg K, and 5kg Ca.

Trellising and pollination: Gac fruit is a climbing vine which requires to be trellised to allow development and fruit production. Trellising prevents fruit from growing on the ground and rotting when it is ripe and soft. Plants are grown on a horizontal trellis with wires placed at 1m, 1.8m, and 2.8m above the ground. The plant starts flowering about two months after being planted. In general, flowering occurs from April to July, and sometimes August to September). The flowers are pollinated by native bees and insects, but hand pollination is essential to get higher fruit set and yield, especially where its natural pollinators are absent (Pessarakli, 2016). Dabbing the stamen (male) on the stigma (female) is the method used to hand pollinate the female flowers by pollen from male flowers. The pollen can be dusted on receptive stigma by using a paint brush, preferably in the morning for higher fruit setting. Male and female flowers can be identified by their characteristics; male flowers have larger petals and are light in color, while female flowers have a darker yellow flower with 5 simple elliptical petals.

Harvest: The harvest time of Gac fruit differs between countries depending on the desired state of consumption. Fruits reach harvestable maturity 15–20days after pollination if the whole fruit is to be consumed as vegetables as preferred in India and Bangladesh. Beyond this time, the seeds become hard and the skin becomes leathery. The fruit is harvested at a ripe stage for its red aril at 90–110 days and 45–50 days after pollination as preferred in Vietnam and Malaysia, respectively, when the fruit turns soft quickly after harvesting (Osman et al., 2017). The fresh fruit ranged from 390.8g to 1057.8g. A plant produces 30–60 fruits on average in a season.

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Azolla: An Alternative Source for Cattle Feed

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Abstract

The escalating costs associated with traditional high-protein livestock feeds, such as groundnut cake and cotton seed cake, pose a significant financial challenge to the dairy industry. This article proposes the cultivation and integration of Azolla (a nutrient-rich aquatic fern) as a sustainable and cost-effective alternative. Azolla, which contains 25%−35% protein, can directly substitute conventional protein sources, leading to a projected 15%−20% increase in milk yield and a 20%−25% reduction in overall feed expenses. The article outlines the simple, scalable method for Azolla production and provides essential guidelines for successful cultivation and safe integration into livestock diets.

Introduction

The profitability of the dairy industry is heavily influenced by the high cost of quality cattle feed. Conventional protein supplements like groundnut cake and cotton seed cake represent a substantial economic burden for farmers. To mitigate this financial strain, agricultural research has identified Azolla as a potent and locally-producible feed supplement. Azolla is a rapidly growing green fern species that floats on water, containing not only 25% protein in its fresh form but also 10%−15% essential minerals, carotene, and vitamin B_{12} when dried. This high nutritional profile and its low lignin content make it highly digestible for livestock. The subsequent sections detail the tangible benefits of adopting Azolla and provide step-by-step instructions for its cultivation and safe use.

Benefits and Applications of Azolla in Livestock Farming

Azolla serves as a powerful supplement suitable for dairy cattle, sheep, goats, pigs, rabbits, and chickens. Its key advantages include:

- **Milk Production Enhancement**: Daily consumption of 1.5kg to 2kg of fresh Azolla by dairy cattle can result in a 15%−20% improvement in milk yield.
- **Economic Savings:** Farmers can achieve a 20%−25% reduction in feed cost by replacing traditional supplements with Azolla on a pound-for-pound basis.
- **Improved Milk Quality and Income:** The addition of Azolla increases the milk's fat content and Solid-Not-Fat (SNF), which translates into higher returns, potentially adding ₹0.60 to ₹1.50 per liter of milk.
- **Flexible Feeding:** Fresh Azolla can be mixed with regular cattle feed in a 1:1 ratio or fed directly, potentially reducing the use of conventional cattle feed by half.
- **Enhanced Animal Health:** Regular use of Azolla is associated with overall improved livestock health and better milk quality.

Cultivation and Maintenance Protocol

Azolla can be produced cost-effectively using simple bed structures. To produce approximately 4kg of Azolla daily, three beds of 2.25m×1.5m are required.

Azolla Bed Preparation

1. **Preparation:** Level the ground and remove all weeds.
2. **Structure:** Construct a tank (2.25m×1.5m) using bricks set to a 10cm height.
3. **Lining:** Line the pit with plastic bags to prevent root penetration, followed by a 150GSM Silpaulin sheet (2.50m×1.8m).
4. **Soil Base:** Spread 30–35kg of sieved fertile soil evenly over the sheet (10kg per square meter).
5. **Fertilization:** Create a slurry by mixing 4−5kg of 25-day-old cow dung, 16–20liters of water, and 40g of mineral mixture. Pour this mixture into the bed.

6. **Water Level & Inoculation:** Maintain a water level of 7−10cm. Sprinkle 1−1.5kg of fresh mother culture Azolla evenly over the surface and sprinkle with fresh water to help the plants stand upright.

Harvesting and Maintenance

- **Harvesting:** Azolla covers the pit in 7–10 days. The yield from 1kg of initial culture is 8–10kg per week. Harvesting can begin daily from the 7^{th} day.
- **Weekly Maintenance:** Add 1kg of cow dung, 20g of mineral mixture, and 5liters of water as a slurry once per week.
- **Water Management:** Remove one-fourth of the bed's water every 10 days and replace it with fresh water.
- **Soil Renewal:** Remove 5kg of old soil and replace it with 5kg of new soil every 60 days. The entire bed (soil, water, and Azolla) should be fully renewed every six months.

Safety Precautions

- ✓ Avoid direct sunlight or heavy shade; partial shade is ideal.
- ✓ Prevent leaves from falling into the bed, as this can cause the Azolla to rot.
- ✓ Maintain a minimum water level of 5cm evenly throughout the bed.
- ✓ Do not use Azolla as feed if it has been treated with pesticides or is infected with pests or fungus. Infected material must be removed and buried.
- ✓ Harvested Azolla should be washed by placing it in a plastic tray with holes over a bucket, and pouring water over it to remove the cow dung odor before feeding.

Conclusion

Azolla represents a significant opportunity for farmers to enhance dairy productivity while simultaneously tackling the rising costs of protein supplements. Its cultivation is simple, low-cost, and sustainable, offering a high-protein, easily digestible feed source that directly translates into increased milk yield, improved milk quality (higher fat and SNF), and a substantial reduction in overall livestock maintenance costs. By integrating Azolla, farmers can establish a more profitable and environmentally friendly feeding system.

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Vapour pressure deficit: The invisible driver of plant stress

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Abstract

Vapour Pressure Deficit (VPD), defined as the difference between saturation vapour pressure and actual vapour pressure of air, is a key atmospheric variable that directly governs plant water loss, transpiration rate and physiological stress. Although temperature, humidity, radiation and wind are well-known drivers of crop performance, VPD provides a more precise measure of the atmospheric demand for water and has become increasingly important under changing climatic conditions. Rising temperatures and fluctuating humidity levels have contributed to a global trend of atmospheric drying, intensifying VPD and altering crop responses in both open and controlled environments. High VPD accelerates plant dehydration, induces stomatal closure, reduces photosynthesis, impairs reproductive processes and lowers water-use efficiency, ultimately decreasing yield. Conversely, excessively low VPD limits transpiration, inhibits nutrient transport and increases the risk of fungal diseases. Research across multiple crop species shows that maintaining optimal VPD levels enhances gas exchange, biomass accumulation, hydraulic conductance and overall plant performance, especially in greenhouse systems where humidity and temperature can be regulated. As climate variability intensifies, integrating VPD into agricultural decision-making offers a vital pathway toward improving crop resilience, irrigation efficiency and climate-smart farming practices.

Introduction:

The physical state of the atmosphere at a given place and given time is called weather. Weather plays a crucial role in determining the success of agricultural production. The primary weather elements influencing crop growth include temperature, rainfall, solar radiation, wind and relative humidity. In addition to these well-known factors, an often overlooked but equally important variable is the vapour pressure deficit (VPD), which plays a critical role in regulating plant water loss and physiological stress. As climate patterns become increasingly unpredictable and extreme, understanding VPD has become crucial for forecasting crop responses, managing water resources, and supporting resilient agricultural practices. Awareness of VPD's impact enables farmers and scientists to more accurately evaluate plant stress, adjust growing conditions and protect crop productivity under changing environmental conditions.

Vapour pressure deficit (VPD):

The troposphere is known as the weather-making layer of the atmosphere, contains most of the atmospheric water vapour that drives weather processes. Like all gases, water vapour exerts pressure due to its weight per unit area, known as vapour pressure, which represents its partial pressure within the atmosphere. The pressure exerted by the actual amount of water vapour present at a given time is referred to as the actual vapour pressure. When the air holds the maximum possible amount of water vapour at a specific temperature, it becomes saturated, and the corresponding pressure is called the saturated vapour pressure. The quantity of water vapour required to reach saturation increases with rising air temperature. The difference between the saturation vapour pressure (the moisture holding capacity of air) and its actual vapour pressure is termed as vapour pressure deficit (VPD). The evaporation rate is controlled by the vapour pressure deficit. Accumulating evidence indicates that Earth is currently undergoing a global "atmospheric drying" as a result of an increase in atmospheric water vapour pressure deficit (VPD), a phenomenon that is expected to further amplify as climate change intensifies.

Impacts of VPD on plants:

Dehydration of plants:

When VPD is high, the air becomes dry and pulls more water from plant leaves. This rapid water loss increases the risk of dehydration, especially when soil moisture is limited. Studies show that elevated VPD can cause steep increases in transpiration rates, often leading to hydraulic stress as the plant struggles to maintain water supply to leaves and growing tissues. This imbalance between water uptake and water loss is one of the primary pathways through which VPD stresses crops.

Stomatal response:

To prevent excessive water loss under high VPD, plants close their stomata. Although this response reduces transpiration, it also restricts CO_2 entry into leaves, thereby reducing photosynthesis and carbon assimilation. The consequence is lower biomass production and reduced growth. Evidence from physiological studies indicates that high VPD leads to stomatal limitation of photosynthesis across multiple crop species, including maize, wheat and soybean. This makes sustained high VPD a major constraint on crop productivity, even in well-watered conditions.

Effects on reproductive process and yield:

High VPD also affects reproductive development, often leading to reduced flowering, increased flower or fruit drop and impaired pollination. Crops such as tomato, rice and cotton show significant declines in fruit set and yield when exposed to high VPD during flowering periods. The physiological mechanism behind this is linked to stress-induced reductions in pollen viability, stigmatic receptivity and flower retention. Thus, VPD has direct consequences not only on vegetative growth but also on the final yield potential of many crop species.

Impacts on water use efficiency:

When VPD is high, it lowers water-use efficiency (WUE) because plants lose more water per unit of carbon gained. This means that crops require more irrigation to maintain growth under high VPD conditions. Research shows that irrigation models that ignore VPD underestimate crop water requirements, especially during hot, dry periods when VPD spikes. With increasing temperature and VPD under climate change, irrigation scheduling must increasingly account for VPD rather than relying solely on soil moisture or temperature indicators.

Low VPD conditions and disease susceptibility:

While high VPD creates drought-like stress, very low VPD can also negatively affect crops. Low VPD reduces transpiration, limiting nutrient transport from roots to leaves. This may result in nutrient deficiencies, reduced leaf expansion and delayed growth. Additionally, low VPD increases humidity levels in the canopy, favouring fungal diseases such as powdery mildew and Botrytis in many horticultural crops. Thus, both extremes of VPD are harmful, making optimal VPD management essential in controlled environments such as greenhouses.

VPD in open environment:

In open field conditions, Vapour Pressure Deficit (VPD) is controlled entirely by natural weather variables such as temperature, relative humidity, wind and solar radiation. These factors change continuously throughout the day and across seasons, which causes VPD to fluctuate widely. High solar heating and strong winds increase VPD by warming the air and removing the moist boundary layer around leaves. Under these conditions, plants experience higher evaporative demand, faster transpiration and greater water stress, especially during hot and dry weather. Such high VPD events often restrict stomatal opening, reduce photosynthesis and lower crop productivity, and these effects are widely reported in field based studies. Since open environments cannot be regulated, crops are more vulnerable to extreme VPD that occur during heat waves and dry winds.

VPD in controlled conditions:

In controlled environments such as greenhouses and plant growth chambers, temperature and humidity can be adjusted using ventilation, shading, fogging, misting and heating systems. This allows growers to maintain VPD within an optimal physiological range for plant growth. Research shows that moderate VPD values encourage balanced transpiration, efficient nutrient transport and improved biomass accumulation, while preventing excessive plant stress and reproductive losses. Controlled environments offer a major advantage over open fields by providing stable VPD conditions that support higher growth rates. However, very low VPD can sometimes occur due to excessive humidity inside enclosed structures, and this may reduce transpiration and increase disease risk, so careful humidity management remains essential. The effects of VPD on plant growth in controlled conditions are described in table 1.

Table 1: Effects of VPD regulation on plant growth in controlled environmental conditions.

Species	Growth condition	Effects	Citation
Solanum lycopersicum cv. Diten (Tomato)	Greenhouse with VPD ranging from 4 to 5 kPa and fogging system reducing VPD to 1 to 2 kPa	Increase in leaf gas exchange Improvement in plant hydraulic conductance Reduction in crop water stress changes in plant morphology including leaf area ratio and crop growth rate	Zhang *et al.*, 2017
Solanum lycopersicum cv. Alina (Tomato)	Greenhouse at 34 to 35°C, relative humidity about 68 percent, VPD around 1.75 kPa	Increase in leaf length, plant height and stem diameter. Changes in stomatal traits including density, length and index. Increase in leaf gas exchange	Zhang *et al.*, 2015
Celtis occidentalis (common hackberry)	Growth chambers with temperature between 25 and 30°C and VPD between 0.66 and 1.74 kPa under well watered and low water conditions	Changes in leaf gas exchange. Adjustment of xylem water potential under different VPD levels	Will *et al.*, 2013
Cucumis sativus (cucumber)	Growth chambers at 22°C with controlled humidity using dehumidifiers	Increase in dry matter production, leaf area and relative growth rate. Transpiration rate influenced by VPD	Matsuo *et al.*, 2015
Zea mays var. rugose (Sweet corn)	Growth chambers at 22°C with humidity control producing different VPD levels	Changes in water use efficiency, carbon dioxide assimilation and transpiration coefficient. Biomass of leaves, stems and roots affected by VPD	Ben-Asher *et al.*, 2013
Glycine max (soyabean)	Greenhouse at 22 to 32 °C with VPD between 1 and 3 kPa using cooling coil system	Increase in gas exchange including transpiration and net carbon exchange	Fletcher *et al.*, 2007
Arabidopsis thaliana (Thale cress)	Growth chambers at 22°C with relative humidity at 60 and 92 percent producing different VPD levels	Changes in stomatal aperture and length. Influence on water use efficiency. Variation in leaf transpiration observed using infrared imaging	Arve *et al.*, 2017
Vicia faba cv. Longpod (Broad bean or faba bean)	Growth chambers with relative humidity at 55 and 90 percent forming VPD 1.05 and 0.23 kPa	Changes in stomatal conductance, transpiration rate, relative water content and specific leaf area. Variation in chlorophyll fluorescence and stomatal morphology. Changes in abscisic acid content	Aliniaeifard *et al.*, 2014

Optimum Vapour Pressure Deficit (VPD) range:

For most plants, the optimal vapour pressure deficit range is thought to be between 0.4 and 1.6 kPa. This, of course, varies between plants. For different stages of development, each plant has its own favourable conditions. During the later stages, VPD should be on the higher side of the optimal range.

Factors affecting Vapour Pressure Deficit (VPD):

Air temperature

Air temperature is the primary driver of VPD because warmer air can hold more water vapour. As temperature increases, the saturation vapour pressure rises exponentially, which increases the difference between actual and saturation vapour pressure. Even if the amount of moisture in the air remains constant, higher temperatures will increase VPD. This means hotter conditions generally create stronger drying power of the air and greater evaporative demand on plants.

Relative Humidity

Relative humidity directly determines the amount of moisture already present in the air. When relative humidity is high, the actual vapour pressure approaches saturation vapour pressure, resulting in low VPD. Conversely, dry air with low relative humidity has a lower actual vapour pressure, which increases VPD. Thus, VPD is always inversely related to relative humidity.

Leaf Temperature

VPD at the leaf surface depends not only on the surrounding air but also on the temperature of the leaf itself. If the leaf becomes warmer than the ambient air due to sunlight or reduced transpiration, its boundary layer will contain more water vapour. This increases the difference between leaf vapour pressure and atmospheric vapour pressure, raising leaf-to-air VPD and intensifying plant water loss.

Soil Moisture Availability

Soil moisture indirectly influences VPD by affecting transpiration and leaf cooling. When soil moisture is adequate, plants maintain transpiration, which cools leaves and lowers leaf temperature and therefore VPD. Under drought, transpiration declines, leaf temperature rises, and VPD at the leaf surface increases. This creates a feedback loop that intensifies plant stress.

Air Movement and Wind Speed

Wind reduces the thickness of the leaf boundary layer, allowing water vapour to diffuse more rapidly away from the leaf surface. This increases the effective VPD experienced by the plant. Strong air movement therefore enhances evaporative demand, while still air creates a thicker boundary layer and temporarily reduces VPD around the leaf surface.

Atmospheric Pressure and Altitude

Altitude influences the saturation vapour pressure because lower atmospheric pressure reduces the air's capacity to hold moisture. At high altitudes, even with the same temperature, the saturation vapour pressure is lower. This modifies the relationship between temperature, humidity and VPD, often resulting in unique evaporative conditions in mountainous regions.

Canopy Structure and Plant Density

Dense canopies create their own microclimate by trapping moisture and reducing air movement. This decreases VPD within the canopy, even when VPD outside the crop is high. In contrast, open canopies or sparse plant stands have higher internal air flow and lower humidity, which increases VPD at the leaf surface.

Conclusion

Vapour Pressure Deficit (VPD) has emerged as one of the most critical yet often overlooked determinants of crop growth, water use and stress physiology. While traditional weather variables such as temperature, rainfall, humidity and radiation are well recognised, VPD provides a more direct measure of the atmospheric demand for water and therefore offers a clearer understanding of plant environment interactions. As climate change intensifies temperature extremes, alters humidity patterns and increases the frequency of droughts, VPD is becoming an essential indicator for predicting crop performance and managing agricultural systems. Overall, incorporating VPD into crop management frameworks represents a major step forward in developing resilient, resource-efficient and climate-smart agriculture. By recognising VPD as a key link between weather and plant physiology, we can better safeguard crop health and ensure sustainable food production in a rapidly changing climate.

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Effective Strategies for Managing Ginger Rhizome Rot Disease

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Ginger is a widely cultivated spice known for its medicinal and culinary uses. However, its production is often hampered by various diseases, among which Rhizome Rot Disease poses a significant threat. This disease causes rotting of the ginger rhizomes, leading to reduced yield and quality. To effectively combat this problem, an integrated disease management (IDM) approach is essential.


Symptom

- Softening of the rhizome tissue, often accompanied by a water-soaked appearance.
- Discoloration of the affected tissue, turning brown or black.
- Presence of rot or decay on the surface of the rhizome, often emitting foul odor.
- Soft, mushy, and disintegrated tissue when cut open.
- Presence of fungal or bacterial growth, sometimes visible as mold or bacterial ooze.

1. Cultural Practices

Use Disease-Free Planting Material: Select healthy, disease-free ginger rhizomes from certified sources to prevent initial inoculums.

Crop Rotation: Avoid planting ginger in the same field year after year. Rotate with non-host crops like maize, legumes, or other suitable crops to break the disease cycle.

Field Sanitation: Remove and destroy infected plant debris and volunteer plants to reduce pathogen inoculums.

Proper Planting Practices: Ensure well-drained soil to prevent water logging, which favors pathogen development. Space plants adequately to promote air circulation.

Flooding: In some cases, intermittent flooding can help suppress soil-borne pathogens.

2. Biological Control

Use of Antagonistic Microorganisms: Application of beneficial microbes like *Trichoderma harzianum, Pseudomonas fluorescens*., or *Bacillus* spp. can suppress pathogenic fungi.

Use biocontrol agents like Trichoderma harzianum or Pseudomonas fluorescens to suppress pathogen growth.

Organic Amendments: Incorporate organic matter such as compost or neem cake to enhance soil health and suppress disease.

3. Chemical Control

Seed Treatment: Treat rhizomes with fungicides such as carbendazim or thiram before planting.

Soil Drenching: Apply fungicides around the root zone during crop growth if necessary, following recommended doses and safety guidelines.

Integrated Use: Combine chemical treatments with other practices to reduce chemical dependency.

Conclusion

An integrated approach combining healthy planting materials, cultural practices, biological control, and judicious use of chemicals offers the best defense against Ginger Rhizome Rot Disease. Farmers adopting these strategies can significantly reduce disease incidence, leading to healthier crops and better yields.

Principles and Benefits of Vertical Garden

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Abstract

Urbanization and limited space have given rise to innovative methods of cultivation such as vertical gardening. It involves growing plants in vertically stacked layers or structures, often integrated into walls, fences, or other upright surfaces. Vertical gardening not only enhances the aesthetic appeal of urban environments but also contributes to air purification, temperature regulation, and efficient use of resources. This article explores the concept, types, techniques, advantages, and applications of vertical gardening, along with its environmental and economic importance in sustainable urban agriculture.

Keywords: Vertical Garden, Concepts, Principles, Types and Benefits.

Introduction

With the rapid pace of urbanization, cities are facing the dual challenges of limited space and deteriorating air quality. Traditional horizontal gardening methods require vast areas of land, which are increasingly unavailable in urban settings. To overcome this issue, vertical gardening also known as green walls or living walls—has emerged as an effective and sustainable solution. This technique enables plant cultivation on vertical surfaces, transforming unused walls into green spaces. Vertical gardening is not only a decorative practice but also a practical way to promote environmental balance and improve human well-being. It integrates art, architecture, and horticulture to create eco-friendly urban landscapes.

1. Concept and Principles of Vertical Gardening

Vertical gardening involves growing plants in vertically stacked arrangements or along vertical supports. These systems can be freestanding or attached to existing structures like walls and fences. The main principle behind vertical gardening is space optimization and sustainable resource use. A vertical garden typically consists of a support structure, growing medium, irrigation system, and drainage system. Plant selection plays a vital role in the success of a vertical garden. Shade-tolerant and lightweight plants such as ferns, money plants, spider plants, and herbs are ideal.

2. Types of Vertical Gardens

1. Green Façades
2. Living/Green Wall
    - i Wall-Climbing Green Wall
    - ii Hanging-Down Green Wall
    - iii Green Wall Modular
    - iv Vegetated Mat Wall

1. Green Facades:

Green facades are a type of green wall system in which climbing plants or cascading ground covers are trained to cover specially designed supporting structures. Plants are either grown in the ground or in the elevated containers where they are watered and fertilized.

Figure: 1 Green Facades

2. Living Wall/Green Walls

Living wall system composed of pre-vegetated panels, vertical modules or planted blankets that are fixed vertically to a structural wall or frame.

Figure: 2 Living Wall/Green Walls

i. Wall-Climbing Green Wall

It is intense process climbing plants can cover the walls of building naturally.

Figure: 3 Wall-Climbing Green Wall

ii. Hanging-Down Green Wall

It can easily form a complete vertical green belt on a multi-story building through planting at every story compare to the wall-climbing type.

Figure: 4 Hanging-Down Green Wall

iii. Green Wall Modular

It provides instant solution for making garden in your residing place It has attractive look, highly durable in nature and it can be easily.

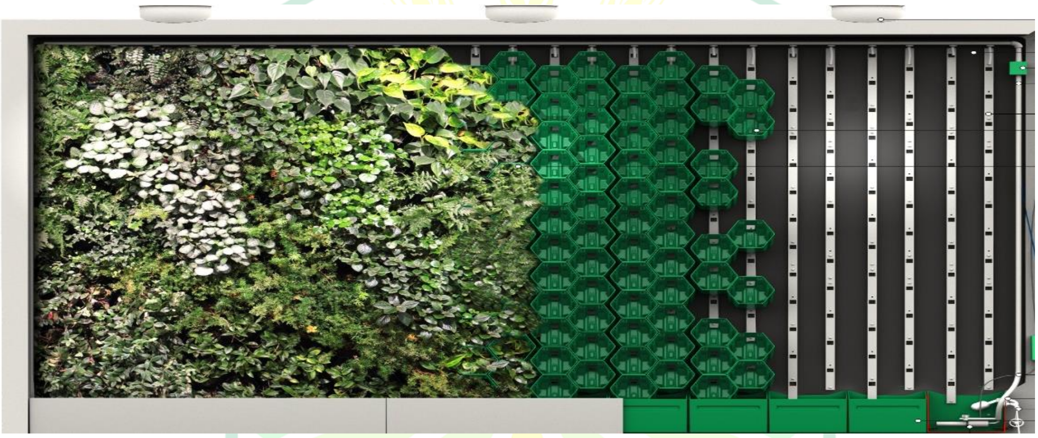

Figure: 5 Green Wall Modular

iv. Vegetated Mat Wall

This system, pioneered by Patrick Blanc, is composed of two layers of synthetic fabric with pockets filled with the plants and growing media. The fabric walls are supported on a frame work and backed by a waterproof membrane against the building wall.

Figure: 6 Vegetated Mat Wall

3. Techniques and Materials Used

The success of a vertical garden depends on the technique used. Common methods include hydroponics, aeroponics, and soil-based systems. Essential materials include lightweight growing media, drip irrigation kits, vertical frames, and sensors for moisturand nutrient monitoring.

4. Benefits of Vertical Gardening

Vertical gardening offers numerous environmental, economic, and social benefits such as space efficiency, air purification, temperature regulation, noise reduction, and aesthetic appeal. It also allows urban residents to grow vegetables and herbs at home and contributes to mental well-being and biodiversity.

5. Challenges and Maintenance

Despite its benefits, vertical gardening poses challenges such as high initial setup cost, regular maintenance requirements, structural issues, and limited plant choices for extreme weather conditions. However, with proper design and automation, these challenges can be minimized.

6. Applications and Future Prospects

Vertical gardening is increasingly being adopted in urban homes, commercial buildings, public infrastructure, and campuses. With advancements in hydroponic and sensor-based technologies, the future of vertical gardening looks promising as an essential component of smart and sustainable cities.

7. Conclusion

Vertical gardening represents a harmony between modern urban living and environmental sustainability. It effectively transforms unused walls into productive green spaces while conserving resources. As urbanization continues, vertical gardens will play a significant role in promoting food security, improving air quality, and enhancing urban aesthetic

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Assessment of Soil Fertility Status Using GIS and Remote Sensing Techniques for Precision Agriculture

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1. Introduction

Agricultural land use relies heavily on soil fertility for optimal production of plants and crop yields. The use of fertilizer applications historically has been based upon a composite sample taken across an entire field (the field) that represents an overall or average nutritional status of that field. An application of fertilizer is then made uniformly across the field. This method is very easy to implement; however, it completely neglects the inherent heterogeneity found in agricultural fields. These differences include variations in field topography, parent materials, past management techniques and past crops grown. As a result, there will be significant variation in the levels of some of the most critical indicators of soil fertility (e.g., pH, SOM, NPK).

Precision agriculture (PA), reconciles this paradox, by providing the "right" inputs in the "right" quantities; delivered in the "right" place; at the "right" time. For PA to be successful, it requires a spatial dataset that is both highly accurate and highly resolved. It is here that the integration of remote sensing (RS) with geographic information systems (GIS) can provide the necessary tools to obtain large datasets quickly; and to utilize a spatial analytical tool set to collect, analyze and present the spatial data to support decision making. This article reviews the methods used to evaluate spatial levels of soil fertility using these integrated technologies.

2. The Imperative of Spatial Soil Fertility Assessment

Based on what we discussed during lecture, soil fertility is not a fixed property, but rather a constantly evolving property in both time and space. The big three macro-nutrients (N, P, K), the secondary actors (Ca, Mg, S), and the microns that we do need to pay attention to (such as Zn, Fe, B) are the primary determinants of it. Next is the response of the soil (pH), the extent of organic matter that is in it (SOM) and the electric conductivity (EC) that indicates the amount of dissolved salts present.

These spatial variations in these values actually strike crop yield due to the Law of the Minimum: the increase in yield can only be as great as the increase in the scarcest nutrient. As an example, the phosphorus in a field may not be able to be absorbed by plants because even though the overall phosphorus level in the field is decent, there may be some areas with low pH. These areas of constraint are lost in the mean numbers unless a fine spatial evaluation is performed.

3. Remote Sensing Applications in Soil Analysis

The whole idea of remote sensing is to seize information on the surface of the Earth, but not to touch it, typically by detecting reflected or emitted light in various parts of the light spectrum. In the case of soil fertility, RS tends to operate in two fashions where by one either looks at the soil directly, or assumes information based on the plants that require the soil.

3.1 Direct Soil Observation

The physical and chemical makeup of a bare soil is much to be determined by the manner in which it reflects light. When the sun is exposed to the soil, not all the wavelengths are absorbed and others are reflected.

a) **Soil Organic Matter (SOM):** Generally, soils with a higher organic matter appear darker and are less reflective in the visible and near-infrared (NIR) regions of the spectrum.

b) **Soil Moisture:** As with SOM, increased moisture is likely to reduce the reflectance of the soil.

c) **Soil Texture and Iron Oxides:** Clay and iron oxides and their presence bring about certain characteristics of absorption that we can see using hyperspectral sensors.

By this, however, we are typically restricted by the vegetation covering the ground and any remnants of the crop, thus direct observation is most effective when the area is fallow or when we are about to plant it.

3.2 Indirect Assessment

In most cases RS determines the soil fertility through observation of the state of crops. The spectral signature will be a healthy crop with sufficient nutrients: low reflectance in the visible red (due to the chlorophyll absorbing that light) and high reflectance in the NIR (due to the scattering light off the leaf structure).

By calculating Vegetation Indices (VIs) such as the Normalized Difference Vegetation Index (NDVI) the researchers can make guesses as to what the soil is actually doing under the plants. The low NDVI of a crop is likely to indicate that the crop is lacking nitrogen or is otherwise stressed in that area.

Courtsy: Shutterstock

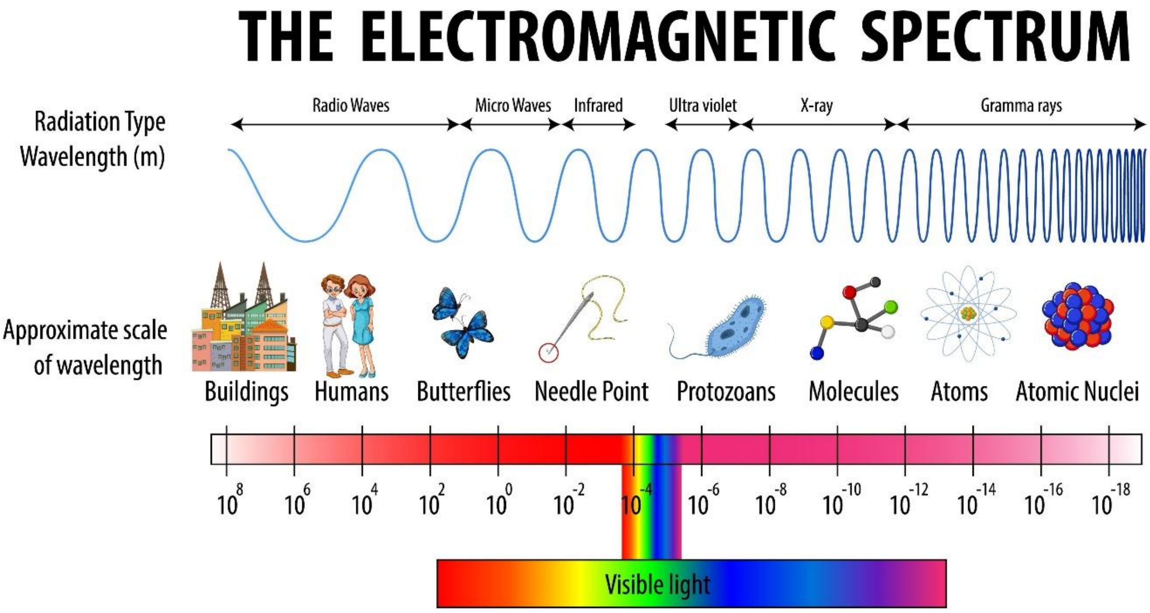

Figure 4. Generalized spectral reflectance curves illustrating the difference between healthy vegetation (high NIR, low red reflectance) and bare soil, which shows a more linear increase in reflectance. Variations in soil composition shift the soil curve vertical

In modern RS, a combination of tools, including freely available satellite data (such as Sentinel 2 and Landsat 8), which might be used to map time-consuming areas, to expensive high-resolution satellites, and even drones (UAVs) with multispectral cameras that can be used to study the farm on an incredibly local level.

4. Geographic Information Systems (GIS): The Analytical Engine

Remote sensing provides user with raw images but GIS provides processing power. GIS is a computer platform that is aimed at gathering, storing, editing, analysing, managing, and visualizing geographical information. GIS is the centre in which all the various layers of information combine in soil fertility work.

4.1 Data Integration and Management

A GIS allows user to overlay a collection of data that determines the fertility of the soil. When we have a common precision-ag project user might have the following layers:

- Digital Elevation Models (DEM) to determine the topography and slope, which influence the movement and runoff of water and nutrients.
- Soil type maps from legacy surveys.
- Remote sensing imagery (e.g., NDVI maps over several seasons).
- Previous yield monitor information.
- Point data from geo-referenced soil sampling.

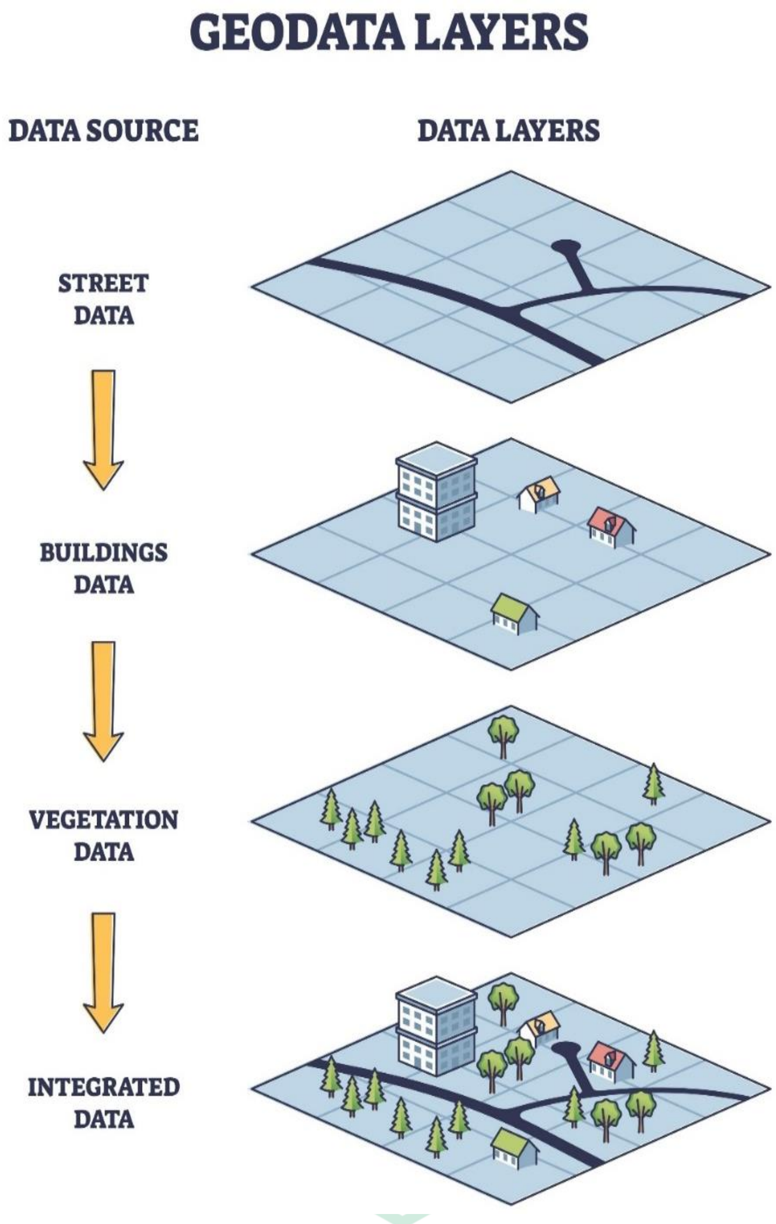

Figure 5. The GIS Layering Concept. Data from various sources satellite imagery, soil samples, topography, and yield data are stacked geographically to reveal relationships and patterns influencing soil fertility. (Source: Shutterstock)

4.2. Geostatistics and Interpolation

The primary contribution of GIS to the fertility analysis is the fact that discrete point data, which consists of soil samples collected at particular locations, becomes smoothed and continuous surfaces (maps). It is simply not feasible to sample out each square meter. This is why we apply geostatistical interpolation.

Other methods like Kriging or Inverse Distance Weighting (IDW) are used to estimate quantities at unmeasured points using the local known ones. The reason why kriging is particularly helpful is that it takes into consideration the spatial aspect of autocorrelation: similarity between soil properties located closer together than the ones located more distant. The final product is a raster map of each nutrient concentration.

5. Integrated Methodology for Fertility Assessment

Table 6. A Structured Workflow for GIS and RS-Based Soil Fertility Assessment

Phase	Step	Description	Technology Involved
1. Planning	Preliminary Survey	Collection of boundary data, historical cropping records, and existing maps.	GPS
	Sampling Design	Designing a geo-referenced sampling scheme (grid-based or zone-based) to ensure representative coverage.	GIS
2. Data Acquisition	Soil Sampling	Physical collection of soil samples at pre-determined GPS coordinates.	GPS, Field Tools
	Remote Sensing	Acquisition of satellite or UAV imagery (preferably multi-temporal).	Satellite/UAV Sensors
	Ancillary Data	Obtaining DEMs, yield data, etc.	Various Sources
3. Laboratory Analysis	Chemical Analysis	Analyzing soil samples for pH, EC, OC, N, P, K, and micronutrients using standard protocols.	Soil Testing Lab
4. Geospatial Analysis	Data Processing	Pre-processing RS imagery (atmospheric correction) and organizing lab data into databases.	Image Processing Software
	Spatial Interpolation	Using geostatistical models (e.g., Kriging) to create continuous maps from soil sample points.	GIS (Geostatistical Analyst)
	Data Integration	Overlaying interpolated soil maps with RS indices (NDVI) and topography to identify correlations.	GIS
5. Output & Application	Map Generation	Creating thematic fertility maps showing spatial distribution of nutrients.	GIS
	Zonation	Delineating Management Zones comprising areas with similar fertility characteristics.	GIS (Clustering Algorithms)
	VRA Prescription	Generating prescription maps for Variable Rate Application equipment.	Farm Management Software

6. Moving from Maps to Management Zones

The actual purpose of mapping spatial fertility is not merely to make a map beautiful but to cut out actionable Management Zones (MZs). MZs are minor sub-units of a field with relatively homogeneous combinations of yield-limiting factors and need management in the same way.

Instead of managing a 50-hectare field as one unit, GIS analysis might reveal three distinct zones:

- **a) Zone A:** Large native fertility, large historical productivity. Strategy: Maintenance fertilizer.
- **b) Zone B:** Moderate fertility, pH limitation. Strategy: Lime application and moderate fertilizer rates.
- **c) Zone C:** infertile, sandy, low water-holding capacity. Strategy: Reduce the target yield and reduce input in order to maximise ROI.

These areas form the basis of Variable Rate Technology (VRT) whereby based on the GPS position of the tractor in relation to the GIS prescription map, smart spreaders are capable of adjusting the quantity of fertiliser (or lime) on a case-by-case basis.

Table 7. Comparison of Conventional vs. GIS/RS-Based Precision Approach

Feature	Conventional Agriculture	Precision Agriculture (GIS/RS Based)
Sampling Method	Composite sampling (random or zig-zag) providing one average value.	Grid or Zone sampling providing spatially referenced data points.
Data Resolution	Field-level average (low spatial resolution).	High spatial resolution, mapping variability within the field.
Input Application	Uniform, blanket application based on average needs.	Variable Rate Application (VRA) matched to local soil needs.
Efficiency	Low. Over-application in high-fertility areas; under-application in low-fertility areas.	High. Inputs go only where needed, optimizing crop response.
Environmental Impact	Higher risk of nutrient runoff and leaching from over-fertilized zones.	Reduced risk. Targeted application minimizes excess nutrients in the environment.
Economic Model	Focus on maximizing gross yield across the whole area.	Focus on maximizing profit per unit area (optimizing ROI).

7. Challenges and Future Directions

7.1. Limitations and Challenges

a) **Cost and Complexity:** It is prohibitively expensive to the small-holder farmers in the form of high-resolution imagery, specialised software and the technical expertise required.

b) **Ground Truthing Dependency:** Remote sensing is difficult to use unilaterally in regards to soil fertility. It primarily identifies spectral stand-ins (such as crop colour). A lot of soil sampling is required to calibrate RS data and confirm geostatistical models.

c) **Temporal Variability:** A soil-fertility map is simply a snapshot. Nutrient concentrations, notably, nitrogen, change rapidly depending on weather and uptake of crops.

7.2. Future Directions

a) **Hyperspectral Sensing:** Compared to multispectral sensors, which operate over 4-10 broad bands, hyperspectral sensors emit hundreds of narrow bands, and it allows us to identify particular biochemical imprints in the soil depending on the finesse absorption trends.

b) **Proximal Soil Sensing:** Tractor mounted real time sensors that look at EC, pH, or NIR reflectance at any point in the field are now becoming common, reducing the amount of lab work required.

c) **Machine Learning (ML) Integration:** ML algorithms are beginning to enter GIS to sort through large numbers of data (weather, multi-year satellite data, past yield) and forecast soil-fertility patterns more accurately than pure geostatistics.

8. Conclusion

The analysis of the soil fertility situation through the GIS and Remote Sensing methods is a breakthrough in the contemporary agronomy. These techs enable us to view the actual spatial variations within the farmland by abandoning the old field-average model. To map, monitor, and control nutrients at a pixel-level implies that we are now able to actually apply Precision Agriculture and perform Variable Rate Application as opposed to merely spraying all the things.

Certainly, the financial and technological sophistication still sting. However, the trend is obvious, there is a declining price of sensors, an increased ease of software, and it will not take long before spatial fertility assessment is considered normal. This focus is critical to increasing on-farm profits by reducing input waste, and also to facing the vast international demand of sustainable farming by reducing that ugly footprint of fertilizers.

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Impact of Climate Change on Soil Physico-Chemical Properties and Agricultural Sustainability

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1. Introduction

The soil health is completely related to the sustainability of world agriculture. Soil is not merely dirt; it is a kind of living ecosystem, which recycles nutrients, filters water, and stores carbon. And when we disregard that over the time-periods with which we are concerned, we are really wasting a non-renewable resource.

The current climate change is the ultimate multiplier to soil degradation. Agricultural ecosystems continue to be extremely vulnerable as claimed by the IPCC. It is a two-way street: climate over geologic time changed soil, but at present climate is changing so rapidly that processes in soil are unable to keep up. Besides, whatever we do to the soil is actually returning to the climate through GHG fluxes.

It is important to know how climate change is playing around with the physical and chemical characteristics of soil in order to create resilient farms. The thing is: it is not a choice but a necessity of the future food security, proactive soil management.

2. Primary Climatic Drivers Affecting the Edaphic Environment

While atmospheric carbon dioxide (CO_2) enrichment directly affects plant physiology, the primary climatic drivers influencing soil properties physically and chemically are:

a) **Elevated Temperature:** Increases surface and subsurface temperature, accelerates reactions, microbes and evapotranspiration.

b) **Altered Precipitation Patterns:** Alters in the total precipitation, intensity and seasonality, that is, more drought and more flood.

c) **Extreme Weather Events:** More intense storms of a high frequency devastate soil surface energy structures.

3. Impact on Soil Physical Properties

These properties determine the mechanical behaviour of soil, water and air behaviour of the soil. Kinetic energy of water and heat is enormous determiners.

3.1 Soil Structure and Aggregation

Soil structure the arrangement of soil particles into aggregates is central to pore space distribution, root penetration, and aeration.

- **Intense Precipitation:** Agglut fracture of aggregates due to kinetic energy deposited on the surface resulting in slaking. The small particles block pores, coat the surface, slow down infiltration, and increase runoff and erosion.
- **Drought Conditions:** Extensive dry periods reduce the size of some clay lattices (Vertisols). A little cracking is good to allow the water to infiltrate as the soil again gets rained, and excessive drying causes the soil to become too hard resulting in tilling that is hard and the roots are constrained.

3.2 Soil Water Dynamics

- **Reduced Water Holding Capacity (WHC):** Heat increases evapotranspiration; unless it is replenished by rain, water moisture is lost quickly, and deteriorated structure closes off macropores, thus the soil becomes unable to hold plant-available water.
- **Waterlogging and Anaerobiosis:** Intensive rains flood the drainage, kill aerobic root respiration, and increase denitrifying bacteria, which expel nitrous oxide (N_2O) which is a gaseous of high emission.

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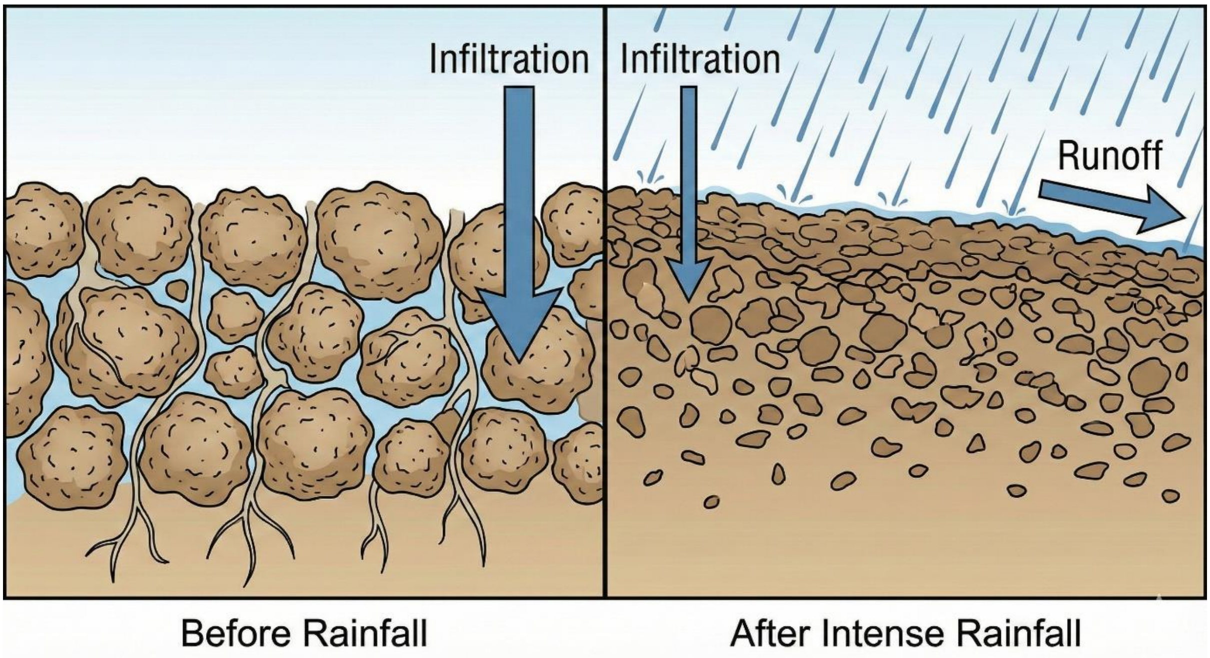

Figure 6. Conceptual diagram illustrating the impact of high-intensity rainfall raindrops hitting soil aggregates, causing disintegration (slaking) and subsequent surface sealing, which reduces water infiltration

3.3 Soil Texture

While soil texture is generally considered a stable property over human timescales, climate change-induced erosion can alter topsoil texture selectively. Intense rainfall events preferentially transport finer particles (silt and clay) and organic matter downslope, leaving coarser, less fertile material behind in the upper horizons.

4. Impact on Soil Chemical Properties

The chemical environment of the soil dictates nutrient bioavailability and toxic element mobility. Temperature and moisture are master variables controlling these chemical and bio-chemical processes.

4.1 Soil Organic Carbon (SOC) Dynamics

The main measure of soil health is the SOC, balancing structure and nutrients. Climate forces the balance of carbon inputs (litter, root exudates) and outputs (microbial burn-down).

- **The Temperature Effect:** According to Arrhenius kinetics, hotter the temperature, the faster the enzymes increase; therefore, microbes can chew SOM at a quicker rate emitting CO_2 and in turn, there is a loop of feedback, which further warms the planet.
- **The Moisture Effect:** Microbes require water, excessively wet (anaerobic) depersonalizes them, excessively dry halts them as well. The largest SOC losses occur in zones that become both warmer and retain sufficient moisture permafrost thaw zones, and warming temperate locations.

4.2 Soil pH and Salinization

Changes in hydrology directly impact soil reaction (pH) and salt concentrations.

- **Acidification:** During the heavy rains in moist areas, the basic cations (Ca, Mg, K, Na) are washed away, reducing the base saturation and acidifying the soil. These fractures open toxic elements such as Al and Mn leaving them easier to plant tissues.
- **Salinization:** The drier the place, the higher the amount of evaporation is. That draws salty groundwater up, spills to the surface, evaporates and the salts accumulate forming osmotic stress, sodicity and deteriorating structure. Besides, the rising of the sea level transports the saltwater to the inland areas.

4.3 Nutrient Cycling and Bioavailability

Climate regulates the biogeochemical cycles of major plant nutrients like Nitrogen (N) and Phosphorus (P).

- **Nitrogen Mineralization:** Warming has an accelerating effect on the rate at which microbes convert organic N to plant-available forms. That works well in the short term, but when crops fail to absorb it at a rate that matches that of the crop, it may be washed away in water or be fixed in GHGs.
- **Phosphorus Availability:** P depends on the pH. It is bound by acidification to iron and alumina phosphates, such that when the total P is large, the plants are unable to access it.

Table 8. Matrix of Climatic Drivers and their Impact on Key Soil Chemical Properties

Climatic Driver	Soil Property Affected	Primary Mechanism	Consequence for Agriculture
Increased Temperature	Soil Organic Carbon (SOC)	Accelerated microbial respiration (decomposition).	Net loss of SOC; reduced fertility and water holding capacity.
	Nitrogen (N) Availability	Increased rate of N mineralization.	Potential short-term N boost, but high risk of nitrate leaching if not synchronized with crop uptake.
Increased Precipitation / Intensity	Soil pH (Humid Regions)	Leaching of basic cations (Ca^{2+}, Mg^{2+}, K^{+}).	Soil acidification; aluminium toxicity risk.
	Nutrient Status (General)	Physical removal of nutrients via runoff and deep leaching.	Nutrient depletion; increased fertilizer requirement; eutrophication downstream.
	Redox Potential (Waterlogging)	Anaerobic conditions promoting denitrification.	Loss of plant-available N; increased emissions of N_2O (greenhouse gas).
Decreased Precipitation / High Evaporation	Soil Salinity (Arid Regions)	Capillary rise of saline groundwater and surface evaporation.	Osmotic stress on crops; ion toxicity; soil structure degradation (sodicity).

5. The Nexus: Soil Health and Agricultural Sustainability

The degradation of soil physico-chemical properties under climate change is not an isolated environmental concern but a direct threat to the pillars of agricultural sustainability: productivity, economic viability, and environmental soundness.

5.1 Yield Penalties and Food Security: Soil unable to retain water loses nutrients and roots can no longer grow through it and this results in huge yield gaps. Plants on eroded soil are less resistant to climatic shocks. An example is a low SOC and bad soil structure will also attain permanent wilting point much quicker than a healthy one in case of drought event. That is a true threat to world food security particularly in the developing nations relying on rainfed agriculture.

5.2 Economic Implications When soil is degraded this implies that farmers will incur additional costs in inputs. The loss of natural fertility causes the increased utilization of synthetic fertilizers to maintain the yields and the increase of the amounts of energy-intensive tillage operations to prepare seedbeds. Besides, erosion will forever destroy the top soil, the hottest land capital, and this will reduce land value with time.

5.3 Ecosystem Service Disruption Other than food, agricultural soils also offer important ecosystem services. Poor quality soils do not absorb as well the pollutants of water and cannot control its floods as well and may even transform to net carbon sources. That is a risky feedback in the global climatic system.

6. Mitigation and Adaptation Strategies: Building Soil Resilience

The agri-systems must change with climate smart soil practices since the climate change is intractable. The objectives of these are to reduce GHG emissions and increase the resilience of the soil to climate stress. The main premise is the protection and improvement of Soil Organic Carbon (SOC).

6.1 Conservation Agriculture (CA)

CA is based on three principles: minimum soil disturbance (no-till or reduced till), permanent soil organic cover (crop residues or cover crops), and species diversification (rotations).

- **Mechanism:** Reduced tilling preserves soil aggregates and inhibits the oxidation of SOC. The retention of residues evenly the soil temperature, minimizes the evaporation process, and also protects the surface against the impact of rainfall, which reduces crusting and erosion.

6.2 Integrated Nutrient Management (INM) and Organic Amendments

Moving beyond sole reliance on synthetic fertilizers to include organic sources like manure, compost, and biosolids.

- **Mechanism:** Organic amendments increase the amount of carbon directly, enhance the stabilization of aggregates and enhance the water-holding capacity. They also increase the biomass of the microbes which are critical in the cycle of nutrients.

6.3 Biochar Application

Biochar is a stable, carbon-rich product of biomass pyrolysis (heating in low oxygen).

- **Mechanism:** Long-term carbon sequestration is provided by its great resistance to decomposition. Its porous nature enhances aeration and water retention and its big surface area and charge density have the potential to improve cation-exchange capacity (CEC) trapping nutrients and buffering acidification.

6.4 Agroforestry and Perennial Systems

Integrating trees into agricultural landscapes.

- **Mechanism:** Deep roots fix the soil layers and reach deep nutrient pools. Leaf litter adds a lot to SOC. The canopy reduces temperatures of the microclimate and decreases the surface temperatures on soil and the evaporation.

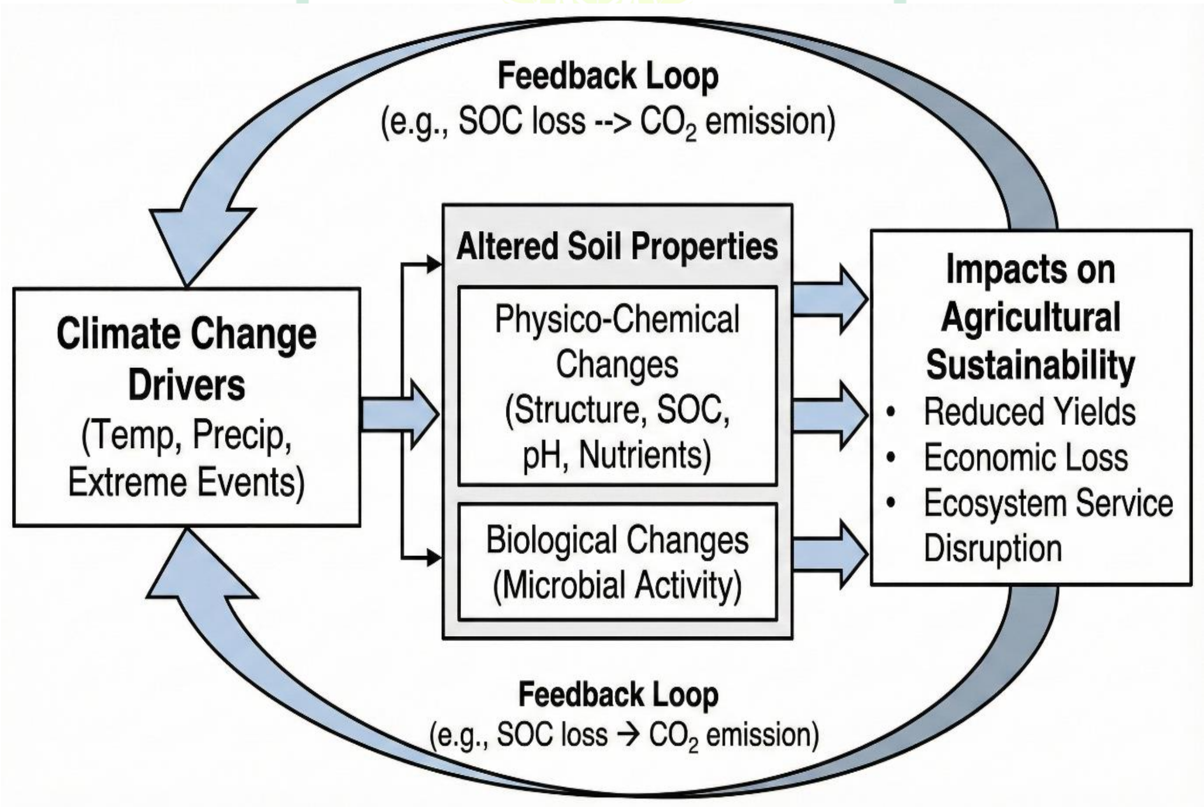

Figure 7. Conceptual framework illustrating the feedback loops between climate change drivers, alterations in soil physico-chemical properties, and the subsequent impacts on agricultural sustainability and ecosystem services.

Table 9. Adaptation Strategies for Enhancing Soil Resilience to Climate Change

Adaptation Strategy	Primary Target Soil Property Improvement	Secondary Benefits
Conservation Tillage (No-Till/Strip-Till)	**Physical:** Improved structure, reduced erosion, increased water infiltration.	**Chemical:** Slower SOC oxidation; **Economic:** Reduced fuel/labour costs.
Cover Cropping/Residue Management	**Physical/Hydrological:** Increased surface protection, reduced evaporation, better aggregation from root exudates.	**Chemical:** Addition of biomass Carbon; Nitrogen fixation (if legumes used).
Organic Amendments (Compost/Manure)	**Chemical/Biological:** Increased SOC, enhanced microbial activity and nutrient cycling.	**Physical:** Increased Water Holding Capacity (WHC) and lower bulk density.
Biochar Application	**Chemical:** Long-term C sequestration, increased Cation Exchange Capacity (CEC).	**Physical:** Improved porosity and water retention in sandy soils.
Improved Drainage/Irrigation Efficiency	**Hydrological/Chemical:** Prevention of waterlogging (reducing N_2O emissions) and salinization.	**Physical:** Maintenance of aerobic soil conditions for root health.

7. Conclusion

One of the issues facing the 21st century is climate change and soil resources. The fact is obvious: changes in climate are destroying the basic physical and chemical characteristics of soil, which underpin agriculture. An increase in temperature poses risks to the stocks of carbon contained in the soil and distorted rainfall interferes with soil structure and chemistry.

Maintaining the status quo of business, which is farming that worsens the soil, will increase the effects of climate, compromising food security and ecosystem security. A real way to go is to switch to regenerative, climate- smart practices which prioritize soil health first. Knowing the way the soils respond physically and chemically to the drivers of climate, agronomists and policymakers are able to develop systems that not only adapt to the changing world, but also contribute to alleviating the crisis by increasing the extent of carbon sequestration in the soils. The future of agriculture is literally beneath us in the strength of the pedosphere.

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Influence of Soil Thermal Properties on Crop Growth and Development under Varying Climatic Conditions

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1. Introduction

The soil environment is basically an intricate, muddled porous medium in which solid material, water and air all coexist. Temperature is the emperor in this blend, it almost all in the soil (physical, chemical, biological) is influenced by it. Soil temperature changes gradually unlike air temperature that can jump around within seconds and this combination of slow change is what gives soil temperature a fairly unique little climate provided to plant roots and soil microbes to spend their days.

Thermal properties of the soil are all about the ability of the soil to absorb, store and conduct heat. Those properties inform us about the rate at which the root zone warms in the spring, the extent of frost in the winter and the severity of heat stress in the hot summer. Understanding soil thermal processes is overly important since despite the presence of adequate water and nutrients, both excessive or insufficient temperatures are still the primary source of yield restraint.

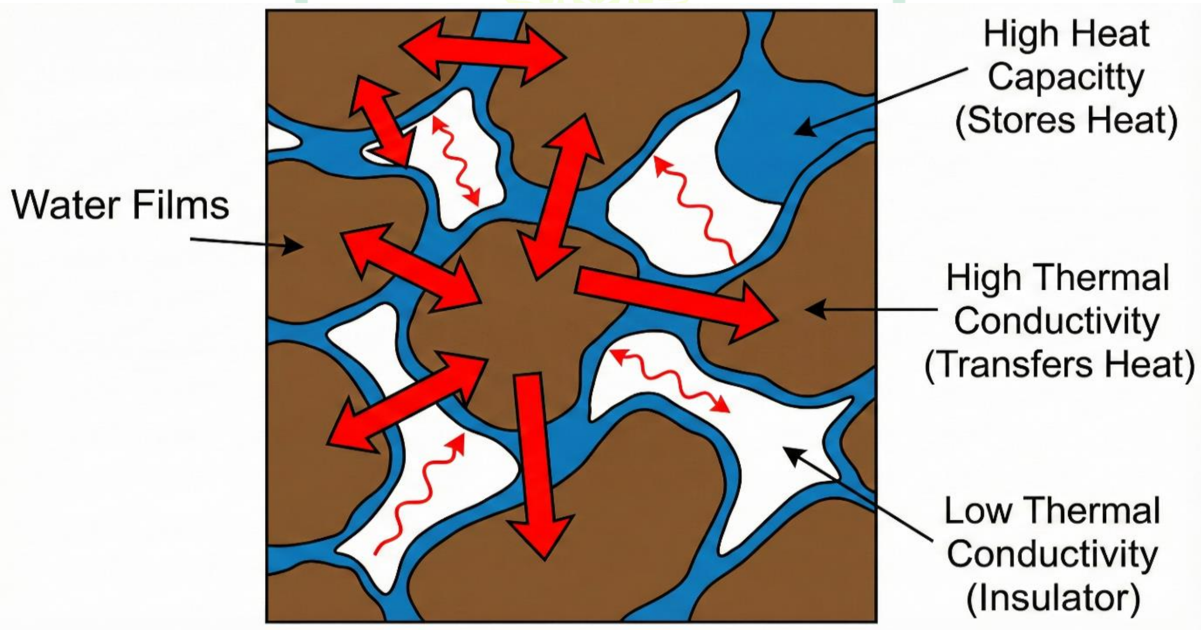

Figure 8. Microscale Thermal Interactions in a Soil Aggregate

2. Fundamental Soil Thermal Properties

2.1 Volumetric Heat Capacity (C_v)

The volumetric heat capacity is the amount of energy (Joules) required to raise one cubic meter of soil mass by one Kelvin ($Jm^{-3}K^{-1}$). It demonstrates the level of heat retention by soil. The big factor then on C_v is our soil water since the heat capacity of water is greater than that of minerals and air. In air, there is hardly any heat storage. It would require a lot more energy to warm up wet soil than dry soil, but it retains it longer as well, providing it with greater stability.

2.2 Thermal Conductivity (λ)

Thermal conductivity is the capability of soil to transfer heat, or the number of watts per meter per Kelvin ($Wm^{-1}K^{-1}$). In essence, conduction is the movement of heat between adjacent molecules and is based on the kinetic energy transfer of the bulk density of water. Air pockets in a dry airy soil serve the purpose of insulation, reducing. With increased water content of the soil, water films fill the spaces between the particles increasing contact and lifting up to saturation. Hard-packed soil contains a larger portion of solid-to-solid contact therefore it has a greater λ compared to a loose tilled soil.

2.3 Thermal Diffusivity (D)

The product of thermal conductivity over volumetric heat capacity is called thermo-diffusivity (D). The greater D is, the greater the speed with which the temperature changes spread through the profile. D in $m^2 s^{-1}$ is a measure of the rate at which a soil will heat or cool at depth in response to changes in surface temperature. A dry soil is one with low λ, but it is also characterized by low C_v, resulting in a large D--heat rises very fast but only at the surface. The wet soil contains a high λ and a high C_v, so the lower D -heat will take longer to reach deeper levels:

$$D = \frac{\lambda}{C_v}$$

3. Physiological Impacts of Soil Temperature on Crops

The thermal state of the rhizosphere (the root zone) directly regulates plant metabolic processes. Every enzyme-catalyzed reaction has a minimum, optimum, and maximum temperature range.

3.1 Germination and Emergence

The most sensitive thing in the development of a crop is seed germination. The metabolism of soil is induced to go into dormancy and start-up by soil temperature. Cool soil retards emergence and increases seedlings susceptibility to soil pests and insects. Hot soil will even kill seedlings or induce thermoinhibition.

3.2 Root Growth and Morphology

When the soil temperature reaches the optimum point of each species, the growth of roots becomes accelerated. The viscous effect is caused by cold soils, which make water less permeable and less permeable cell membranes, so physiological drought may arise despite the presence of an abundance of moisture. Warm soil will promote side root development, although higher than 35ºC temperatures in the top layer have been found to kill roots in most crops of moderate climates, restricting root penetration and access to closer nutrients such as phosphorus.

3.3 Nutrient Cycling and Microbial Activity

The degradation of nitrogen in organic matter is done by microbes- this is the principal nutrient-cycling process. Their rates increase about 2 times per 10ºC (Q_{10}) up to an optimum. Early spring cold soil inhibits microbes, and this can cause temporary nutrient deficiencies even insofar as the overall fertility is good.

Table 10. Cardinal Soil Temperatures for Selected Agronomic Crops

Crop	Minimum Germination Temp (°C)	Optimum Growth Temp Range (°C)	Maximum Survival Temp (°C)
Wheat (*Triticum aestivum*)	3 - 5	15 - 25	35 - 38
Maize (*Zea mays*)	8 - 10	25 - 30	40 - 42
Soybean (*Glycine max*)	8 - 10	25 - 32	38 - 40
Cotton (*Gossypium hirsutum*)	14 - 16	28 - 34	42 - 45
Potato (*Solanum tuberosum*)	7 - 9	15 - 20	28 - 30
Note: Potato tuberization is severely inhibited above 20-22°C.			

4. Interactions with Varying Climatic Conditions

The interaction between inherent soil thermal properties and external climatic forcing creates distinct soil thermal regimes across different agro-ecological zones.

4.1 Arid and Semi-Arid Climates

These regions are characterized by high solar irradiance and low precipitation. Soils are typically dry with low organic matter.

a) **Thermal Behaviour:** C_v decreases with low moisture hence these soils vary widely on their daily temperatures. During the day, surface can heat quickly, up to 50-60ºC and this temperature can kill seedling stems. During the night the retention of heat is poor thus leading to a sudden decrease in temperature.

b) Crop Challenges: The primary complaint is heating stress in the upper root zone and evanescence. High temperature difference between the hot surface and colder subsoil results in a high upward vapor flux, which pulls out more water in the soil.

4.2 Temperate and Cold Climates

These regions are defined by distinct seasons, with significant periods where air temperatures are below freezing.

a) Thermal Behaviour: Soils in spring are often wet due to snowmelt and seasonal rainfall. This high-water content increases volumetric heat capacity, meaning the soil requires substantial energy inputs to warm up.

b) Crop Challenges: It is not about hot weather, it is that the continuous heat accelerates the process of decomposing organic matter (carbon sequestration becomes difficult), and that there is a high pressure on soil-dwelling pests and pathogens which survive best in hot and wet soil.

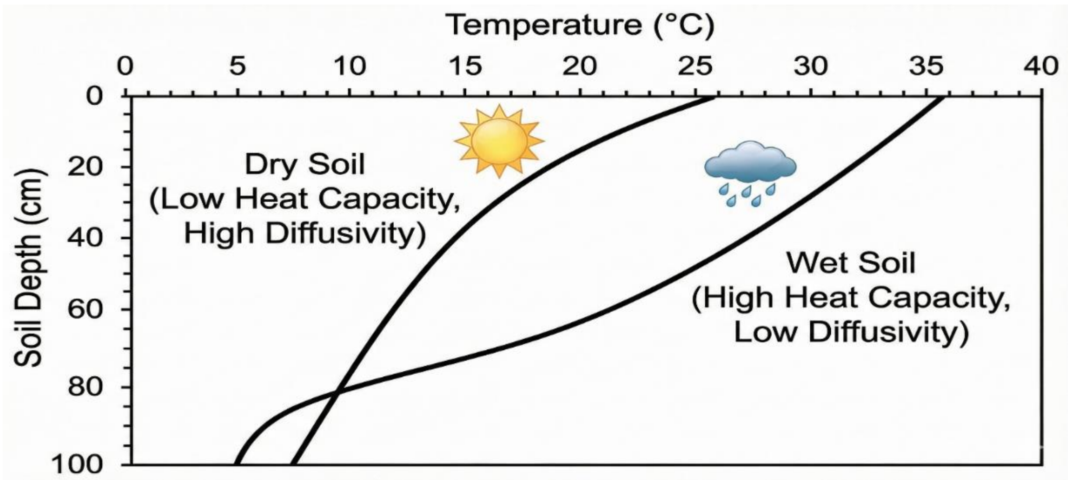

Figure 9. Soil Temperature Profiles under Varying Moisture Conditions

5. Management Strategies to Modify Soil Thermal Regimes

Farmers and agronomists can influence soil thermal properties through various management practices to mitigate adverse climatic impacts. The primary levers for manipulation are soil water content, surface cover (residue or mulch), and soil bulk density (tillage).

5.1 Mulching and Residue Management

Surface cover is the most effective tool for modifying the soil energy balance.

a) Organic Mulches: Straw or stover is like insulation- it is not very thermal conductive. In the hot climates they reflect the sunlight and make the surface of the soil cooler reducing the evaporation. Packed residue in the spring of cool climates may actually cause the soil to warm faster thus preventing the early-season crops to begin growing.

b) Plastic Mulches: Extremely widespread in the production of veggies. Crystalline plastic allows the shortwave light to pass through but blocks the longwave radiation (greenhouse effect), and thus the soil is heated quickly. Black plastic captures heat after which it is transferred to the soil through conduction, as well as it prevents weeds.

5.2 Tillage Practices

Tillage alters soil structure, bulk density, and surface roughness, all of which affect thermal properties.

a) Conventional Tillage: his is what loosens the soil, lowers bulk density, and produces air pores. It permeabilizes initially and desiccates surfaces, and dissects thermal conductivity. A dry and rough surface absorbs heat rapidly during the day then falls rapidly at night.

b) **No-Tillage (Conservation Tillage):** Leaves a greater amount of bulk density and residue on the surface. Un-tilled soils tend to be damper and colder during spring since the leftovers provide insulation and the added moisture enhances thermal capacity.

5.3 Irrigation Management

Since water is the principal factor governing both soil heat capacity and conductivity, irrigation is a powerful thermal regulator.

a) **Pre-planting Irrigation:** To keep the heat levels in hot areas reduced with a higher capacity to withstand heat, watering the soil prior to planting makes the soils less prone to temperature changes and provide the seedings with a cooler and more stable environment to sprout.

b) **Frost Protection:** In areas with a temperate climate, humans irrigate in the lead-up to a forecasted freeze. Wet soil is more effective in retaining heat than dry soil and releases latent heat of freezing, which may save roots or crowns of lethal cold.

Table 11. Impact of Agronomic Practices on Soil Thermal Properties and Regimes

Agronomic Practice	Effect on Bulk Density	Effect on Soil Moisture	Net Thermal Impact on Soil	Best Application
Conventional Tillage	Decreases	Decreases (surface)	Faster surface warming in spring; greater diurnal fluctuation.	Cool climates needing rapid spring warmup.
No-Tillage with Residue	Maintains/Slight Increase	Increases	Slower spring warming; cooler summer temperatures; reduced diurnal fluctuation (insulation).	Hot/Arid zones to reduce heat stress; erosion-prone areas.
Clear Plastic Mulch	No direct effect	Conserves	Rapid soil heating via greenhouse effect.	High-value crops in cool regions requiring early harvest.
Organic Straw Mulch	No direct effect	Conserves	Insulation: keeps soil cooler in day, warmer at night.	Hot climates to prevent root zone heat stress.
Irrigation	Increases (transiently)	Increases	Increases heat capacity and conductivity; buffers temperature extremes.	Universal regulator for both heat stress and frost risk.

6. Conclusion and Future Perspectives

The important physical objects that determine the climatic conditions of energy around the roots are soil thermal characteristics. They are not merely passive constants, but they positively contribute to the ability of crops to grow. The interplay between the soil texture, moisture and sunlight concept makes the soil either welcoming or unfriendly towards plants.

Trying to keep the one-size-fits-all suggestions old school because of the increasing unpredictability of weather due to climate change. We should have subtlety in the perception of the process of soil heating. As an example, no-till may be excellent at soil health during cool, wet springs, but may slow down the production of yields because it slows the soil warming, which is required to have dry land to plant. In hot dry regions, it is not just the issue of preventing erosion that is of concern regarding management of residues, but it is rather a key to ensuring that the soil does not overheat.

The future studies need to develop elaborate and location-explicit soil thermal models incorporating weather forecast and real-time soil information to provide farmers with current information. They should also breed plants that have the capacity to withstand heat stress at the root level as opposed to the leaves. Finally, strong farming implies sustaining soils are not simply nutrient-containing containers, but rather fluid physical systems in which temperature and water cannot be separated.

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Integrating Conservation Agriculture into Climate-Smart Farming: Enhancing Adaptation and Sustainability in Agroecosystems

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1. Introduction

The Anthropocene period has brought about unprecedented climatic uncertainty which has presented existential challenges to world agroecosystems. Increasing average temperatures, changing rainfall distribution and the increasing occurrence of extreme climatic events like long droughts and extreme flooding is disrupting agricultural production capacity. The traditional paradigm of agriculture, where intensive cultivation, monocultures and synthetic inputs were heavily employed, managed to increase the productivity rates over the years, but also managed to undermine the natural resource base, making the systems more susceptible to the natural disasters of climate.

In order to cope with this crisis, the Food and Agriculture Organization (FAO) came up with the idea of Climate-Smart Farming (CSF). CSF is not a specific set of methods but an idea of coming up with an agricultural strategy depending on the specific local conditions with a view towards accomplishing three things happening at once (pillars):

1. **Productivity:** Sustainably increasing agricultural incomes and yields.
2. **Adaptation:** Establishing climate change and variability resilience.
3. **Mitigation:** To decrease and/or eliminate greenhouse gas (GHG) emissions.

Although CSF is the umbrella framework, agronomic practices will need particular and evidence-based application. A proven set of such practices are offered by Conservation Agriculture (CA). Three principles are used concurrently and are defined by CA:

1. **Minimum Soil Disturbance:** Reducing or eliminating tillage (e.g., no-till or strip-till) to preserve soil structure and biology.
2. **Permanent Soil Organic Cover:** Maintaining crop residues or growing cover crops to protect the soil surface.
3. **Species Diversification:** Utilizing varied crop rotations, associations, or agroforestry to enhance ecosystem functions.

2. Theoretical Framework: The Convergence of CA and CSF

The correlation between Conservation Agriculture and Climate-Smart Farming is that of pragmatic approach to a strategic paradigm. Whereas CSF determines what must be accomplished in relation to climate change, CA tends to give the how on the field level.

The fact that the three principles of CA directly refer to the three pillars of CSF is synergized. The traditional tillage practices can be marked by net carbon loss in the soil, lack of water penetration through surface sealing and compaction, and excessive reliance on fossil fuels to power up the machinery. CA is a major force of adaptation and mitigation by turning these trends around.

The conceptual diagram of the CA principles to the CSF outcomes as shown in the diagram below indicates the interconnected influence pathways.

The integration is synergistic as indicated in the diagram. An example that crops residues (CA Principle 2) can be held back to prevent erosion (Adaptation Pillar), which ultimately decomposes into soil organic matter (sequestration of carbon (Mitigation Pillar) and enhancement of nutrient cycling by future crops (Productivity Pillar).

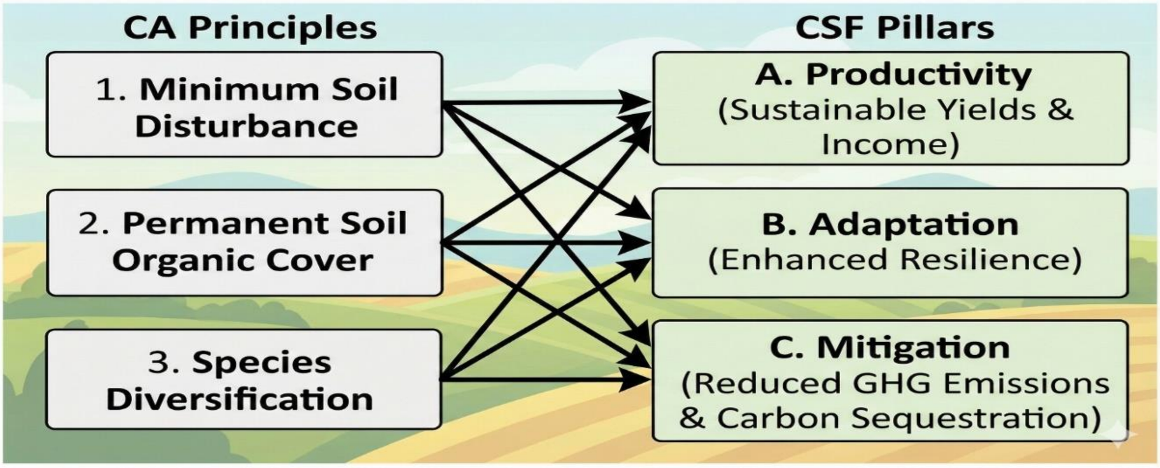

Figure 10. Synergistic Linkages between Conservation Agriculture (CA) and Climate-Smart Farming (CSF)

3. Mechanisms of Adaptation and Resilience

The main input that CA made to the CSF framework is the increase in agroecosystem resilience to drought and thermal extremes. This happens mostly via betterment of soil health and hydrology.

3.1. Edaphic Restoration and Water Dynamics

The most direct risk of climate concern perhaps is water scarcity in most agricultural areas. The traditional tillage causes the destruction of soil aggregates, making soil less porous and forming plow pans that limit penetration of roots and water uptake.

CA reverses this through minimal disturbance and residue cover.

a) **Infiltration:** Infiltration Crop residues perform the physical barrier effect, absorbing the impact of raindrops and not sealing the surface. At the same time, tillage is not applied, and therefore, the soil macropores formed by earthworms and decomposing roots are not destroyed, and they enable quick infiltration of water when it falls heavily in short periods.

b) **Retention:** CA systems with high levels of Soil Organic Carbon (SOC) have been associated with high levels of water-holding capacity. It is calculated that water storage capacity can be enhanced by a 1 percent rise in soil organic matter by over 20,000 gallons per acre that serve as a buffer during dry periods.

c) **Evaporation Reduction:** Surface mulch greatly suppresses soil water evaporation that allows moisture to be maintained longer to support crop transpiration.

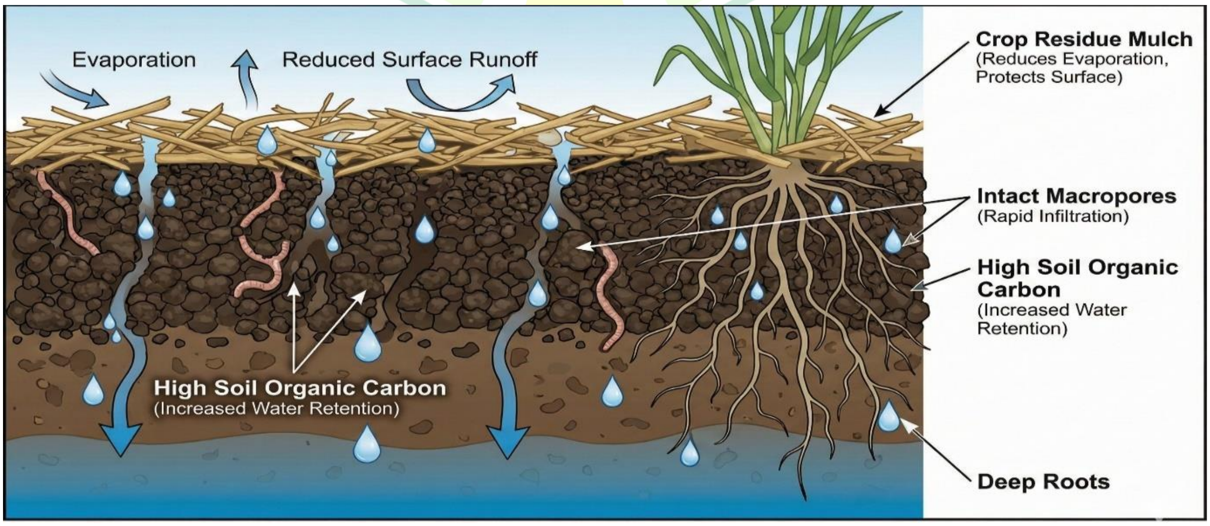

Figure 11. Enhanced Soil Hydrology under Conservation Agriculture

3.2. Thermal Regulation and Biological Resilience

Raw soil subjected to direct solar radiation adopts excessive temperature changes, thus preventing root functioning and microbial activities. CA systems have their permanent soil cover, which regulates the temperatures of soil surfaces during hot summer and cold winter soils. This thermal buffering safeguards key root zones as well as keeps a stable environment of valuable soil biota that are essential to nutrient cycling and pathogen suppression. Moreover, the diversification of species interrupts the cycle of pests and diseases which is often accelerated by the changing climate conditions, which provide an additional level of biological resilience.

4. Productivity and Mitigation Co-benefits

While adaptation is often the primary driver for adopting CA in vulnerable regions, the contributions to productivity and mitigation are significant, aligning fully with CSF goals.

4.1. Sustainable Productivity

Sometimes, the move to CA may result in a temporary yield levelling or even a temporary slight decrease over the first 2-5 years, sometimes because of surface residue immobilization of nitrogen, or learning management curves. Nevertheless, in long-term trials there is always a finding that when the health of the soil is recaptured, CA systems achieve equal or better yields than the conventional systems. More to the point, CA systems are more stable to yield with time. The high-water conservation of CA systems typically leads to high yields in the year of drought, when other regular neighbours could have close to no yield, and the farm households survive.

4.2. Mitigation Potential

Agriculture is a major source of GHGs, but it also holds immense potential as a sink. CA contributes to mitigation through three primary avenues:

a) **Carbon Sequestration:** CA decreases this oxidation of soil carbon through reducing soil disturbance. At the same time, carbon inputs are raised due to the incorporation of both crop residues and root biomasses of cover crops. With time, this causes an overall accrual of the SOC, whereby the CO_2 is transferred out of the atmosphere and stored in the long-run pools of soil.

b) **Reduced Fossil Fuel Emissions:** Multiple tillage passes can be eliminated to cut down the use of diesel per hectare.

c) **Optimized Nitrogen Use:** Soil structure and biological processes in mature CA systems can be better, which can result in tightened nitrogen cycling, which can lead to a decreased leaching and nitrous oxide (N_2O) emission as long as nitrogen fertilizers are applied in a proper way.

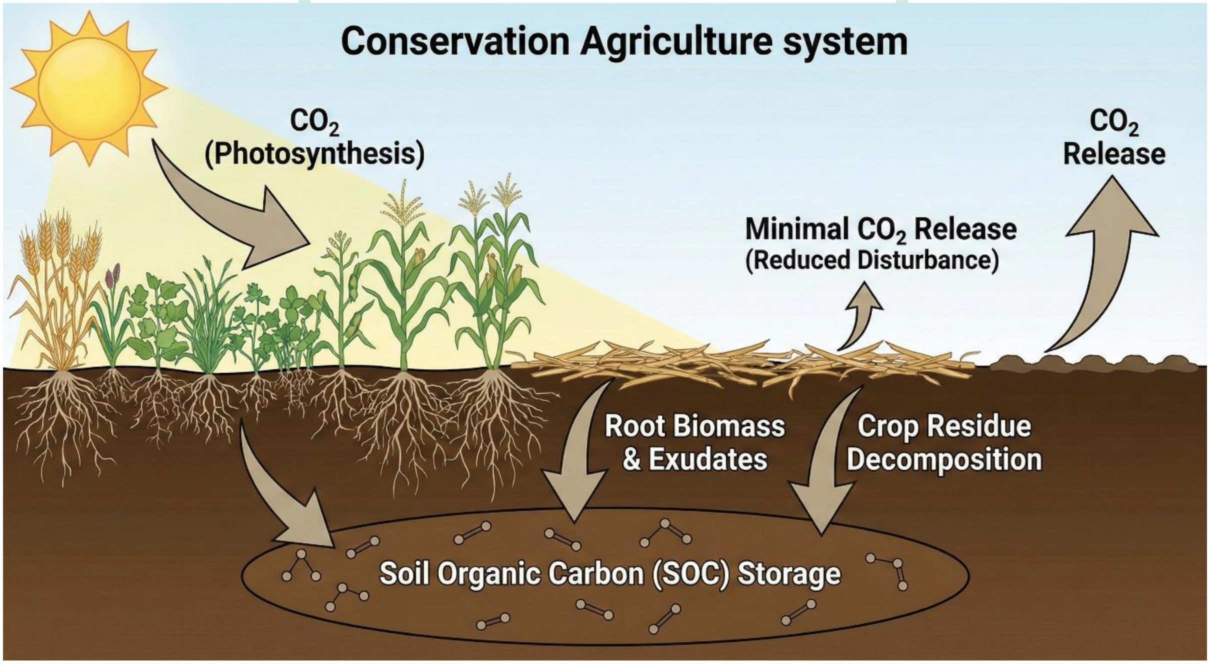

Figure 12. The Carbon Sequestration Cycle in No-Till Systems

5. Comparative Analysis: Conventional vs. Integrated CA/CSF

Table 1 compares the salient features of conventional systems, which are intensive tillage systems, against an integrated Conservation Agriculture/Climate-Smart Farming (CA/CSF) model under a continuum of agroecological measures to explain the underlying paradigm shift.

Table 12. Comparative Analysis of Conventional Tillage Systems versus Integrated Conservation Agriculture within a Climate-Smart Framework

Parameter	Conventional Tillage System	Integrated CA/CSF System	Implications for Climate Change
Soil Physical State	Physically pulverized; prone to compaction, crusting, and erosion by wind/water.	Intact structure; increased aggregation, macroporosity, and biological activity.	CA offers high resilience to intense rainfall events and erosive winds.
Water Management	Low infiltration, high surface runoff, high evaporative losses from bare soil.	High infiltration, reduced runoff, high moisture retention due to mulch and SOC.	CA maximizes "green water" utility, crucial for adaptation to drought.
Soil Organic Carbon	Net loss due to accelerated oxidation from tillage and removal of residues.	Net gain (sequestration) over the medium-to-long term due to protection and inputs.	CA acts as a mitigation strategy and enhances biophysical fertility.
Crop Diversity	often monoculture or simple two-crop rotations. Vulnerable to specific pests/diseases.	diversified rotations, intercropping, and cover crop integration.	CA enhances ecological resilience and breaks pest cycles exacerbated by climate.
Energy Inputs	High dependency on fossil fuels for intensive machinery operations (ploughing, harrowing).	Reduced fuel dependency due to fewer field passes (direct seeding).	CA reduces production costs and immediate carbon footprint from machinery.
Yield Dynamics	High potential in optimal years; highly vulnerable to collapse in drought/flood years.	Stable yields long-term; significantly higher resilience and yield protection in "bad" years.	CA ensures food security stability under climate volatility.

6. Barriers to Integration and Scaling Up

To make CA a part of Climate-Smart Farming, one must go beyond the technology-transfer model to a systems-innovation one. The shift in the transition needs to be a central role of the public policy to de-risk producers. The trajectories in the future should focus on:

Table 13. Key Barriers to Integrating Conservation Agriculture and Corresponding Strategic Interventions.

Category of Barrier	Specific Challenge	Strategic Policy/Programmatic Interventions
Biophysical/Technical	**Weed Management:** reliance on tillage for weed control makes shifting to no-till difficult, often increasing herbicide reliance initially.	Investment in R&D for integrated weed management (IWM) in no-till; breeding cover crops for high allelopathic weed suppression.
	Residue Trade-offs: In mixed crop-livestock systems, crop residue is often highly valued as livestock feed, creating competition for soil cover.	Developing dual-purpose crops; promoting forage legumes; rotational grazing strategies that leave sufficient residue.
	Lack of Appropriate Machinery: Smallholders often lack access to affordable no-till seeders capable of planting through heavy residue.	Promoting service provider models (machinery rings); subsidizing local manufacturing of scale-appropriate direct seeders.
Socio-Economic	**Short-term Economic Risks:** Potential for initial yield dips and need for new equipment investment can deter risk-averse farmers.	Implementing Payments for Ecosystem Services (PES) or carbon credits to bridge the transition gap; offering low-interest loans for CA equipment.
	Mindset and Cultural Norms: Tillage is deeply embedded in cultural definitions of "good farming" (the clean field syndrome).	Strengthening farmer-to-farmer extension networks and demonstration farms; shifting extension focus from inputs to knowledge management.
Institutional	**Fragmented Policy:** Agricultural subsidies often favour conventional inputs (fuel, fertilizer) rather than sustainable practices.	Realigning agricultural subsidies to reward stewardship outcomes (soil health, water conservation) rather than just production inputs.

7. Policy Implications and Future Pathways

To make CA a part of Climate-Smart Farming, one must go beyond the technology-transfer model to a systems-innovation one. The shift in the transition needs to be a central role of the public policy to de-risk producers. The trajectories in the future should focus on:

a) **Realigning Incentives:** It is necessary to shift out of input-based subsidies to outcome-based subsidies. Programs that compensate the farmers based on quantifiable changes in the metrics of soil health, including the augmentation of soil organic carbon, can provide the required financial buffer in the period of transition when the yields might be low.

b) **Knowledge-Intensive Extension:** A is based on knowledge as opposed to inputs. Extension services should be renewed to deliver site specific advice on complicated crop rotations, selection of cover crops and integrated pest management, avoiding general advice.

c) **Systems Research:** More studies are necessary on how to integrate livestock into CA systems- especially Crop-livestock integration in semi-arid settings in order to overcome residue-competition issues and how to perfect non-chemical weed-management in zero-tillage systems.

8. Conclusion

The twenty-first century agricultural sustainability strategy is Climate Smart Farming. However, without an effective biophysical basis, CSF is mostly an imaginary construct. Conservation Agriculture provides that basis. CA addresses the fundamental weaknesses of contemporary agriculture against climate change by reinstating soil capability to permeate water, ecosystem cycle nutrients, and regulate temperature extremes. Though the process is fraught with technical and socio-economic issues, the idea of implementing CA principles into more comprehensive climate-smarter initiatives is not a mere choice but a necessity to improve the overall adaptation and sustainability of the global agroecosystems. It requires a concerted action on the part of policymakers, researchers, and growers to understand that soil health is not only a production resource but also a highly important climate tool.

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Interaction Mechanisms Between Nanobiochar and Heavy Metals: Implications for Soil Remediation and Food Safety

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1. Introduction

The widespread presence of heavy metals (HMs) including cadmium (Cd), lead (Pb), arsenic (As), chromium (Cr) and mercury (Hg) in farm soils is an environmental issue of significant scale worldwide. These pollutant species are first of all anthropogenic such as industrial emissions, mining, overuse of agrochemicals, and wastewater irrigation. Being non-biodegradable, they remain in the soil structure, which is a juxtapose of threat: they suppress the organic functions of the soil by interfering with the exchange of nutrients in the soil; on another, they contribute to the introduction of toxic substances into the food chain of humans because of their absorption by plants.

Conventional remediation methods, i.e. excavation or chemical washing, are often prohibitively expensive and ecologically invasive. In turn, in-situ stabilization through organic amendments has become one of the salient alternatives. Biochar -a carbon-rich product, which is a pyrolysis product of biomass under oxygen-restricted conditions, has shown effectiveness in immobilizing HMs. However, the bulk biochar has relatively low surface area and reactivity, which limits the performance of bulk biochar.

When agricultural science and nanotechnology have chased their convergence, nanobiochar (NBC) has been generated. It is possible to increase the physicochemical properties of biochar by reducing it to a nanoscale. Compared to other media, NBC has a higher surface-area-volume ratio, increased pore volume and increased exposure of reactive functional groups. The current article clarifies the complex processes of controlling the NBC-HM interactions and reflects upon the practical implications of the NBC application towards the implementation of the dual goals of attaining the remediation of the soil and meeting the food safety standards.

2. Nanobiochar: Production and Physicochemical Superiority

NBC is not merely a smaller analogue of biochar, its condensation to the nanoscale in effect changes its reactive properties.

2.1 Production Pathways

There are two major routes through which NBC can be produced:

a) **Top-down approach:** Bulk biochar made by a typical and common pyrolysis (usually 300-700 ºC) is mechanically disintegrated into nanoparticles by using high-energy ball milling or ultrasonication.

b) **Bottom-up approach:** This method is not used in agricultural applications, because of cost reasons, but synthesizes carbon nanomaterials by chemical vapor deposition or hydrothermal carbonization of molecular precursors.

The top-down approach with the use of agricultural waste residues (straw, manure, wood chips) is the most viable one in terms of agricultural scalability.

2.2 Key Physicochemical Properties

The efficacy of NBC in heavy metal remediation is governed by three defining characteristics that distinguish it from bulk biochar. To better understand this distinction, visual aids are helpful.

a) **Specific Surface Area (SSA):** Although bulk biochar typically has a SSA of between 10 and 300 m^2/g The NBC can be 500-1000 m^2/g. This gives a significantly greater quantity of binding sites of metal ions on a unit mass of amendment.

b) **Hierarchical Porosity:** NBC possesses a complex network of micro-, meso-, and macropores. The increase in micropores (<2 nm) and mesopores (2–50 nm) during the nanoscale reduction process is crucial for trapping smaller metal ions and facilitating diffusion into the carbon matrix.

c) **Surface Functional Groups:** NBC surfaces are abundant in oxygen-based functional groups including carboxyl (-COOH), hydroxyl (-OH), phenolic, and carbonyl (C=O) and are often negatively charged at common soil pH levels creating strong electrostatic bond between the functional groups and positively charged metal cation. The concentration of these reactive sites on NBC is significantly increased as compared to the bulk biochar because of the expanded exposed surface area.

3. Mechanisms of Interaction Between Nanobiochar and Heavy Metals

The immobilization of heavy metals by NBC is rarely the result of a single process. Instead, it is a synergistic interplay of physical and chemical mechanisms. Understanding these is vital for predicting remediation success in varying soil environments.

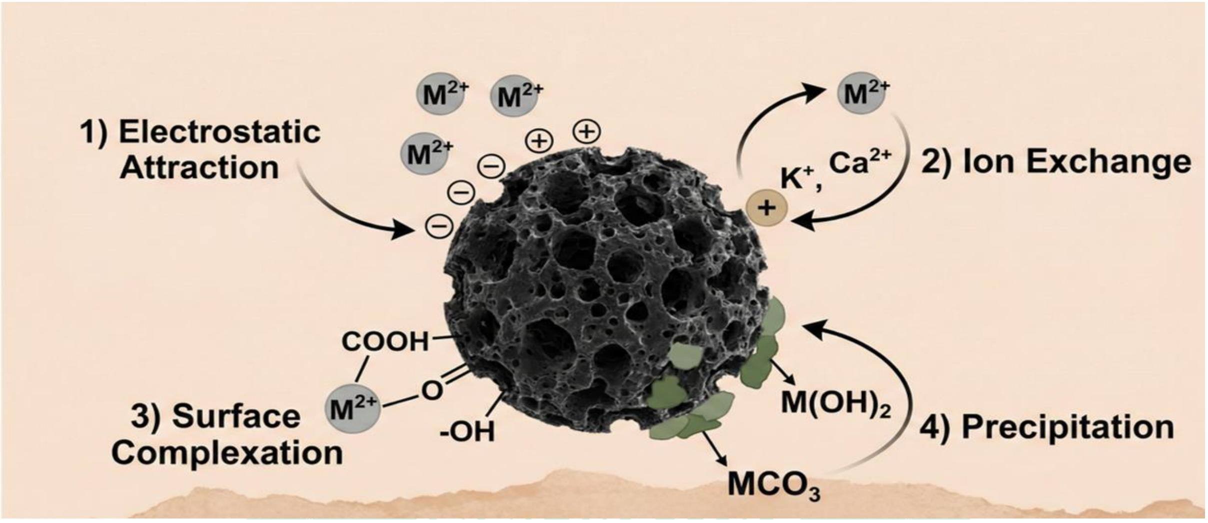

Figure 13. Schematic representation of the primary physiochemical interaction mechanisms between nanobiochar and heavy metal cations.

3.1 Physical Adsorption

This mechanism involves the nonspecific binding of metal ions to the NBC surface through relatively weak forces.

a) **Electrostatic Attraction:** The vast majority of HMs are present in the form of cationic species in soil solution (e.g., Pb^{2+}, Cd^{2+}, Zn^{2+}). NBC surfaces, in particular those produced at lower pyrolysis temperatures, are characterized by a net negative charge due to deprotonated functional groups, and hence create a potent electrostatic attraction, which brings cations to the NBC surface.

b) **Van der Waals Forces:** Ssuch weak and short-range intermolecular forces are involved in the physical adsorption of metals in the porous structure of NBC. The forces are comparatively insignificant when considered separately, but have a cumulative effect on the vast surface of NBC.

3.2 Ion Exchange

NBC contains basic cations, such as calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and sodium (Na^+), originally present in the biomass feedstock. When placed in contaminated soil solution, toxic heavy metal cations can displace these non-toxic exchangeable cations on the NBC surface. The general reaction can be represented as: $NBC\text{-}M_{exchangeable} + HM^{2+}_{solution} \rightleftharpoons NBC\text{-}HM_{adsorbed} + M^{2+}_{solution}$

This mechanism is particularly relevant for metals like Pb^{2+} and Cd^{2+} and is highly dependent on the Cation Exchange Capacity (CEC) of the NBC, which is generally higher than that of bulk biochar.

3.3 Surface Complexation

This is considered one of the strongest and most stable mechanisms for heavy metal immobilization. It involves the formation of chemical bonds between metal ions and specific functional groups on the NBC surface. Depending on the metal chemistry and the type of functional group, these complexes can be:

a) **Monodentate:** The metal binds to a single donor atom (e.g., oxygen in a hydroxyl group).

b) **Bidentate/Polydentate:** The metal binds to two or more donor atoms simultaneously (e.g., coordinating with both oxygen atoms in a carboxyl group). Bidentate chelation forms very stable complexes that are resistant to desorption, effectively locking the metal away.

3.4 Precipitation and Co-precipitation

Heavy metals can form insoluble solid phases on the surface or within the pores of NBC.

a) **Surface Precipitation:** As metal concentrations increase near the NBC surface due to adsorption, they may exceed their solubility limits, forming precipitates like metal hydroxides, carbonates, or phosphates. The alkaline nature of many NBCs (which raises local pH) facilitates this process.

b) **Redox-Induced Precipitation:** NBC possesses redox-active moieties (e.g., quinone/hydroquinone groups) that can transfer electrons to metal ions. A prime example is the reduction of highly toxic, mobile Chromium (VI) to less toxic, immobile Chromium (III), which subsequently precipitates as $Cr(OH)_3$ on the NBC surface.

Table 1: Summary of Primary Interaction Mechanisms for Common Heavy Metals

Mechanism	Description	Target Metals (Examples)	Key NBC Characteristic
Electrostatic Attraction	Attraction between negatively charged NBC surface and cationic metals.	Pb^{2+}, Cd^{2+}, Zn^{2+}, Cu^{2+}	Negative Zeta Potential, Surface charge density
Ion Exchange	Displacement of non-toxic cations (Ca^{2+}, Mg^{2+}, K^{+}) on NBC by toxic metal cations.	Pb^{2+}, Cd^{2+}, Ni^{2+}	Cation Exchange Capacity (CEC)
Surface Complexation	Formation of coordinating bonds between metals and functional groups (-COOH, -OH).	Pb, Cu, Cd, Hg, As (via Fe/Al oxides on NBC)	Oxygen-containing functional groups
Precipitation	Formation of insoluble solids (hydroxides, carbonates, phosphates) on NBC surfaces.	Pb (as carbonate), Cr (as hydroxide after reduction)	Alkalinity (pH), mineral ash content
Redox Reaction	NBC donates electrons to reduce metal ions to less mobile valence states.	Cr(VI) → Cr(III); As(V) → As(III)	Redox-active functional groups (quinones)

4. Implications for Soil Remediation

The application of nanobiochar dramatically changes the remediation goal whereby it is not focused on contaminant elimination but rather contaminant entrapment. NBC significantly minimises the ecological risk of contaminated soils by transforming bioavailable heavy metals into non-extractable forms.

4.1 Enhanced Immobilization Efficiency

Empirical studies always prove that NBC has significantly better performance on immobilization efficiencies compared to bulk biochar at the same rates. The role of the nanoscale size of NBC is penetration of smaller soil aggregates, which provides entry to heavy metals, which would otherwise be inaccessible by bulk amendments. As a result, distribution of the pollutants and faster stabilization is more homogenous.

4.2 Influence of Soil pH

The most significant variable which determines the solubility of the heavy-metals is the soil pH. Most NBCs are alkaline in nature. They raise the soil PH on incorporation and this in itself naturally reduces the solubility of cationic metals like Pb and Cd by increasing hydrolysis and precipitation. In addition, the pH increase facilitates deprotonation of acidic functional groups on the NBC surface, hence, enhancing the negative charge density and augmenting electrostatic attraction to metal cations.

4.3 Longevity and Stability

One of the most critical points to be taken into account during remediation is long-term immobilization stability of metals. Considering the abundance of strong chemical processes, such as surface complexation (chelation) metals detached by NBC have a lower ability to be re-released into the soil solution under environmental perturbations (e.g., moderate acidification because of rainfall or root exudates). This is in contrast to those metals which were loosely held through simple physical adsorption to bulk biochar.

5. Implications for Food Safety

The ultimate measure of farmland soil recovery achievement is the reduction of contaminant movement into foodstuff. Nanobiochar has a strong impact on the soils to plant to human continuum.

5.1 Reducing Plant Uptake (Bioaccumulation)

The primary sources of heavy metals to plants include the soil solution. The NBC can reduce the Bioaccumulation Factor (BAF) or the ratio of metal concentration in plant tissue and soil by adequately reducing the concentration of soluble and exchangeable metal fraction in the rhizosphere (root zone). They have been found to have shown great decreases in Cd uptake in rice paddy and Pb uptake in leafy vegetable after NBC amendment. These results are supported by the following mechanisms:

a) **Direct Immobilization:** As has been outlined above, in this method, the soil is protected by removing metals out of the soil solution.

b) **Phytostabilization Support:** NBC improves the general healthiness of soils such as water retention and nutrient retention make plants flourish and may be more resistant to residual metal stresses without hyperaccumulation.

5.2 Mitigating Trophic Transfer and Human Health Risk

A lower level of metal in the edible parts of crops is directly proportional to a lower dietary exposure of humans. In the case of staple crops like rice, wheat, and vegetables grown in historic contaminated areas, the use of NBC can be critical in ensuring that the yield meets within the acceptable low limits set by international food standards (e.g. Codex Alimentarius). This, in its turn, greatly alleviates the related health hazards, e.g. renal dysfunction caused by cadmium, or neurological impairments caused by lead.

6. Challenges, Future Perspectives, and Conclusion

Although nanobiochar is a paradigm shift in the remediation technology, there are a number of challenges that need to be overcome before a day comes when nanobiochar can be extensively applied in agriculture.

6.1 Potential Environmental Risks of Nanoparticles

The same properties that make NBC effective, i.e. the smaller particle size and increased reactivity, also cast doubt on its behaviour in the environment. Theoretical risks consist of the possibility of transporting NBC particles to the groundwater or bio-accumulating them in the soil organisms (e.g. earthworms) and the roots of the plants. Though initial investigations have indicated that pure carbon based NBC would be less ecotoxic, extensive field trials over long periods would be necessary to ensure that the amendment is not transformed into a pollutant.

6.2 Economic Viability and Scalability

The production of nanobiochar, especially by using energy-intensive milling methods, is now more power-oriented and expensive than the bulk production of biochar. Subsequent studies must focus on coming up with energy saving and cost effective ways of industrial production so that NBC can be economically viable as a large scale agricultural production project.

6.3 Long-Term Field Stability

The body of knowledge that exists is more of a lab incubation or pot experiments. The stability (more than ten years) of NBC metallic complexes in realistic, variable field conditions that include freeze-thaw cycles, intense rainfall, and microbial degradation of the carbon matrix are needed in large measure.

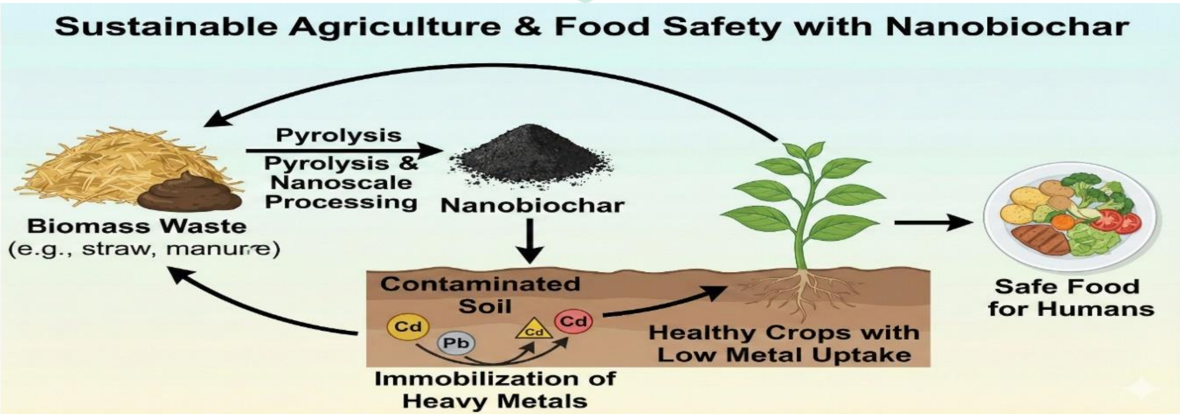

Figure 14. Conceptual framework illustrating the circular integration of nanobiochar in sustainable agriculture and food safety.

7. Conclusion

The epitome of the powerful technological change of the traditional biochar amendments is nanobiochar. It has a very high surface area and a dense functional group system that allows effective and quick immobilization of heavy metals in a complex interaction between adsorption, ion-exchange and surface complexation.

As an efficient means of curbing bioavailability of contaminants in the soil, nanobiochar plays a dual, essential role: it can restore the health of already degraded agricultural lands, as well as break the main pathway of the heavy metals accretion in human food chain. Although there are doubts about the long-term environmental influence and the size of production scale, nanobiochar holds the first place among the innovative methods of ensuring the safety of food production in a more polluted world.

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Comparative Evaluation of Biochar and Nanobiochar Amendments on Soil Fertility and Crop Productivity

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1. Introduction

Modern day farming is currently playing a game of balancing a very large, fed-up global population with combating this current problem of land becoming useless. Commonly used is fertilizer (which is synthetic) and though it can make soil acidic, it also can result in the leakage of the nutrients to rivers and it may actually reduce the organic matter (SOM) in the soil. This is why biochar; a pyrogenic biomass carbon is gaining popularity as a sustainable and multi-purpose soil amendment.

Biochar is a solid product obtained by doing pyrolysis (burning biomass with little oxygen). Its ability to remain in the soil permanently to serve as a carbon sink in addition to enhancing the texture and chemistry of the soil is due to its stolid and tough nature.

In recent years, nanotech technologies have been concentrated on the minute size of such materials. Nanobiochar (NBC) is simply biochar reduced to the nanoscale, typically through heavy grinding, ultrasonic waves, or special hydrothermal processes. The theory is that the smaller the size a particle get, the greater the surface area and the more functional groups there are, and thus the more interactive it becomes with soil nutrients, pollutants and microbes compared to regular biochar.

2. Fundamental Differences and Mechanisms of Action

BC and NBC are different primarily because of the size effect. The starting material may be the same, but the size of the particles is what would dictate how they interact with the soil.

2.1 Bulk Biochar: The Macroscopic Conditioner The bulk biochar particles are typically the range of millimetre to centimetre. They chiefly do this physically and structurally and behave like a sponge or micro-habitat in the soil. Big pore structure is important in:

- **a) Aeration and Drainage:** It introduces additional macropores in hefty infiltrates.
- **b) Water Retention:** It retains water in the middle and small pores to ensure that roots do not run dry during dry seasons.
- **c) Microbial Housing:** Provides safe places of bacteria and fungi against predation.

2.2 Nanobiochar: The Colloidal Reactor At the scale of operation of NBC, the surface forces are essentially dominant over gravity. It's colloidal. Due to the enormous surface area per unit mass its contribution changes not only to being structural but also an active chemical reactor. The main NBC mechanisms are:

- **a) Enhanced Surface Reactivity:** Nanoscale exposes a large number of oxygen functional groups (carboxyl, hydroxyl, phenolic) per mass. This increases the Cation Exchange Capacity (CEC) and allows NBC to bind nutrients such as ammonium (NH^{4+}), potassium (K^+) and calcium (Ca^{2+}) better than bulk BC.
- **b) Mobility and Penetration:** NBC particles are very small and can move with the soil water through meso- and micropores, further into the aggregates and may be able to bring nutrients or alter properties to areas that bulk amendments cannot reach.
- **c) Agglomeration Dynamics:** NBC has a high surface energy, which causes it to clump with the soil minerals (clays/oxides), accelerating the process of forming stable micro-aggregates, which is essential to long-term carbon storage.

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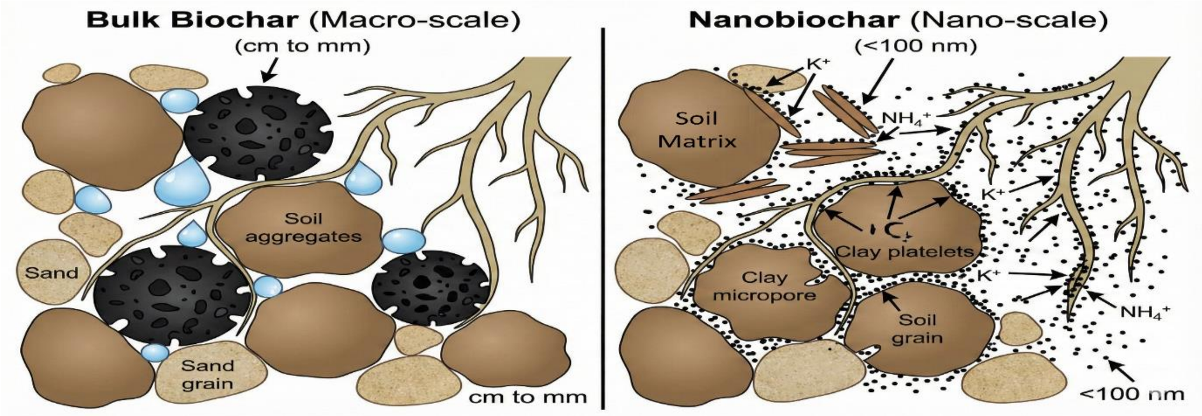

Figure 15. Schematic comparison of bulk biochar acting as a physical conditioner and nanobiochar integrated into the soil matrix as a reactive colloidal fraction.

3. Comparative Impact on Soil Fertility Parameters

3.1 Physicochemical Properties Both forms generally increase soil pH (liming effect) due to the presence of alkaline ash residues, beneficial for acidic soils. However, their influence on other parameters differs distinctly.

a) **Cation Exchange Capacity (CEC):** NBC typically is significantly more CEC than bulk BC using the same feedstock at the same pyrolysis temperature. The grinding reveals inner surfaces and new edge defects which are extra reactive to cation adsorption.

b) **Nutrient Leaching Mitigation:** Bulk BC reduces the nitrate and phosphate leaching by trapping and partial adsorption of the elements, yet NBC is much more efficient when considering the amount of carbon used. Its activity enables it to capture ions rapidly in solution to become a high-affinity slow-release fertilizer.

c) **Soil Bulk Density and Water Holding Capacity (WHC):** Bulk BC tends to be more successful in the short run. Its big pores reduce bulk density and increases WHC of sandy soils. The small size of NBC can sometimes plug existing pores or even increase bulk density when applied to large proportions of certain textures; its effects on water retention when high tension is still being investigated.

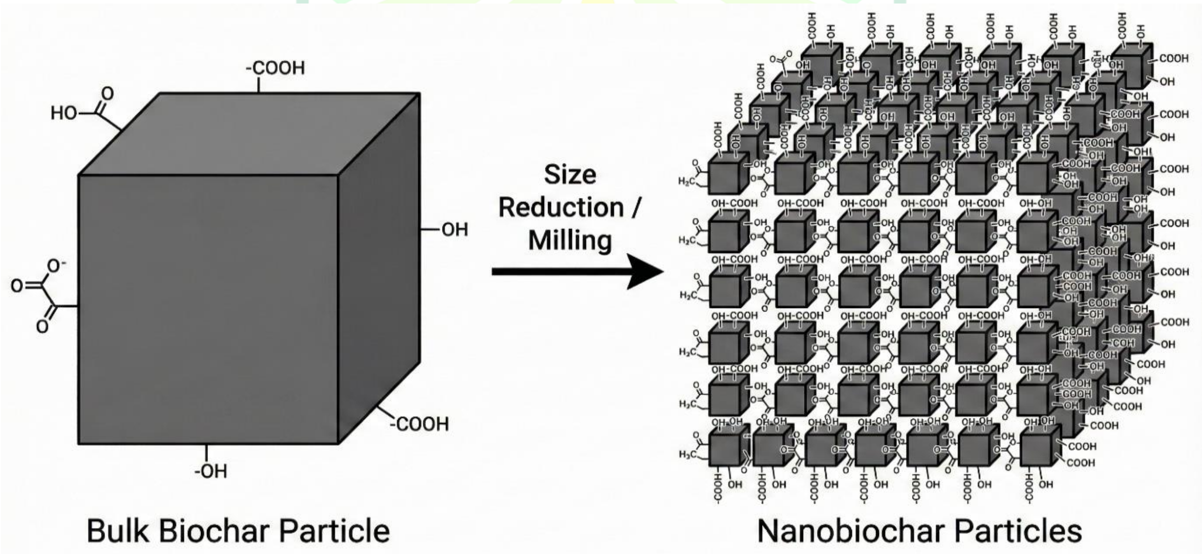

Figure 2. Conceptual illustration showing the exponential increase in exposed surface area and reactive functional groups resulting from the size reduction of bulk biochar to nanobiochar.

Table 14. Comparative Effects of Bulk Biochar and Nanobiochar on Key Soil Properties

Soil Parameter	Mechanism of Influence	Relative Efficacy: Bulk Biochar (BC)	Relative Efficacy: Nanobiochar (NBC)
Soil pH	Release of alkaline carbonates/oxides.	High (Liming effect)	High (Potentially faster reaction due to surface area)
CEC	Exposure of negative surface functional groups.	Moderate	**Very High** (Due to exponential SSA increase)
Specific Surface Area (SSA)	Porous structure resulting from pyrolysis.	Moderate (mostly internal pores)	**Extremely High** (External + internal exposure)
Bulk Density Reduction	Physical dilution of soil mineral fraction with lower density material.	**High** (Significant immediate impact)	Low to Moderate (Can sometimes increase density by filling pores)
Water Holding Capacity	Capillary action within pores.	**High** (Acts as a sponge)	Moderate (Affects tightly bound water more)
Nutrient Retention (e.g., NH_4^+)	Electrostatic attraction and physical trapping.	Moderate	**High** (Superior adsorption kinetics)
Carbon Sequestration	Recalcitrant aromatic carbon structure.	**High** (Long mean residence time)	High (Though potentially faster degradation due to microbial accessibility)

3.2 Biological Properties

Interactions between microorganisms are complex. Bulk biochar is considered to be in Favor of the microbial biomass, providing them with micro-habitats. Nanobiochar is trickier. Although its capacity to adsorb carbon can initiate the microbial activity (the priming effect), its nano-size can be sometimes deadly to sensitive microbes. Nanoparticles can cause damage to cell membranes or the formation of reactive oxygen species, although NBC is not as toxic as engineered metal nanoparticles. Also, NBC reacts strongly with the extracellular enzyme, and it is likely to stabilize them and increase the activity of total soil enzymes which is important in the cycling of nutrients.

4. Impact on Crop Productivity and Physiology

Ultimately, the measure of an amendment's success is agricultural output. Both BC and NBC have demonstrated positive impacts on crop yields, particularly in degraded or nutrient-poor soils.

4.1 Yield and Biomass

Meta-analyses are more likely to demonstrate bulk biochar increasing yields by approximately 10-25% and it depends on the type of soil and feedstock. The primary causes are the increased water access and reduced acidity. Nanobiochar is able to get similar or higher yields at far lower application rates. Bulk biochar may be used at 10 -20 t/ha, whereas NBC may be used at 100-500 kg/ha. That is because of its fast colonization of the rhizosphere and its instant impact on nutrient supply.

4.2 Nutrient Use Efficiency (NUE) and Physiology

Compared to NBC, the latter appears to be a more beneficial choice. On a time, we put it with fertilizers, it takes hold to it pretty well and does not jump off into the air or is washed away in rain so the plants always have something to hang onto.

a) **Enhanced Root Architecture:** Fine carbon particles are seen to burn up the roots, causing them to be longer and branched, hence enabling the plants to reach deeper into the soil.

b) **Stress Tolerance:** Both BC and NBC assist in tolerating the dryness and salty soils in plants. This is primarily done by BC through holding water, and grabbing sodium. NBC goes an extra mile by increasing the antioxidant defences of the plant by increasing the mild stress signals on a nanoscale, a cool phenomenon called hormesis.

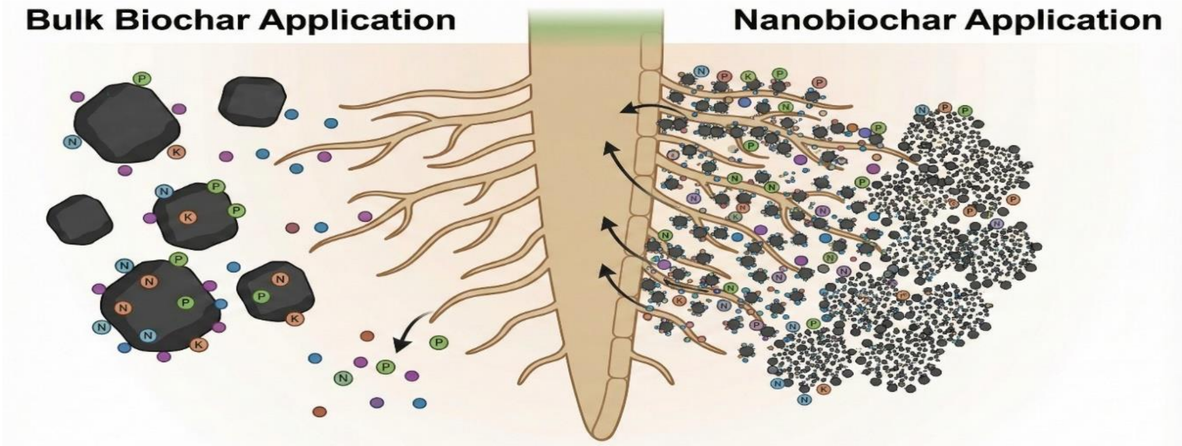

Figure 3. Schematic showing the enhanced localized nutrient bioavailability provided by nanobiochar particles that closely associate with plant roots, compared to the more dispersed interaction of bulk biochar.

5. **Challenges, Limitations, and Practical Considerations**

   a) **Production Economics:** With pyrolysis, bulk biochar is quite easy to make. But nanobiochar requires a step that is energy-weighted, either top-down grinding or a complex bottom-up accretion process, such that it is many times more expensive per gram.

   b) **Application Logistics:** To apply tonnes of bulk biochar in the field is like compost. Nano biochar powder is a nightmare when sprinkled since the wind can blow it off and farmers may be exposed to it. The trick is to suspension/put in a slurry NBC, it will coating the seeds/fertile grains, however, that would require additional steps to be undertaken.

   c) **Environmental Fate and Safety:** Bulk biochar remains, although we still do not understand what small NBC particle does in the long-term. This raise concerns that they might mobilise concealed pollutants in the ground water such as heavy metals or pesticide due to their extreme mobility in the soil.

Table 2: Operational SWOT Analysis of Nanobiochar vs. Bulk Biochar

Feature	Bulk Biochar (BC)	Nanobiochar (NBC)
Strengths	• Proven long-term soil carbon sink. • Simple production technology. • Excellent physical soil conditioner (aeration/water). • Low toxicity risk.	• Extremely high surface reactivity and CEC. • High efficacy at low application rates. • Superior nutrient retention and delivery. • rapid integration into soil micro-aggregates.
Weaknesses	• High application rates required (logistical burden). • Lower immediate chemical reactivity per mass. • Can immobilize nitrogen temporarily if C:N ratio is high.	• High energy cost of production (milling). • Difficult field handling (dust hazard). • Potential for colloidal transport of pollutants. • Risk of clogging soil pores at high rates.
Opportunities	• Large-scale waste biomass utilization. • integration into standard carbon credit markets.	• Development of high-value nano-fertilizers. • Seed coating applications for germination enhancement. • Targeted remediation of specific contaminants.
Threats	• Competition with biomass use for energy. • Inconsistent quality depending on feedstock.	• Regulatory uncertainty regarding nanomaterials in food chains. • Unknown long-term ecological impacts on soil microbiomes.

5. Conclusion and Future Perspectives

There is no selection between biochar and nanobiochar it is selecting the appropriate tool to the task.

Bulk biochar remains the standard in large scale conditioning of soils- to help structure of rough soils, increase number of cracks to allow air entry and to sequester carbon over the long term. Its simplicity makes it retain its popularity in general farming.

Nanobiochar is excellent where the target is accuracy, a high-efficiency nutrient knock-on, particularly that of a cation exchange and that of retaining fertilizers. It is also likely to be most effectively employed in targeted low-volume applications: as an ornamental treatment to fertilizer, as a seed treatment to enhance early growth or even in the cleanup of soils that harbour certain pollutants where reactivity is important.

In the future, it is all a matter of evaluating the total life-cycle of NBC, weighing the energy expenses incurred in its production against the nutrition benefits which it provides. Also, we should have field trials, long-term, solid, so we can step out of the pot lab and understand the real reason that nanocarbons act in the way they do in actual soils. It may be a hybrid in the future: bulk biochar in the large-scale structure, and nanobiochar in the chemical adjustments.

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Phosphorus-Solubilizing Microorganisms: Key to Sustainable Crop Nutrition Management

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1. Introduction

The key aspect of global food security is to increase the crop production and at the same time reduce the ecological footprint of intensive farming. The second most essential macro-nutrient in plant growth after nitrogen is phosphorus (P) and it coordinates the essential functions of plants like transfer of energy through ATP, photosynthesis, respiration, and movement of genetic material (DNA/RNA).

Phosphorus management, regardless of its supreme significance, offers a unique agronomic dilemma commonly referred to as phosphorus paradox. Many agricultural soils contain large proportions of total phosphorus, accumulated over many decades of fertilizer use -the so-called legacy P but only a minute fraction (usually less than 1%) of it is in the form of soluble orthophosphate ions ($H_2PO_4^-$ or HPO_4^{2-}).

Historically, one way to close this gap has been to extensively apply soluble chemical phosphate fertilizers (e.g. diammonium phosphate) or superphosphates. However, the yield of these fertilizers is notorious and lies in the range of 10-30 %. The overwhelming proportion of applied phosphorus is rapidly bound to the soil cations, calcium in alkaline soils, iron and aluminium in acidic soils, to form precipitates or to be adsorbed to clay minerals, thus making it unavailable to plants.

Furthermore, use of mined phosphate rock is not sustainable, considering that it is non-renewable and of limited global reserve. The ecological effects of over fertilization using P are dire and include but are not limited to the run-off of residual phosphorus into water bodies, precipitation of eutrophication, harmful algal proliferation, and eventual destruction of aquatic ecosystems.

Therefore, the release of the massive pool of insoluble phosphorus in the soil is a decisive breakthrough in the field of sustainable agriculture. Phosphorus-solubilizing microorganisms (PSMs), offer one of the most promising biological solutions to this dilemma, whereby phosphorus utilization efficiency is increased and dependence on synthetic inputs is reduced.

2. The Nature of Soil Phosphorus Unavailability

To value the importance of the PSMs, it is important to first understand the dynamics of phosphorus in soils. Phosphorus circulates primarily by geological and soil-based processes unlike nitrogen, which is majorly circulated in the atmosphere and through the biological system.

Phosphorus is present in two major pools in soil:

1. **Inorganic Phosphorus (Pi):** The inorganic phosphorus makes up around 35-70 % of total soil P, and is also extremely influenced by the pH of the soil.
   - **1.1. Acidic Soils (pH < 5.5):** Acidic Soils (pH: less than 5.5): Phosphorus is combined with iron (Fe), and aluminium (Al) oxides and hydroxides to form very insoluble iron and aluminium phosphates.
   - **1.2. Alkaline/Calcareous Soils (pH > 7.5):** This pool is part of total soil P, 30 % to 65 %, that is located in soil organic material as inositol phosphates (phytates), phospholipids and nucleic acids. The enzymes need to mineralize this pool in order to make it available.
2. **Organic Phosphorus (Po):** Comprising 30% to 65% of total soil P, this pool resides in soil organic matter, primarily as inositol phosphates (phytates), phospholipids, and nucleic acids. This pool must be mineralized by enzymes to become available.

The excessive absorption of the applied fertilizer P in these storage mechanisms results in crops commonly being exposed to P deficiency despite excessive fertilizer application in the soils.

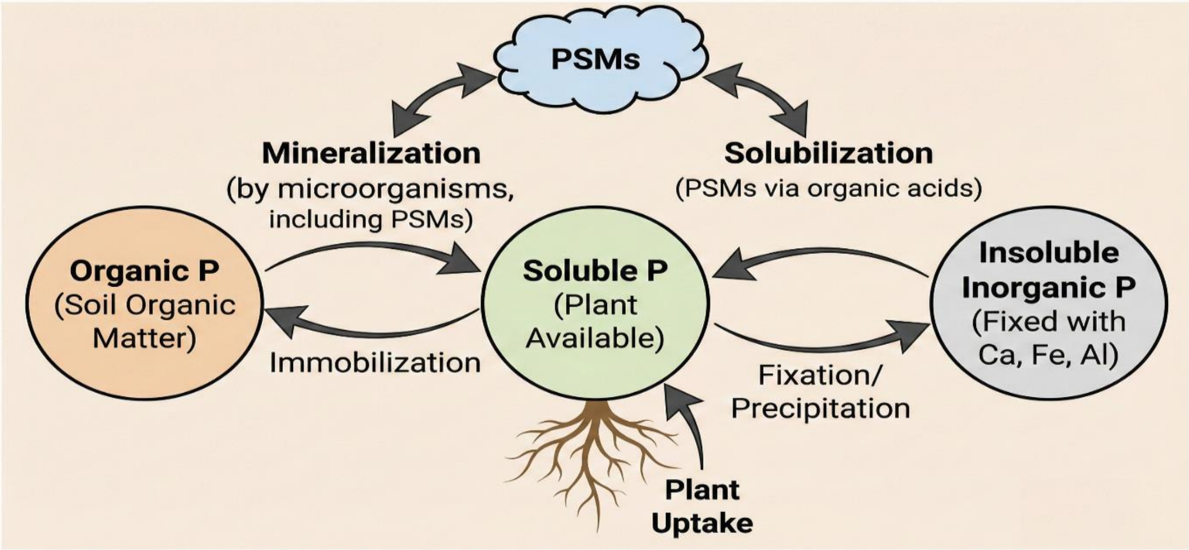

Figure 16. Phosphorus cycle

3. Phosphorus-Solubilizing Microorganisms (PSMs): An Overview

PSMs are a heterogeneous community of rhizospheric microorganisms that are able to transform insoluble phosphorus into soluble compounds. Even though they can be found in the soils, they are usually inadequate to meet the instant needs of the high-yielding crops.

The rhizosphere - the thin layer of soil around the roots of plants that are affected by root secretions - is a hot spot of activity of the PSM. These microbial populations are attracted and supported by exuding sugars, amino acids, and organic acids that the plants produce, and in return, provide soluble nutrients.

Major Groups of PSMs:

a) **Bacteria (PSB):** The most popular in terms of population and studies. Among the important genera are *Pseudomonas*, *Bacillus*, *Rhizobium*, *Enterobacter* and *Burkholderia.*

b) **Fungi (PSF):** The hyphae of the fungi are generally less dense in population compared to the bacteria; however, they can traverse a greater volume of soil. In addition, fungi tend to be very good in solubilizing rock phosphate, and they are more tolerant of acidic soils. The main genera are *Aspergillus*, *Penicillium*, and *Trichoderma*.

c) **Actinomycetes:** Filamentous bacteria that share characteristics with both bacteria and fungi. Key genera include *Streptomyces*.

Table 15. Common Genera of PSMs and Their Primary Mechanisms

Microbial Group	Genus Examples	Primary Mechanisms of P Solubilization	Other Beneficial Traits
Bacteria	*Pseudomonas spp.*	Organic acid production (gluconic acid)	Biocontrol of pathogens, Siderophore production
	Bacillus spp.	Organic acid production, Phosphatase activity	Spore formation (stress tolerance), PGPR hormones
	Rhizobium spp.	Organic acid production during symbiosis	Nitrogen fixation
Fungi	*Aspergillus spp.*	Strong organic acid production (citric, oxalic)	High tolerance to acidity
	Penicillium spp.	Organic acid production, Phytase activity	Rapid colonization
Actinomycetes	*Streptomyces spp.*	Enzymatic activity, Acid production	Antibiotic production

4. Mechanisms of Action

The ability of PSMs to move phosphorus is based on a number of complex biochemical activities which can be broadly classified as solubilization of inorganic P and the mineralization of organic P.

4.1. Solubilization of Inorganic Phosphorus

The major process of solubilizing inorganic phosphate compounds (calcium, iron, and aluminium phosphates) is the generation of low-molecular weight organic acids.

a) **Organic Acid Production:** Organic Acid Production: As a result of metabolizing glucose, PSMs produce a range of organic acids, gluconic, citric, oxalic, lactic, and malic acid.

b) **Acidification:** These acids dissociate protons (H^+) in the rhizosphere and reduce soil pH in the area. This reduction in pH in alkaline soils increases the solubility of the calcium phosphates.

c) **Chelation:** These organic acids (e.g. citrate, gluconate) anions act as powerful chelating agents. They attach to metal cations (Ca^{2+}, Fe^{3+} Al^{3+}) which captures phosphorus thereby releasing phosphate ions into the soil solution which is absorbed by plants.

4.2. Mineralization of Organic Phosphorus

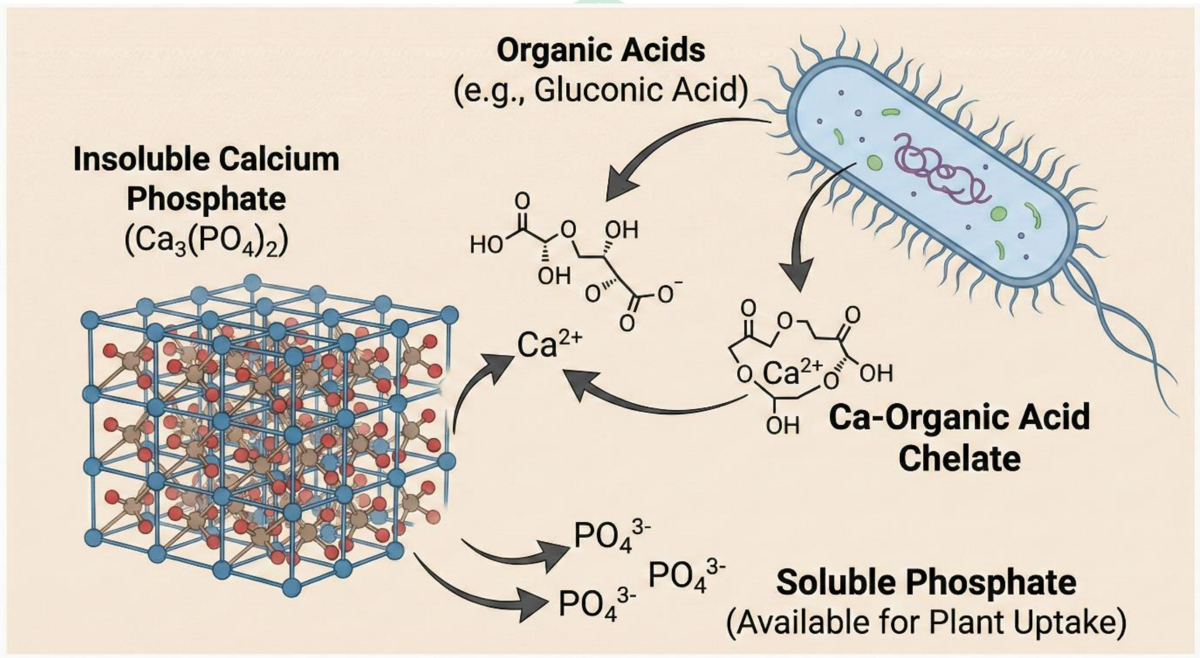

Figure 17. Diagram depicting a bacterium releasing organic acids which chelate calcium, releasing phosphate ions

Organic matter traps a large proportion of the phosphorus in the soil. This reservoir is mobilized by enzymatic hydrolysis using PSMs.

a) **Phosphatases:** PSMs secrete enzymes, which are called phosphatases (acid as well as alkaline phosphatases, according to the pH of soil). These enzymes are used in breaking down the ester bonds of organic phosphate compounds to release inorganic orthophosphate.

b) **Phytases:** This is a specialised group of enzymes that are required to break down phytate (inositol hexaphosphate) which is the main form of organic P in most soils, especially those which are fertilised with manure or plant debris. Plants in general do not have high phytase activity, and microbial phytases are therefore necessary to reach this pool.

5. Multifaceted Benefits Beyond Phosphorus

Although they are defined as P-solubilization, most effective PSMs are in reality, Plant Growth-Promoting Rhizobacteria/Fungi (PGPR/PGPF) which have collateral activity imparting to the overall crop wellness.

a) **Phytohormone Production:** Phytohormone Production: Indole-3-acetic acid (IAA), gibberellins and cytokinins are produced by a wide range of PSMs, especially *Pseudomonas* and *Bacillus* strains. These hormones mimic growth of roots and augmentation of root surface area which indirectly promotes the capacity of foraging of all nutrients and not just phosphorus by the plant.

b) **Nitrogen Fixation Synergy:** There are free-living nitrogen fixers, which are PSMs, allowing two nutrient benefits. Moreover, legumes that are inoculated with *rhizobia* (to fix N) and with the PSMs tend to display an upgraded nodulation, because the power requirement of N-fixation necessitates proper phosphorus content levels.

c) **Biocontrol Agents:** Some PSMs produce hormones (e.g., antibiotics) or hydrogen cyanide (HCN), or hydrolytic enzymes (chitinases) which suppress soil-borne pathogens (e.g., *Fusarium* or *Rhizoctonia*), which reduce the occurrence of crop disease.

d) **Abiotic Stress Tolerance:** There are those that have an enzyme called 1-aminocyclopropane-1-carboxylate (ACC) deaminase which reduces the amount of ethylene in plants causing them to be resistant to stressors such as salinity and drought.

6. Factors Affecting PSM Efficacy in the Field

One of the most common problems in agricultural microbiology is the laboratory-to-field inconsistency, where strains that are very good in controlled conditions on petri dishes do not give the same results in the field. Biotic and abiotic environmental factors impact on the efficacy of PSMs greatly:

a) **Soil Organic Matter (SOM):** SOM is the food of the heterotrophic PSMs. Low carbon soils will not sustain high populations of applied microbial inoculants.

b) **Soil pH:** PSMs have the capability of modifying local soil pH with extreme soil pH preventing microbial growth and enzyme activities. The fungal PSMs normally thrive well in acidic soils, as compared to bacteria.

c) **Native Microbial Competition:** Competition between Introduced PSM strains and Existing Soil Microflora: Introduced PSM strains have to compete against native microflora in the soil regarding resources and niche occupancy. In many cases, the strains of foreigners are competed and perish quickly upon application.

d) **Environmental Stress:** Stress in the Environment Temperature extremes, drought, and salinity may have a devastating effect on the survival and metabolism of microbes.

7. Application as Biofertilizers: Current Status and Challenges

Commercially, PSMs are used as biofertilizers, seed treatment, seedling root dipping, or applied to the soil. They are commonly made along with carriers such as peat, lignite or liquid polymers to make sure that they can last on the shelf and survive till they are transported.

Table 16. Comparative Analysis of Chemical P Fertilizers vs. PSM Biofertilizers

Feature	Chemical Phosphate Fertilizers	PSM Biofertilizers
Source of P	External (mined rock phosphate)	Internal (solubilizes existing soil legacy P)
Availability Mechanism	Direct supply of soluble P	Biological transformation of insoluble P
Efficiency	Low (10–30%); rapid fixation	Moderate to High (over time); sustained release
Environmental Impact	High (eutrophication risk, energy-intensive production)	Positive (improves soil health, reduces runoff)
Cost	High and volatile	relatively low
Impact on Soil Health	Can degrade soil structure and microflora over time	Enhances soil biological activity and structure
Consistency of Result	Generally high (short term)	Variable (dependent on environmental conditions)

Challenges in Widespread Adoption:

PSM biofertilizers have challenges in spite of their benefits. The main issue is unstable field performance based on the factors that have been discussed in Section 6. Moreover, biofertilizers are frequently less regulated than chemicals resulting in mixed quality products and viable spore counts on the market. Crop-specific strain selection and soil-specific strain selection is also required since a one-fits-all method is seldom successful in microbiology.

8. Future Perspectives and Conclusion

The future of PSM technology is to go further than the one-strain inoculants. Studies are beginning to concentrate on:

- **Microbial Consortia:** Production of cocktails of microorganisms that contain PSMs, nitrogen fixers and mycorrhizal fungi (that transport P over long distances). The synergistic effects that are sometimes portrayed by these consortia are usually better than the performance of single strains.
- **Genetic Engineering:** Genetic engineering of PSMs is under consideration to produce organic acids or phosphatase enzymes but there are still obstacles due to regulatory and publicity issues.
- **Molecular Tools:** o learn more about the native P-solubilizing communities to optimize inoculation strategies in various soils, metagenomics will be used.

Conclusion

The phosphate fertilization methods adopted at the moment are unsustainable, which leads to the need to shift to the biological methods of nutrient management. Phosphorus-solubilizing microorganisms are an irreplaceable instrument in this change. PSMs will provide a mechanism to sustain the high yield of crops in the farm soils by unlocking the enormous reserves of legacy phosphorus already in the soil and helping in the restoration of soil health and the reduction of environmental damage. Although there are still difficulties in achieving the consistency of the field performance, a key to the future sustainable agriculture is the implementation of PSM of high quality in the Integrated Nutrient Management programs.

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