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Beyond Cavendish: How Traditional Bananas can Help Fight Hidden Hunger?

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Abstract
Although the Cavendish banana dominates global markets, many traditional and indigenous banana cultivars possess significant nutritional qualities that can contribute to addressing micronutrient malnutrition or "hidden hunger." Across regions such as Papua New Guinea, Micronesia, East Africa, and India, diverse banana varieties have been conserved by farmers, many of which are rich in provitamin A carotenoids, iron, zinc, antioxidants, and dietary fiber. Cultivars such as Karat, Asupina, Utin Iap, Fe'i bananas, and several Indian landraces have been reported to contain comparatively higher nutrient levels than commonly cultivated commercial bananas. These nutrient-dense genetic resources are important donors for biofortification programs aimed at improving vitamin A and micronutrient intake. This article highlights the nutritional diversity of traditional bananas, their role in food and nutritional security, and the importance of conserving banana biodiversity for future crop improvement.

Introduction
When people think of bananas, the image that usually comes to mind is the familiar yellow Cavendish banana found in supermarkets and fruit markets around the world. This single cultivar dominates international trade and contributes significantly to global banana production. Yet, hidden behind this commercial success is a remarkable treasure of banana diversity that has been nurtured by farmers for centuries.

Across tropical regions of Asia, Africa, and the Pacific Islands, hundreds of traditional banana varieties continue to be cultivated in home gardens, small farms, and indigenous farming systems. Many of these local cultivars are not only adapted to specific environments but are also rich sources of vitamins, minerals, antioxidants, and dietary fiber. In recent years, scientists have begun to recognize that these traditional bananas may hold an important key to addressing one of the world's most persistent nutritional challenges - hidden hunger (Davey et al., 2009; Fungo et al., 2010).

Unlike visible hunger, which results from insufficient food intake, hidden hunger occurs when people consume enough calories but do not receive adequate amounts of essential micronutrients such as vitamin A, iron, and zinc. More than two billion people worldwide suffer from micronutrient deficiencies, leading to impaired growth, weakened immunity, poor cognitive development, anemia, and increased susceptibility to disease (Bailey et al., 2015).

Traditional banana varieties, many of which possess naturally high concentrations of provitamin A carotenoids and other micronutrients, offer a promising and sustainable approach to improving nutrition through agriculture. By conserving and utilizing banana biodiversity, we can strengthen food systems while improving human health.

Banana: More than Just an Energy Fruit
Banana is one of the world's most important fruit crops and serves as a staple food for over 400 million people in tropical and subtropical regions. It is valued not only for its taste and convenience but also for its nutritional benefits.

Bananas provide:
1. Easily digestible carbohydrates that supply energy
2. Dietary fiber that supports digestive health
3. Potassium, important for heart function and blood pressure regulation
4. Vitamins such as vitamin C and vitamin B6
5. Bioactive compounds including flavonoids, phenolics, and antioxidants

Interestingly, the nutritional value of banana extends beyond the fruit pulp. Banana flowers, pseudostems, peels, and leaves contain several beneficial phytochemicals and are increasingly being explored for food, nutraceutical, and medicinal applications.

Although commercial bananas provide valuable nutrients, research has shown that many traditional cultivars contain substantially higher levels of carotenoids, minerals, and antioxidant compounds.

Understanding Hidden Hunger
The term hidden hunger refers to deficiencies of essential vitamins and minerals that often go unnoticed until serious health problems emerge.

Three of the most widespread micronutrient deficiencies are:

Vitamin A Deficiency: Vitamin A is essential for vision, immune function, and healthy growth. Deficiency can lead to night blindness, increased risk of infections, and, in severe cases, permanent blindness.

Iron Deficiency: Iron deficiency is the leading cause of anemia worldwide. It reduces physical work capacity, impairs cognitive development, and increases maternal health risks.

Zinc Deficiency: Zinc plays a crucial role in growth, immune response, and wound healing. Deficiency can result in stunted growth and increased vulnerability to disease.

Conventional strategies such as supplementation and food fortification have helped reduce these deficiencies. However, such interventions require continuous investment and infrastructure. This has led scientists to explore more sustainable approaches, including biofortification.

Biofortification: Improving Nutrition through Crops

Biofortification is the process of increasing the nutrient content of food crops through plant breeding, agronomic practices, or biotechnology. Instead of adding nutrients during food processing, biofortification enhances nutritional value directly in the crop itself (HarvestPlus, 2018).

The approach offers several advantages:

1. Reaches rural populations with limited access to fortified foods
2. Requires only a one-time investment in crop development
3. Provides continuous nutritional benefits over generations
4. Integrates nutrition improvement with agricultural production

Banana is considered an excellent candidate for biofortification because of its widespread consumption and rich genetic diversity.

Why Bananas are Ideal for Biofortification?

Several characteristics make bananas particularly suitable for nutritional improvement:

High Consumption: In many tropical countries, bananas are eaten daily and contribute significantly to calorie intake.

Year-Round Availability: Unlike seasonal crops, bananas are available throughout the year, ensuring a continuous supply of nutrients.

Cultural Acceptance: Bananas are deeply integrated into local diets and culinary traditions.

Vegetative Propagation: Bananas are propagated through suckers and tissue culture, helping maintain desirable nutritional traits across generations.

Vast Genetic Diversity: Thousands of banana accessions exist worldwide, providing a rich pool of genes for breeding nutrient-dense cultivars.

These advantages position banana as an important crop for combating micronutrient deficiencies.

India's Treasure Trove of Nutrient Rich Bananas

India is one of the world's largest producers of bananas and possesses extraordinary banana diversity. Several indigenous cultivars are recognized for their superior nutritional qualities.

Nendran: Widely cultivated in Kerala and parts of Tamil Nadu, Nendran is known for its rich carotenoid content and high dietary fiber. It is commonly used for chips, baby foods, and traditional dishes.

Red Banana: The attractive red-skinned banana contains comparatively higher levels of carotenoids and antioxidants than many dessert bananas. Its creamy texture and nutritional richness make it a valuable dietary component.

Nutritional Wealth of Northeast India

The northeastern states of India are home to unique banana diversity that remains largely unexplored.

Bhimkol: Derived from Musa balbisiana ancestry, Bhimkol is valued for its high fiber content and mineral richness. It forms an important part of traditional diets.

Malbhog: Known for its sweetness and consumer preference, Malbhog also possesses a balanced nutritional profile.

Athiakol, Jahaji, and Champa: These local cultivars contribute significantly to dietary diversity and represent valuable genetic resources for future breeding programs.

The region's red banana types are particularly notable for their elevated carotenoid and antioxidant content.

Banana Diversity in the Andaman and Nicobar Islands

The Andaman and Nicobar Islands represent a unique hotspot of Musa biodiversity.

Several cultivated and wild banana species thrive in these islands under diverse ecological conditions. Among them, the Korangi banana has attracted attention because of its relatively high carotenoid content, making it a potential source of provitamin A (ICAR-CIARI, 2026).

The islands are also home to rare wild species such as:
1. *Musa sabuana*
2. *Musa indandamanensis*

Although these species may not be consumed directly, they represent valuable reservoirs of genes for disease resistance, climate resilience, and nutritional enhancement.

Preserving these unique genetic resources is essential for future banana improvement programs (Pillay and Tenkouano, 2011).

Remarkable Bananas Beyond India

Papua New Guinea: A Centre of Banana Diversity: Papua New Guinea is recognized as one of the world's major centres of banana diversity. Local communities have conserved hundreds of traditional cultivars over generations.

Among them are some of the most nutrient-rich bananas known.

Fe'i Bananas: Fe'i bananas are easily recognized by their bright orange pulp. Their striking colour reflects exceptionally high concentrations of provitamin A carotenoids.

Asupina: This cultivar has been identified as a rich source of beta-carotene and is frequently cited in biofortification research.

Utin Iap: Utin Iap contains some of the highest carotenoid levels reported in bananas, making it a particularly valuable genetic resource.

Micronesia's Karat Banana: The Karat banana has become famous for its deep orange flesh and exceptionally high provitamin A content.

Nutrition programs in Micronesia have successfully promoted Karat consumption to help reduce vitamin A deficiency among children and women. It remains one of the most celebrated examples of using traditional crops to improve public health (Englberger et al., 2006; Fungo et al., 2010).

Africa's Nutritional Bananas: In East Africa, highland bananas serve as staple foods and provide a substantial portion of daily calorie intake.

Plantains in West and Central Africa are another important food source. Although primarily valued for energy, several plantain cultivars contain higher carotenoid levels than Cavendish bananas and contribute valuable micronutrients.

How Different are these, Bananas?

The nutritional differences among banana cultivars can be dramatic.

Approximate provitamin A carotenoid levels in fresh fruit are:

Table 2. Approximate provitamin A carotenoid content:

Banana Type	Provitamin A Carotenoids (µg/100 g FW)
Cavendish	20–30
Red Banana	100–300
Nendran	150–400
Asupina	1500–3000
Karat	1000–2200
Utin Iap	5000–7000

Englberger et al. (2006), Fungo et al. (2010), Davey et al. (2009), and HarvestPlus (2018).

These figures illustrate how certain traditional bananas can contain dozens or even hundreds of times more provitamin A than standard Cavendish bananas.

Such variation offers enormous opportunities for breeding and nutritional improvement.

Conserving Banana Biodiversity for the Future

Despite their importance, many traditional banana varieties are under threat.

Several factors contribute to their decline:
1. Expansion of commercial monocultures
2. Changing consumer preferences
3. Urbanization
4. Loss of traditional knowledge

5. Climate change and environmental pressures

When a traditional cultivar disappears, unique genes for nutrition, disease resistance, stress tolerance, and adaptation may be lost forever.

Conservation efforts therefore play a critical role. These include:

Gene banks: National and international germplasm collections preserve banana diversity for future use.

Field collections: Living collections maintain plants under field conditions for evaluation and research.

Community conservation: Farmers remain the most important custodians of banana diversity. Supporting local cultivation and traditional knowledge is essential for long-term conservation.

A Path Toward Better Nutrition

As global populations grow and nutritional challenges persist, agriculture must contribute not only to food production but also to better nutrition.

Traditional bananas demonstrate how biodiversity can support human health. Varieties such as Karat, Asupina, Utin Iap, Fe'i bananas, Nendran, Bhimkol, and Red Banana show that naturally nutrient-rich crops already exist within farming communities. By studying, conserving, and utilizing these valuable genetic resources, scientists and farmers can work together to develop more nutritious banana varieties for future generations.

The story of banana improvement is therefore not simply about producing more fruit. It is about rediscovering the nutritional treasures hidden within traditional cultivars and using them to address one of the world's most pressing public health challenges.

Conclusion

The familiar Cavendish banana may dominate global markets, but it represents only a small fraction of banana diversity. Across India, Africa, Micronesia, and the Pacific Islands, traditional banana cultivars offer remarkable nutritional advantages, particularly in terms of provitamin A carotenoids, minerals, and antioxidants.

These nutrient-dense bananas provide valuable opportunities for combating hidden hunger, strengthening food security, and supporting sustainable agriculture. Their conservation and utilization will be essential for future biofortification efforts and for ensuring that banana cultivation contributes not only to food production but also to better nutrition and healthier communities.

The future of nutrition may lie not in discovering new crops, but in rediscovering the extraordinary diversity that farmers have preserved for generations.

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Fe'i bananas, the cut-opened fruit showing the characteristic deep orange pulp associated with high provitamin A carotenoid content.

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Edible Dyes: Sources, Applications, Safety Aspects, and Future Prospects

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Introduction

Colour is one of the most important sensory attributes influencing consumer perception, acceptance, and purchasing behaviour of food products. Consumers often associate bright, uniform colours with freshness, flavour quality, and nutritional value. To preserve visual appeal, compensate for colour losses during processing and storage, and maintain product consistency across different production batches, the food industry extensively utilizes edible dyes, also known as food colorants.

Edible dyes are food-grade substances approved for human consumption under strict regulatory guidelines. These colorants are broadly classified into two categories: natural colorants, derived from plants, microorganisms, algae, and insects, and synthetic colorants, produced through chemical synthesis.

Growing consumer preference for healthier and cleaner-label products has accelerated the shift toward natural colorants. Consequently, researchers are focusing on innovative extraction, stabilization, and formulation technologies to enhance the performance of natural pigments and make them competitive with conventional synthetic dyes.

Natural Edible Dyes

Natural colorants are pigments obtained from biological sources. In addition to imparting colour, many natural pigments possess bioactive compounds that exhibit antioxidant, anti-inflammatory, and antimicrobial properties.

Curcumin (Yellow):

- **a. Source:** Extracted from the rhizomes of turmeric (*Curcuma longa*).
- **b. Applications:** Widely used in dairy products, beverages, confectionery, and spice mixtures.
- **c. Advantages:** Possesses strong antioxidant activity and aligns well with clean-label product requirements.
- **d. Limitations:** Sensitive to light and alkaline conditions (pH > 7), resulting in gradual colour degradation.

Anthocyanins (Red, Purple, and Blue):

- **a. Source:** Found in berries, grapes, red cabbage, and purple sweet potatoes.
- **b. Applications:** Commonly incorporated into fruit juices, soft drinks, jams, and fruit-flavoured yogurts.
- **c. Functional Characteristics:** Highly pH-sensitive, displaying red hues in acidic conditions and shifting toward blue-green shades as pH increases.

Carotenoids (Yellow to Red):

- **a. Major Compounds:** ß-Carotene, lycopene, lutein, and zeaxanthin.
- **b. Source:** Derived from carrots, tomatoes, paprika, and palm oil.
- **c. Applications:** Suitable for fat-containing products such as margarine, cheese, bakery products, and salad dressings.
- **d. Health Benefits:** Several carotenoids function as provitamin A compounds that support vision and immune health.

Betalains (Red and Yellow):

- **a. Source:** Primarily extracted from red beetroot (*Beta vulgaris*).
- **b. Applications:** Used in ice cream, yogurt, confectionery products, and powdered beverage mixes requiring vibrant red shades.
- **c. Advantages:** Provide intense colour with minimal impact on flavour.

Phycocyanin (Blue):

- **a. Source:** Obtained from the microalga *Spirulina* (*Arthrospira platensis*).
- **b. Applications:** Used in candies, chewing gums, and clear beverages.
- **c. Significance:** One of the few commercially available natural blue pigments, offering an alternative to synthetic blue dyes.

Synthetic Edible Dyes

Synthetic food colorants are chemically manufactured pigments valued for their high colouring efficiency, consistency, and resistance to environmental factors.

Dye Name	Hue	Primary Applications
Tartrazine	Bright Yellow	Carbonated sodas, gelatin desserts, confections
Sunset Yellow FCF	Orange-Yellow	Processed snacks, cereals, baked goods
Allura Red AC	Deep Red	Condiments, gelatin, baked sweets, pastries
Brilliant Blue FCF	Vibrant Blue	Ice creams, liqueurs, decorative icings
Erythrosine	Bluish Pink / Red	Glacé cherries, decorative candies, pharmaceuticals

Advantages:

a. High Colour Intensity: Small quantities produce strong and vibrant colours.
b. Excellent Stability: Resistant to heat, light, oxygen exposure, and pH variations.
c. Cost-Effectiveness: Significantly less expensive to manufacture than most natural colorants.

Limitations:

a. Health Concerns: Certain synthetic dyes have been associated with allergic reactions, hypersensitivity, asthma-like symptoms, and behavioural effects in susceptible children.
b. Regulatory Restrictions: Increasingly subject to usage limits, warning labels, and regulatory scrutiny in many countries.

Functions and Applications in Food Systems

Primary Functions:

a. Visual Enhancement: Improves product appearance and consumer appeal.
b. Colour Restoration: Replaces pigments lost during processing, storage, or transportation.
c. Standardization: Maintains uniform product colour despite natural variations in raw materials.
d. Product Identification: Helps consumers associate colours with specific flavours and product types.

Major Industrial Applications

Bakery and Confectionery: Colorants are extensively used in cakes, biscuits, candies, gummies, and decorative frostings to improve attractiveness and marketability.

Dairy Products: Cheese, flavoured milk products, yogurts, and frozen desserts utilize colorants to achieve consistent and appealing appearances.

Beverage Industry: Soft drinks, sports beverages, and fruit juices employ colorants to reflect flavour characteristics and enhance consumer expectations.

Pharmaceutical Products: Edible dyes are incorporated into syrups, capsules, and coated tablets to facilitate product identification and reduce medication errors.

Safety and Regulatory Considerations: The use of food colorants is regulated by international authorities such as the Food and Drug Administration (FDA), the European Food Safety Authority (EFSA), and the Food Safety and Standards Authority of India (FSSAI). These agencies evaluate food colorants and establish safety standards based on toxicological assessments, including:

a. Acceptable Daily Intake (ADI): The estimated quantity of a substance that can be consumed daily throughout life without significant health risk, typically expressed in mg/kg body weight.
b. Purity Requirements: Strict specifications limit contaminants such as lead, arsenic, mercury, and other heavy metals in commercial dye preparations.
c. Labelling Requirements: Many jurisdictions require clear labelling of products containing specific synthetic colorants to help consumers make informed choices.

Emerging Trends and Challenges in Natural Colorants

Technical Challenges: The transition from synthetic to natural dyes presents several obstacles:

a. Limited Stability: Natural pigments are often susceptible to degradation caused by heat, light, and oxygen exposure.
b. Higher Production Costs: Extraction and purification processes are generally more expensive than synthetic manufacturing.
c. Supply Variability: Seasonal and environmental factors can affect pigment availability and consistency.

Technological Innovations

To overcome these challenges, researchers are developing advanced technologies such as:

Microencapsulation: Sensitive pigments are enclosed within protective materials such as maltodextrin, gum arabic, or liposomes to improve stability and shelf life.

Biotechnology-Based Production: Microorganisms, including algae, yeasts, and fungi, are cultivated in controlled bioreactors to provide reliable, year-round pigment production.

Nanoformulations: Nanotechnology enhances pigment dispersion, solubility, colour intensity, and bioavailability within food systems.

Waste Valorization: Natural pigments are increasingly recovered from food-processing by-products such as grape pomace, beetroot residues, pomegranate peels, and mango skins, supporting sustainable and circular economy practices.

Future Prospects

The future of the edible colorant industry is increasingly oriented toward natural and clean-label solutions. Rising consumer awareness, stricter environmental regulations, and growing demand for sustainable products are expected to accelerate the adoption of natural pigments. Continued advancements in pigment stabilization, microbial biotechnology, genetic engineering, and environmentally friendly extraction methods will help transform natural colorants into highly efficient, economical, and sustainable alternatives for the global food industry.

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Machine Learning – Basics, Concepts and Its Application in Fruit Culture

Article ID: 74202

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Summary
Machine learning (ML) allows computers to analyse data and make informed decisions without the need for explicit programming. In the context of fruit cultivation, ML is applied for early pest and disease detection, precision irrigation and nutrient management, yield forecasting, and assessment of crop quality. This article outlines the core concepts of ML and highlights its practical applications in improving productivity and promoting sustainable horticultural practices.

Machine Learning
Machine learning refers to a computer's capability to learn patterns and make predictions from data without explicit programming. This approach is not only easier to manage but also delivers highly accurate outcomes. Common real-world applications of machine learning include search engine result ranking, traffic forecasting, online fraud detection, email spam filtering, virtual assistants, and automated language translation.

Types of Machine Learning
1. Supervised Learning
2. Unsupervised Learning
3. Semi-supervised Learning
4. Reinforcement Learning.

Supervised Learning
Supervised learning involves training models to make predictions or decisions using labelled datasets. It is broadly categorised into classification and regression algorithms. Classification algorithms are applied in scenarios such as fraud detection, email spam filtering, medical diagnostics, and image recognition. Regression algorithms are commonly used for tasks like risk assessment and score prediction.

Important Supervised Learning Algorithms
1. K Nearest Neighbors
2. Linear Regression
3. Logistic Regression
4. Support Vector Machines
5. Decision Tree and Random Forests
6. Neural Networks

Unsupervised Learning
Unsupervised learning is a type of machine learning in which algorithms learn patterns and structures from unlabeled data without predefined outputs. It is commonly categorized into clustering, visualization, and dimensionality reduction techniques.

Semi-Supervised Learning
Semi-supervised learning is a machine learning approach in which algorithms are trained using a combination of a small amount of labeled data and a large amount of unlabeled data. This method leverages the limited labeled information to guide learning from the abundant unlabeled data.

Reinforcement Learning
Reinforcement learning is a machine learning paradigm in which an agent learns by interacting with its environment. The agent selects and executes actions, observes the outcomes, and receives rewards or penalties, using this feedback to improve future decision-making.

Applications of Machine Learning

Applications of machine learning in agriculture are diverse and transformative. It enables accurate yield prediction, allowing farmers to plan and optimize resources effectively. Machine learning also supports early detection of diseases, reducing crop losses and improving plant health. Furthermore, it aids in assessing and maintaining crop quality, ensuring better marketability, and extends to livestock management, enhancing animal health monitoring, productivity, and farm efficiency.

Advantages of Machine Learning in Fruit Cultivation

Effective agricultural management benefits greatly from advanced technologies that enable the timely detection and control of pests and diseases, ensuring crop health and productivity. Precision approaches in irrigation scheduling and nutrient management optimize resource use and enhance plant growth. Additionally, improvements in fruit quality assessment and sorting facilitate better marketability, while accurate crop yield estimation supports informed planning and supply chain decisions. Collectively, these strategies contribute to the adoption of climate-resilient practices, enhancing the sustainability and efficiency of horticultural systems.

Challenges in Applying Machine Learning to Fruit Cultivation

The widespread adoption of machine learning in agriculture faces several challenges. One major limitation is the scarcity of large, annotated datasets for certain crops, which restricts model training and accuracy. Additionally, the high cost of sensors and data acquisition tools can be a barrier for widespread implementation. Successful deployment also requires farmer training and capacity-building to ensure effective use of these technologies. Furthermore, transferring models across diverse agro-climatic regions poses challenges due to variations in environmental conditions and crop responses, highlighting the need for adaptable and region-specific solutions.

Conclusion

Machine learning is reshaping fruit cultivation by facilitating data-driven decision-making that enhances yield, fruit quality, and resource use efficiency. While challenges such as limited datasets and the cost of technology remain, ML offers substantial potential to promote sustainable and resilient fruit production.

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Health Benefits and Risks of Chocolate

Article ID: 74203

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Chocolate is made from the seeds of the tropical Theobroma cacao tree. Chocolate has a rich and fascinating history that dates back thousands of years. It originated from the cacao beans of the tropical regions of Central and South America, where ancient civilizations such as the Maya and Aztecs consumed cacao as a bitter beverage and considered it a valuable and sacred ingredient. The Aztecs used cacao in religious ceremonies and believed it had energizing and medicinal properties. After the arrival of Europeans in the 16th century, cacao was introduced to Europe, where it was transformed by adding sugar and other ingredients to create a sweeter chocolate drink.

Over time, advances in food processing led to the development of solid chocolate, milk chocolate, and various chocolate products. The invention of modern chocolate-making techniques during the 19th century helped make chocolate widely available across the world. Today, chocolate is enjoyed globally not only as a popular confectionery product but also as a food ingredient studied for its nutritional value and potential health benefits, particularly due to the presence of antioxidants and bioactive compounds in cocoa. Since then, chocolate has become a widely enjoyed food product, loved by millions for its unique, rich, and sweet taste.

What Effect does Eating Chocolate Have on our Health?

1. Chocolate consumption has long been associated with conditions such as diabetes, coronary heart disease, and hypertension.
2. Chocolate is believed to contain high levels of antioxidants.
3. Some studies suggest that chocolate may help lower cholesterol levels and prevent memory decline.
4. Chocolate contains a high number of calories.
5. People who are trying to lose or maintain weight should consume chocolate in moderation.

Types of Chocolate

Chocolate has many types and can be classified into different categories depending on its color, composition, uses, flavor potential, and price. There are three main types of chocolate: white chocolate, milk chocolate, and dark chocolate. Dark chocolate has an intense and rich taste due to its high cocoa content. It is made from cocoa butter, cocoa paste (or “cocoa mass”), and sugar. Milk chocolate also contains cocoa butter, cocoa paste, and sugar, but it differs from dark chocolate because powdered milk is added to its basic ingredients. The third type is white chocolate. This variety was invented by the famous Swiss chocolatier Daniel Peter. The main component of white chocolate is cocoa butter, a natural fat obtained from cocoa beans. This unique composition makes it a distinct type of chocolate.

Supervised Learning

Supervised learning involves training models to make predictions or decisions using labelled datasets. It is broadly categorised into classification and regression algorithms. Classification algorithms are applied in scenarios such as fraud detection, email spam filtering, medical diagnostics, and image recognition. Regression algorithms are commonly used for tasks like risk assessment and score prediction.

Eating Chocolate may have the Following Benefits

1. Chocolate may help improve heart health.
2. Dark chocolate helps control insulin sensitivity.
3. Chocolate may help regulate blood pressure.
4. Dark chocolate can help curb other cravings.
5. Chocolate may help reduce cholesterol levels.
6. Pure chocolate provides nutritional benefits.
7. Chocolate may enhance the skin’s natural protection.

Whether dark chocolate is better than white chocolate depends on various factors. Cacao is a popular antioxidant known to support heart health and help reduce inflammation (Katz et al., 2011). It is found in the highest amounts in high-quality dark chocolate. However, white chocolate is not entirely without benefits. High-quality cocoa butter, the main ingredient in white chocolate, is also a rich source of antioxidants that are beneficial to the body.

Milk vs. Dark Chocolate

Chocolate exhibits antioxidant activity primarily due to its high content of cocoa-derived polyphenols, particularly flavonoids. The antioxidant potential increases with cocoa content; therefore, dark chocolate generally possesses greater antioxidant capacity than milk chocolate. Dark chocolate also typically contains less sugar and a higher proportion of cocoa solids and cocoa butter.

In contrast, milk chocolate provides additional nutrients such as protein and calcium from milk ingredients, but its antioxidant activity is generally lower because of its reduced cocoa content and the possible interaction between milk proteins and cocoa polyphenols, which may affect their bioavailability. Overall, dark chocolate is considered a richer source of bioactive compounds associated with potential cardiovascular and metabolic health benefits when consumed in moderation.

How do the Nutrients Compare?

Nutrient	Milk chocolate (100 g)	Dark chocolate (100 g)
Energy	535 kcal	598 kcal
Protein	7.65 g	7.79 g
Carbohydrate	59.4 g	45.9 g
Fat	29.7 g	42.6 g
Sugars	51.5 g	24 g
Iron	2.35 mg	11.9 mg
Phosphorus	208 mg	308 mg
Potassium	372 mg	715 mg
Sodium	79 mg	20 mg
Calcium	189 mg	73 mg

(Internet sources)

The darker the chocolate, the higher the concentration of cocoa, and so, in theory, the higher the level of antioxidants there will be in the bar.

Risks and Precautions

Although chocolate offers several health benefits, excessive consumption may have adverse health effects, particularly due to its high sugar and fat content. Chocolate has been associated with conditions such as acne, obesity, hypertension, coronary artery disease (Yuan et al.,2017), and diabetes when consumed in excess.

1. Weight gain: Chocolate is calorie-dense because of its high sugar and fat content. Individuals who are trying to lose or maintain weight should consume chocolate in moderation and carefully check the nutritional information on product labels.

2. High sugar content: Frequent consumption of chocolate with a high sugar content can contribute to tooth decay and increase the risk of metabolic disorders.

3. Migraine risk: In some individuals, chocolate may trigger migraine attacks. However, current research provides mixed evidence, and there is insufficient scientific proof to recommend avoiding chocolate completely for people with migraines.

4. Heavy metal contamination: Certain cocoa powders, chocolate bars, and cacao nibs may contain elevated levels of cadmium and lead. Long-term exposure to high amounts of these heavy metals may adversely affect the kidneys, bones, and other body tissues.

5. Caffeine content: Chocolate naturally contains caffeine. Individuals who need to limit caffeine intake, such as pregnant women or those with caffeine sensitivity, should consume chocolate cautiously.

Overall, moderate consumption of high-quality chocolate, particularly dark chocolate with a high cocoa content and low added sugar, is recommended to maximize its health benefits while minimizing potential risks.

Conclusion

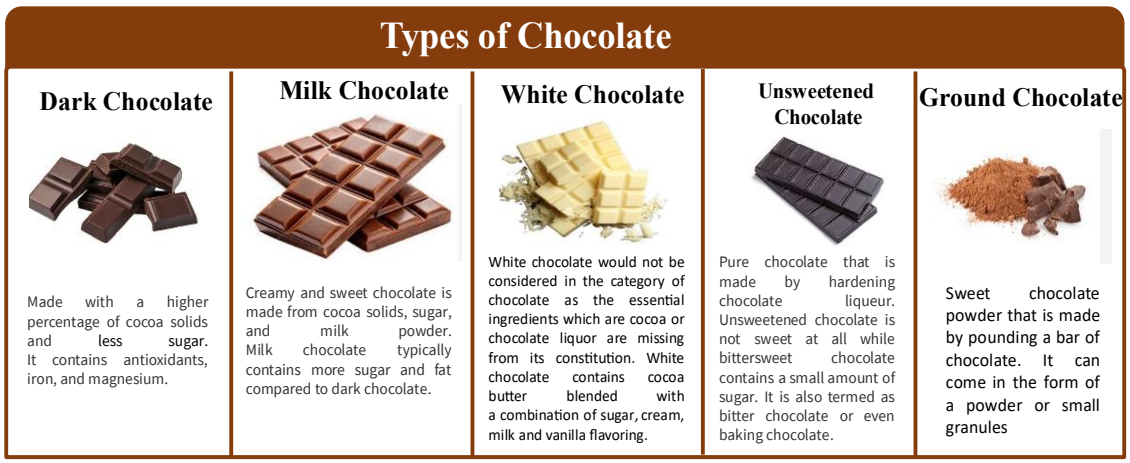
Chocolate is a widely consumed food that offers both nutritional benefits and potential health risks, depending on its type, composition, and level of consumption. Among the three main varieties, dark chocolate contains the highest amount of cocoa-derived polyphenols and antioxidants, making it the most beneficial for supporting cardiovascular health, improving insulin sensitivity, reducing blood pressure, lowering cholesterol, and providing anti-inflammatory effects when consumed in moderation. Milk chocolate provides additional nutrients such as protein and calcium but contains lower levels of antioxidants, while white chocolate contains cocoa butter with some antioxidant properties but lacks cocoa solids, limiting its health-promoting potential. Despite these benefits, chocolate is also a calorie-dense food that often contains high amounts of sugar and fat, which may contribute to obesity, tooth decay, diabetes, and

cardiovascular diseases if consumed excessively. In addition, concerns regarding caffeine, heavy metal contamination, and migraine susceptibility should be considered by sensitive individuals. Therefore, moderate consumption of high-quality chocolate, particularly dark chocolate with a high cocoa content and low added sugar, can be included as part of a balanced diet to maximize health benefits while minimizing potential risks.

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Advances in Hybrid Breeding and Heterosis: Genomic Insights for Yield Gains in Self and Cross-Pollinated Crops

Article ID: 74204

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Introduction

Meeting the food requirements of a growing global population requires continuous improvement in crop productivity without expanding agricultural land. Hybrid breeding has emerged as one of the most successful approaches for increasing yield, improving stress tolerance, and enhancing crop quality. The remarkable success of hybrid maize during the twentieth century demonstrated the immense potential of heterosis, or hybrid vigor, in achieving substantial genetic gains. Today, advances in molecular genetics, genomics, and computational breeding have transformed hybrid breeding into a precision-based approach capable of accelerating crop improvement in both self- and cross-pollinated crops (Hickey et al., 2019; Chen, 2013).

Modern genomic technologies have enabled breeders to better understand the genetic mechanisms underlying heterosis and to identify superior parental combinations with greater accuracy. The integration of molecular markers, genomic selection, high-throughput phenotyping, and artificial intelligence is accelerating hybrid development while improving breeding efficiency. These innovations are expected to play a critical role in developing high-yielding and climate-resilient cultivars capable of sustaining future global food security (Varshney et al., 2021).

Concept of Hybrid Breeding and Heterosis

Hybrid breeding involves crossing two genetically distinct parental lines to produce first-generation (F_1) hybrids that exhibit superior performance compared with either parent. This superiority, known as **heterosis** or **hybrid vigor**, is expressed as increased yield, improved growth, enhanced adaptability, better resistance to pests and diseases, and greater tolerance to environmental stresses. The concept of heterosis was first scientifically described by **George H. Shull** and **Edward M. East** in the early twentieth century, laying the foundation for modern hybrid breeding (Shull, 1908; East, 1908).

Hybrid breeding has become a cornerstone of crop improvement because it combines desirable genes from different parents into a single genotype. The commercial success of hybrid maize, rice, sunflower, pearl millet, and several vegetable crops demonstrates the effectiveness of this approach in increasing agricultural productivity. Continued advances in genetics and genomics are further expanding the scope of hybrid breeding to additional crop species and complex agronomic traits.

Genetic Basis of Heterosis

Although heterosis has been exploited successfully for decades, its genetic basis remains complex. Three major hypotheses have been proposed to explain hybrid vigor: the **dominance hypothesis**, **overdominance hypothesis**, and **epistasis hypothesis**. The dominance hypothesis suggests that favorable dominant alleles from one parent mask harmful recessive alleles inherited from the other parent. The overdominance hypothesis proposes that heterozygous gene combinations perform better than either homozygous state, while the epistasis hypothesis attributes heterosis to positive interactions among genes located at different loci (Birchler et al., 2010).

Recent advances in genomics have revealed that heterosis results from a combination of multiple genetic and epigenetic mechanisms rather than a single genetic model. Genome-wide analyses have identified numerous genes involved in photosynthesis, hormone regulation, nutrient utilization, stress response, and metabolism that collectively contribute to superior hybrid performance. Understanding these mechanisms has greatly improved the efficiency of parent selection and hybrid prediction (Chen, 2013).

Table 1. Major hypotheses explaining heterosis:

Hypothesis	Principle	Significance
Dominance	Dominant alleles mask deleterious recessive alleles	Improved vigor and fitness
Overdominance	Heterozygous genotype is superior to both homozygotes	Higher yield and adaptability
Epistasis	Positive interaction among different genes	Enhanced performance of complex traits

Hybrid Breeding in Self-Pollinated Crops

Hybrid breeding in self-pollinated crops is comparatively challenging because these crops naturally undergo self-fertilization and exhibit limited natural cross-pollination. Nevertheless, the development of cytoplasmic male sterility (CMS), genic male sterility (GMS), environmental genic male sterility (EGMS), and chemical hybridizing agents has enabled the successful commercial production of hybrids in crops such as rice, sorghum, pigeon pea, tomato, and several vegetables (Longin et al., 2012).

Hybrid rice is one of the most successful examples of hybrid breeding in self-pollinated crops, providing significant yield advantages over conventional inbred varieties. Similar progress has been achieved in pigeon pea and several vegetable crops, where hybrids exhibit improved productivity, disease resistance, and stress tolerance. Continued advances in genomics and molecular breeding are expected to further expand hybrid technology to additional self-pollinated species.

Hybrid Breeding in Cross-Pollinated Crops

Cross-pollinated crops naturally maintain high levels of heterozygosity, making them ideal candidates for hybrid breeding. Commercial hybrid development has revolutionized crops such as maize, pearl millet, sunflower, rye, and forage grasses by exploiting strong heterosis for grain yield, biomass production, disease resistance, and environmental adaptability. Hybrid maize remains one of the greatest achievements in plant breeding, contributing substantially to global food production over the past century (Duvick, 2005).

The development of inbred parental lines followed by systematic evaluation of combining ability has become the standard approach for producing superior hybrids in cross-pollinated crops. Modern breeding programmes increasingly integrate molecular markers and genomic prediction to identify elite parental combinations, thereby reducing breeding time and increasing hybrid performance. These advances continue to strengthen hybrid breeding as one of the most effective strategies for improving crop productivity.

Genomic Advances in Hybrid Breeding

Recent genomic innovations have transformed hybrid breeding from a largely empirical process into a data-driven science. High-throughput DNA sequencing, single nucleotide polymorphism (SNP) markers, genome-wide association studies (GWAS), genomic selection, transcriptomics, and artificial intelligence now enable breeders to identify superior parental lines and accurately predict hybrid performance before extensive field evaluation (Crossa et al., 2017).

Genomic selection has become particularly valuable because it estimates the breeding value of parents using genome-wide marker information, allowing breeders to select superior crosses without waiting for multiple seasons of phenotypic testing. Advances in transcriptomics, epigenomics, and genome editing have also improved understanding of the molecular mechanisms controlling heterosis and hybrid performance. Together, these technologies accelerate hybrid development, increase selection accuracy, and support the production of high-yielding, climate-resilient hybrids capable of meeting future agricultural challenges (Varshney et al., 2021).

Molecular Markers and Genomic Selection in Hybrid Development

The incorporation of molecular markers and genomic selection has significantly improved the efficiency and precision of hybrid breeding programmes. Molecular markers such as simple sequence repeats (SSRs), single nucleotide polymorphisms (SNPs), and insertion–deletion (InDel) markers enable breeders to characterize genetic diversity, identify desirable alleles, verify hybridity, and select superior parental lines at an early stage of crop development. Unlike conventional selection, which relies primarily on observable traits, marker-assisted approaches allow direct selection based on the plant's genetic constitution, thereby reducing breeding time and improving selection accuracy (Collard & Mackill, 2008).

Genomic selection (GS) has further revolutionized hybrid breeding by using genome-wide marker information to predict the breeding values of parental lines and estimate hybrid performance before extensive field evaluation. This approach is particularly valuable for complex traits such as grain yield, stress tolerance, and quality attributes, which are controlled by numerous genes with small individual effects. By combining genotypic data with advanced statistical prediction models, breeders can rapidly identify superior hybrid combinations while minimizing the cost and duration of large-scale field trials (Crossa et al., 2017).

The integration of molecular markers, genomic selection, high-throughput phenotyping, and artificial intelligence has transformed hybrid breeding into a data-driven process. These technologies improve parent selection, increase prediction accuracy, and accelerate the development of superior hybrids capable of delivering higher productivity and greater resilience under diverse environmental conditions. Consequently, genomics-assisted hybrid breeding has become a cornerstone of modern crop improvement programmes (Varshney et al., 2021).

Table 2. Molecular tools used in modern hybrid breeding:

Technology	Primary application	Benefit in hybrid breeding
SSR markers	Genetic diversity analysis	Parent selection

SNP markers	Genome-wide genotyping	High-resolution selection
Marker-assisted selection	Trait introgression	Rapid transfer of desirable genes
Genomic selection	Prediction of hybrid performance	Increased genetic gain
GWAS	Identification of favourable alleles	Better understanding of complex traits
High-throughput phenotyping	Precise trait evaluation	Improved selection accuracy

Challenges and Future Prospects

Despite tremendous advances, hybrid breeding continues to face several biological and technological challenges. The development and maintenance of elite parental lines require considerable time, labour, and financial investment. Hybrid seed production in self-pollinated crops remains technically demanding because efficient male sterility systems and reliable pollination management are essential for commercial seed production. In addition, predicting heterosis for complex traits under diverse environmental conditions remains a major scientific challenge (Chen, 2013).

The implementation of genomic breeding technologies also requires advanced laboratory infrastructure, high-throughput genotyping platforms, skilled personnel, and robust computational resources. Small breeding programmes, particularly in developing countries, often face financial constraints that limit the adoption of these advanced technologies. Furthermore, genotype × environment interactions continue to influence hybrid performance, emphasizing the need for extensive multi-location evaluation before cultivar release (Crossa et al., 2017).

Future hybrid breeding is expected to integrate genomic selection, genome editing, pangenomics, artificial intelligence, machine learning, digital phenotyping, and speed breeding into unified breeding pipelines. These emerging technologies will improve prediction accuracy, shorten breeding cycles, and accelerate the development of superior hybrids with enhanced yield, climate resilience, nutritional quality, and resource-use efficiency. Such innovations will play a crucial role in meeting future global food demands while promoting sustainable agricultural development (Varshney et al., 2021).

India's Progress in Hybrid Breeding

India has made remarkable progress in hybrid breeding since the introduction of hybrid maize and hybrid pearl millet during the Green Revolution era. Today, hybrid technology has become an important component of crop improvement programmes for maize, rice, pearl millet, sorghum, cotton, sunflower, mustard, pigeon pea, and several vegetable crops. Research institutions under the **Indian Council of Agricultural Research (ICAR)**, together with State Agricultural Universities and private seed companies, have contributed significantly to the development and commercialization of high-performing hybrids adapted to diverse agro-climatic regions.

Indian breeding programmes increasingly integrate molecular markers, marker-assisted selection, genomic selection, and high-throughput phenotyping to improve the efficiency of hybrid development. Institutions such as the **Indian Agricultural Research Institute (IARI)**, the **Indian Institute of Maize Research (IIMR)**, the **Indian Institute of Millets Research**, and the **International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)** have successfully developed improved parental lines and hybrids possessing higher productivity, disease resistance, and climate resilience.

Looking ahead, continued investment in genomics, artificial intelligence, digital agriculture, and precision breeding will further strengthen India's hybrid breeding programmes. Public–private partnerships, enhanced germplasm conservation, and expanded research infrastructure are expected to accelerate the development of next-generation hybrids capable of improving food security and supporting sustainable agricultural growth.

Conclusion

Hybrid breeding has transformed global agriculture by successfully exploiting heterosis to achieve substantial improvements in crop productivity, adaptability, and quality. The integration of molecular markers, genomic selection, high-throughput phenotyping, and other genomic technologies has significantly enhanced the efficiency and precision of hybrid development, enabling breeders to identify superior parental combinations and predict hybrid performance with greater accuracy than ever before.

Although challenges related to hybrid seed production, prediction of heterosis, infrastructure, and climate variability remain, continuous advances in genomics, genome editing, artificial intelligence, and digital breeding are redefining the future of hybrid crop improvement. The successful application of these technologies in both self- and cross-pollinated crops demonstrates their enormous potential for developing high-yielding, climate-resilient, and resource-efficient cultivars. Continued investment in research, innovation, and collaborative breeding programmes will ensure that hybrid breeding remains one of the most powerful strategies for enhancing global agricultural productivity and achieving long-term food security.

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Breeding Climate-Resilient Crops: Integrating Molecular Genetics with Physiological Approaches for Abiotic Stress

Article ID: 74205

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Introduction

Climate change has become one of the greatest threats to global agriculture, affecting crop productivity, food security, and the livelihoods of millions of farmers. Rising temperatures, irregular rainfall, prolonged droughts, salinity, flooding, and other environmental stresses are increasingly reducing the productivity of major food crops worldwide. As the global population is projected to approach 9.7 billion by 2050, developing crop varieties capable of maintaining stable yields under adverse environmental conditions has become a major priority for plant breeders and agricultural scientists (IPCC, 2023; United Nations, 2022).

Conventional breeding has significantly improved crop productivity over the past century; however, the complexity of abiotic stress tolerance requires the integration of advanced molecular genetics with plant physiological approaches. Modern breeding technologies, including molecular markers, genomic selection, genome editing, and high-throughput phenotyping, enable breeders to identify stress-tolerant genotypes more efficiently. Combining these genetic tools with physiological trait analysis provides an effective strategy for developing climate-resilient crops capable of sustaining agricultural production under changing climatic conditions (Tester & Langridge, 2010; Varshney et al., 2021).

Impact of Abiotic Stresses on Global Agriculture

Abiotic stresses are non-living environmental factors that adversely affect plant growth, development, and productivity. Among these, drought, heat, salinity, flooding, and cold stress are responsible for substantial yield losses in major cereal, pulse, and oilseed crops each year. Climate change has intensified the frequency and severity of these stresses, making crop production increasingly unpredictable. In addition to reducing yield, abiotic stresses negatively influence grain quality, nutrient uptake, photosynthetic efficiency, and reproductive development, thereby threatening both food and nutritional security (Cattivelli et al., 2008; IPCC, 2023).

Water scarcity remains one of the most serious constraints to agricultural productivity, particularly in arid and semi-arid regions. Similarly, increasing soil salinity and rising temperatures reduce crop establishment, biomass accumulation, and grain filling. These challenges emphasize the urgent need to develop crop varieties that can withstand multiple environmental stresses while maintaining stable productivity and efficient resource utilization (Blum, 2011).

Table 1. Major abiotic stresses and their effects on crop production:

Abiotic stress	Major impact on plants	Common physiological response
Drought	Reduced growth and yield	Stomatal closure, osmotic adjustment
Heat	Protein denaturation and pollen sterility	Heat shock protein synthesis
Salinity	Ion toxicity and osmotic stress	Na^+ exclusion, osmolyte accumulation
Flooding	Oxygen deficiency in roots	Aerenchyma formation
Cold	Membrane injury and slow metabolism	Antioxidant activation

Physiological Mechanisms of Abiotic Stress Tolerance

Plants have evolved several physiological mechanisms that enable them to survive under adverse environmental conditions. One of the earliest responses to drought is stomatal closure, which reduces water loss through transpiration but also limits carbon dioxide uptake and photosynthesis. Plants also accumulate compatible solutes such as proline, glycine betaine, and soluble sugars to maintain cellular water balance through osmotic adjustment (Blum, 2011).

Efficient root systems play a vital role in accessing deeper soil moisture during drought conditions, while traits such as stay-green, canopy temperature regulation, chlorophyll stability, and improved water-use efficiency contribute to sustained productivity under stress. In addition, antioxidant enzymes including superoxide dismutase, catalase, and peroxidase protect plant cells from oxidative damage caused by environmental stress. These physiological traits are widely used as selection criteria in modern breeding programmes because they are closely associated with stress tolerance and crop performance (Araus & Cairns, 2014).

Role of Molecular Genetics in Abiotic Stress Breeding

Advances in molecular genetics have greatly enhanced the ability of breeders to identify genes controlling abiotic stress tolerance. Molecular markers linked to quantitative trait loci (QTLs) enable the efficient transfer of desirable genes into elite cultivars through marker-assisted selection, reducing the time required for developing improved varieties. Genome-wide association studies (GWAS), next-generation sequencing, and genomic selection have further improved the understanding of complex traits such as drought tolerance, salinity resistance, and heat adaptation (Collard & Mackill, 2008; Crossa et al., 2017).

Genome editing technologies such as CRISPR-Cas have introduced new opportunities for precise modification of stress-responsive genes without altering other desirable characteristics. Similarly, transcriptomics and gene expression studies have identified numerous regulatory genes involved in osmotic adjustment, hormone signalling, antioxidant defence, and stress perception. These advances have significantly accelerated the development of climate-resilient crop varieties (Varshney et al., 2021).

Integration of Molecular Genetics and Plant Physiology

The successful development of climate-resilient crops requires the integration of molecular genetics with physiological trait evaluation. Physiological screening identifies plants possessing desirable adaptive traits such as deeper roots, improved water-use efficiency, efficient photosynthesis, and delayed leaf senescence, while molecular tools reveal the genes and genomic regions responsible for these characteristics. Combining these complementary approaches enables breeders to select superior genotypes with greater precision and reliability (Araus & Cairns, 2014).

Modern breeding programmes increasingly combine high-throughput phenotyping, genomic selection, molecular markers, artificial intelligence, and environmental modelling to improve breeding efficiency. This integrated strategy accelerates the identification of stress-tolerant breeding lines, shortens variety development time, and increases genetic gain. As climate variability continues to intensify, integrating molecular genetics with plant physiology will remain a cornerstone of breeding programmes aimed at developing high-yielding, climate-smart crops capable of ensuring sustainable agricultural production (Hickey et al., 2019; Varshney et al., 2021).

Modern Breeding Technologies for Climate-Resilient Crops

Recent advances in plant breeding have transformed the development of climate-resilient crops by integrating molecular genetics, genomics, biotechnology, and digital agriculture. Marker-assisted selection (MAS) enables the rapid transfer of genes associated with drought, heat, salinity, and flooding tolerance into elite cultivars, thereby reducing breeding time and improving selection accuracy (Collard & Mackill, 2008). Genome-wide association studies (GWAS) and genomic selection further enhance breeding efficiency by identifying genomic regions controlling complex stress-related traits and predicting the performance of breeding lines before extensive field evaluation (Crossa et al., 2017).

Genome editing technologies, particularly CRISPR-Cas systems, have provided precise tools for modifying stress-responsive genes involved in water-use efficiency, osmotic regulation, antioxidant defence, and hormonal signalling. High-throughput phenotyping, remote sensing, unmanned aerial vehicles (UAVs), artificial intelligence (AI), and machine learning are increasingly integrated with genomic information to accelerate the identification of superior genotypes under diverse environmental conditions. Together, these technologies have established a modern breeding framework capable of producing climate-smart crop varieties more rapidly and accurately than conventional breeding approaches (Hickey et al., 2019; Varshney et al., 2021).

Table 2. Modern breeding technologies for abiotic stress tolerance:

Technology	Major application	Benefit
Marker-assisted selection	Introgression of stress-tolerant genes	Faster selection
Genomic selection	Prediction of breeding value	Increased genetic gain
GWAS	Identification of stress-related loci	Precise gene discovery
CRISPR-Cas genome editing	Targeted gene modification	Rapid improvement of stress tolerance
High-throughput phenotyping	Rapid physiological screening	Accurate trait evaluation
Artificial intelligence	Predictive breeding	Improved breeding efficiency

Applications in Major Crops

Climate-resilient breeding technologies have been successfully implemented in several major crops. In rice, the identification and deployment of the **SUB1** gene have resulted in varieties capable of surviving prolonged flooding, while drought-tolerant cultivars carrying genes such as **DRO1** have improved productivity under water-limited conditions (Xu et al., 2006). In wheat, genomic selection and physiological trait-based breeding have enhanced heat tolerance, drought adaptation, and grain yield stability under changing climatic conditions (Reynolds et al., 2022).

Similarly, drought-tolerant maize hybrids developed through molecular breeding have shown improved yield stability in water-deficit environments. In chickpea and pigeon pea, marker-assisted breeding has accelerated the development of varieties resistant to drought and heat stress, while pearl millet breeding programmes have successfully combined heat

tolerance with improved grain productivity. These examples demonstrate the practical value of integrating molecular genetics and physiological selection for developing resilient crop varieties suitable for climate-smart agriculture (Varshney et al., 2021).

Table 3. Applications of climate-resilient breeding in major crops:

Crop	Major abiotic stress	Technology applied	Outcome
Rice	Flooding	Marker-assisted breeding (SUB1)	Flood-tolerant varieties
Wheat	Heat and drought	Genomic selection	Stable grain yield
Maize	Drought	Molecular breeding	Drought-tolerant hybrids
Chickpea	Drought	Marker-assisted selection	Early maturing cultivars
Pearl millet	Heat	Hybrid breeding	Climate-resilient hybrids
Soybean	Water deficit	Genomic selection	Improved stress adaptation

Challenges and Future Prospects

Despite remarkable progress, breeding for abiotic stress tolerance remains challenging because these traits are controlled by numerous genes and are strongly influenced by environmental conditions. Complex genotype × environment interactions often reduce selection efficiency, while limited phenotyping facilities and high costs associated with genomic technologies restrict their widespread adoption, particularly in developing countries (Crossa et al., 2017).

Future crop improvement is expected to rely increasingly on integrating genomics, phenomics, genome editing, artificial intelligence, and predictive breeding models into comprehensive breeding programmes. Advances in pangenomics, multi-omics approaches, digital phenotyping, and climate modelling will enable breeders to identify superior genotypes with greater precision and accelerate the development of climate-smart cultivars. Strengthening international collaboration, germplasm exchange, and investment in research infrastructure will be essential to maximize the benefits of these emerging technologies (Hickey et al., 2019).

India's Progress in Climate-Resilient Crop Breeding

India has made significant advances in breeding climate-resilient crop varieties through coordinated efforts by the **Indian Council of Agricultural Research (ICAR)**, State Agricultural Universities, and international research organizations. Marker-assisted breeding has led to the development of improved rice varieties carrying the **Sub1** gene for flood tolerance, while genomic-assisted breeding programmes have enhanced drought and heat tolerance in wheat, maize, chickpea, pigeon pea, and pearl millet (Varshney et al., 2021).

Research institutions such as the **Indian Agricultural Research Institute (IARI)**, the **Indian Institute of Wheat and Barley Research (IIWBR)**, the **Indian Institute of Millets Research (IIMR)**, and the **International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)** are actively integrating genomics, physiological screening, high-throughput phenotyping, and precision breeding into crop improvement programmes. Increasing investment in artificial intelligence, genome editing, and digital agriculture is expected to further strengthen India's capacity to develop climate-smart crop varieties capable of sustaining agricultural productivity under changing climatic conditions.

Conclusion

Climate change poses unprecedented challenges to global agriculture, making the development of climate-resilient crop varieties an urgent scientific priority. The integration of molecular genetics with plant physiological approaches has significantly improved the ability of breeders to identify, understand, and utilize traits associated with drought, heat, salinity, flooding, and other abiotic stresses. Modern breeding technologies, including marker-assisted selection, genomic selection, genome editing, and high-throughput phenotyping, have accelerated the development of resilient cultivars while increasing breeding precision and efficiency.

Although challenges related to complex trait inheritance, environmental variability, and technological accessibility remain, continued advances in genomics, artificial intelligence, and precision breeding offer tremendous opportunities for future crop improvement. Strengthening multidisciplinary research, international collaboration, and investment in advanced breeding infrastructure will be essential for developing high-yielding, climate-smart crops capable of ensuring sustainable agricultural production and global food security in the face of a changing climate.

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Biofilm Formation in Dairy Processing Environments: Mechanisms, Detection Methods, and Control Strategies

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Abstract

Milk obtained directly from the udder of a healthy milch animal is almost sterile in nature. However, contamination can occur during milking, transportation, storage, and processing, as well as through the entry of microorganisms from multiple external sources. Inadequate cleaning and insufficient sanitization of dairy equipment allow microbial residues to accumulate, which subsequently develop into biofilms on the equipment. These biofilms are a significant reservoir of contamination, posing serious risks to dairy product safety. Biofilms are aggregates of microbial cells interconnected by extracellular polymeric substances (EPS) that facilitate rapid growth and persistence on diverse material surfaces. Their formation has profound implications for the dairy sector, as they are the principal source of microbial contamination that compromises product quality and safety. The persistence of biofilms leads to economic losses by impairing raw materials and finished products, thereby creating financial challenges for the industry.

Keywords: Biofilm; Dairy industry; Food safety; Detection methods; Control strategies; Extracellular polymeric substances (EPS).

Introduction

The dairy sector is among the most important parts of global food production, providing nutrient-rich dairy items that people use daily worldwide. However, the characteristics that make milk and its products healthy also make them easy to spoil by germs. One of the most difficult types of microbial contamination to remove is biofilms, which are dense microbial aggregates surrounded by extracellular polymeric substances (EPS) that stick to processing surfaces. Once biofilms are formed, they can no longer be removed easily, causing one problem after another in terms of hygiene, diminishing the performance of machinery, and posing serious threats to food safety (Vlková *et al.*, 2008).

Biofilms in the dairy industry are of more than just microbiological interest; they represent a serious industrial risk. For instance, *Listeria monocytogenes*, *Staphylococcus aureus*, and *Pseudomonas spp.* take advantage of the protective biofilm layer to resist cleaning and disinfection. If they remain, they may expose the final products to pathogens, resulting in foodborne diseases, product recalls, inspections, and fines. Additionally, the contaminating organisms residing in the biofilms are capable of changing the flavor or odor of the product, reducing its consumer acceptability. Hence, biofilm-related contamination is a double whammy from both pathogenic and spoilage perspectives, making it extremely necessary to have a thorough understanding of the biofilm behavior in dairy production machines (Kadam *et al.*, 2025).

It is well known that the genesis of biofilms in dairy plants depends on a few factors. Leftover milk components, such as proteins, fats, and sugars, also act as mediators, helping the microbes adhere to the surface. The surfaces of equipment, such as stainless steel, rubber gaskets, and plastic containers, can offer microorganisms spots where they can settle. Other factors include temperature variations, high humidity, and insufficient cleaning, which together intensify the formation of biofilms. Once the biofilm has taken hold, it can resist both chemical sanitizers and thorough physical cleaning due to the protective EPS matrix and cooperation among the microbial cells. While the EPS matrix is crucial, the persistence of biofilms is also heavily dependent on physiological states such as Viable but Non-Culturable (VBNC) cells and persister cells (I. Kabwanga *et al.*, 2018).

Biofilms are a major issue from regulatory and public health perspectives. Global food safety standards, including those set by the Codex Alimentarius and national authorities, underline the importance of maintaining a high level of cleanliness in dairy processing plants. However, despite efforts to meet the requirements, biofilms are still found, indicating a lack of appropriate detection and control measures. Conventional culture-based techniques mostly miss the complex nature of biofilm communities, these challenges are accurate, recent research in "Industry 4.0" is shifting towards affordable, real-time, and non-invasive methods. Mentioning developments such as RF-based sensors, deep learning-based fluorescence imaging, and AI-driven predictive risk assessment would provide a more balanced and forward-looking perspective on detection limitations (Taheri Gorji *et al.*, 2022 Bhattacharya *et al.*, 2024; Lapointe *et al.*, 2025; Yuan *et al.*, 2025). Consequently, there has been a resurgence of primary research on biofilms, which mainly focuses on molecular mechanisms, outbreak detection, and different control methods, including enzymatic and

bacteriophage treatments. However, gaps need to be addressed, particularly regarding the standardization of detection methods and environmentally friendly sustainable sanitization techniques. (Elbehiry & Alajaji, 2026).

Overview of Biofilms

Biofilms are multi-layered communities of microorganisms that adhere to each other and/or to a surface, wrapped in a self-produced layer of extracellular polymeric substances (EPS). This layer not only protects the microbes but also allows them to exchange nutrients and makes them highly resistant to environmental factors and antimicrobial agents. It is mainly composed of polysaccharides, proteins, lipids, and DNA, and helps keep the microbial community together and safe (Stoodley *et al.*, 2004).

In addition to being ubiquitous in nature, biofilms can form on various types of surfaces, such as rocks and pebbles in streams and rivers, stagnant pools, water pipelines, marine engineering systems, sewage pipes, and even materials used in industries. In living organisms, biofilms appear as dental plaque on animal teeth and on the surfaces of plants, both inside and outside (Schwermer *et al.*, 2008).

Significance of Biofilms in Dairy Processing

Biofilm formation in the dairy industry is always seen as a danger that can lead to contamination of the product and thus foodborne illness. Therefore, it is still considered a major public health issue worldwide. Consumers always want products of higher quality in terms of shelf life and safety. The increasing adoption of automation, reduced processing runs, and use of complex equipment, along with a rise in awareness of pathogen problems such as those caused by *Listeria monocytogenes*, are all factors that make biofilms a concern.

Milk and cream may develop a sweet coagulation and bitter taste due to the presence of *Bacillus subtilis* and *Bacillus cereus*, whereas gas-producing *Clostridium tyrobutyricum* is responsible for the spoiled texture and late-blowing in semi-hard cheese. In addition to milk powder, spore-forming thermoduric and thermophilic bacteria are also present in milk powder at high level after 16-20 hours production time because of biofilms, which are on the large internal surfaces of evaporators and spray dryers. To determine the biofilm formation capability and density of the bacteria isolated from dairy production equipment.

Major Biofilm Reservoirs in Dairy Processing Environments

Biofilm formation is not uniformly distributed throughout dairy processing facilities but is concentrated in specific niches characterized by nutrient accumulation, surface irregularities, and limited cleaning efficiency. Table 1 provides an overview of the major biofilm reservoirs and their common locations in dairy processing environments.

Table 1 Biofilm reservoirs and their common locations:

Biofilm Reservoir	Common Locations
Processing equipment	Pipelines, pasteurizers, homogenizers, pumps, storage tanks, silos
Plate heat exchangers (PHE)	Heat exchanger plates, narrow flow channels
Dead legs and low-flow zones	Blind ends, tee junctions, valve seats, threaded fittings
Gaskets, seals, and elastomeric components	EPDM gaskets, silicone seals, O-rings, rubber hoses
Membrane filtration systems	Ultrafiltration (UF), Microfiltration (MF), Nanofiltration (NF), Reverse Osmosis (RO) membranes
Milk contact surfaces	Cheese vats, yogurt fermentation tanks, cream separators, butter churns, ice cream freezers
Valves and pumps	Valve seats, pump impellers, sanitary fittings
Filling and packaging equipment	Filling nozzles, conveyor belts, packaging lines
Floor drains and wastewater channels	Floor drains, trench drains, wastewater collection channels
Air handling and cooling systems	Air ducts, cooling units, evaporator coils, condensate trays
Water distribution systems	Water pipelines, storage tanks, filters, spray nozzles
Cleaning equipment	CIP spray balls, cleaning hoses, brushes, foam applicators
Personnel contact surfaces	Door handles, handrails, control panels, touch screens

Mechanisms of Biofilm Formation

Biofilms formation in dairy processing environment is a very complicated and dynamic process which is revealed by time in many closely interconnected steps. (Stoodley *et al.*, 2002; Breyers and Ratner, 2004; Johnston 2004). The first step, preliminary adhesion, starts when microorganisms come in contact with surfaces such as stainless-steel pipelines, rubber seals, or plastic containers. Usually, these surfaces have conditioning films from residual milk proteins, fats, and sugars, which facilitate the microbial attachment (Vieira *et al.*, 1993; Busscher *et al.*, 1995; Donlan., 2002; Chae *et al.*, 2006; Palmer *et al.*, 2007; Patel *et al.*, 2007; Oulahal *et al.*, 2008;). Bacteria deploy toolsets at their disposal, such as fimbriae, flagella, and surface proteins, to attach themselves, while hydrophobic interactions and electrostatic forces further

secure this attachment (Morris *et al.*, 1997; Harbron and Kent, 1988; Daniels *et al.*, 2004; De Rezende *et al.*, 2005). In dairy plants, pathogens such as *L. monocytogenes* and *Pseudomonas spp*. are very good at initiating adhesion and building biofilms (Carrascosa *et al.*, 2021).

As soon as the adhesion process is complete, the microcolony formation stage begins. The initially attached microorganisms seem to divide and proliferate, thus creating small groups on the surface. Customers simultaneously secrete extracellular polymeric substances (EPS), a mixture of polysaccharides, proteins, and extracellular DNA (Terraf *et al.*, 2012). This EPS matrix traps the cells and provides them with a protective room against the influence of external factors. Nutrient residues, such as lactose and casein from milk, serve as immediate and easily accessible energy sources for cells, enabling faster colony development. Interestingly, biofilms in dairy environments are rarely composed of a single species; rather, they work in concert with multiple microorganisms. For instance, Staphylococcus aureus might lend structural strength, whereas Pseudomonas might be involved in nutrient cycling; thus, a resilient microbial community is formed (Stoodley *et al.*, 2002).

The third stage, maturation, involves the development of a well-organized three-dimensional biofilm structure. Within this structure, water channels are formed to help deliver and distribute nutrients and get rid of waste, thus supporting the community members' sustenance. Meanwhile, bacteria within the biofilm can perform quorum sensing, which is a communication process through signaling molecules that regulate gene expression at the population level. This coordinated behavior allows the biofilm to collectively enhance its stress resistance, virulence, and metabolic efficiency. The EPS matrix is so dense that it is one of the major reasons why the effect of sanitizers and antibiotics is highly negated. Based on the above reasons, mature biofilms in dairy plants have been considered very difficult to deal with as they lead to pipeline clogging, a reduction in the efficiency of heat transfer rates, and, furthermore, they can provide a continuous source of contamination which eventually affects the quality of the products (Jahn and Nielsen *et al.*, 1998). Finally, biofilms disintegrate, that is, in the cell release stage, cells separate from the community and return to the planktonic state. Dispersal may be induced by various factors, such as nutrient starvation, fluid flow-induced shear forces, or environmental changes, such as temperature fluctuations. Detached cells are then free to colonize new surfaces, spreading contamination throughout the dairy processing environment.

This stage is especially critical from a food safety perspective, as dispersed pathogens can enter milk and dairy products, leading to spoilage and foodborne illnesses. The cyclical nature of dispersal ensures that biofilms remain a recurring challenge, perpetuating contamination across equipment and production lines (Sauer *et al.*, 2002; Stoodley *et al.*, 2002).

Detection Methods

Accurate, rapid, and non-destructive detection of biofilms is essential for preventing persistent contamination in dairy processing environments. Recent advances integrate molecular biology, spectroscopy, imaging, biosensors, artificial intelligence (AI), and microfluidics to enable real-time biofilm monitoring.

Table 2 Advanced Technologies for Biofilm Detection in Dairy and Food Processing Environments:

Technology	Principle	Applications in Dairy/Food Industry
Culture-based assays	Growth of microorganisms on selective media	Enumeration and isolation of biofilm-forming microorganisms
Light microscopy	Direct visualization using visible light	Preliminary observation of biofilm formation on surfaces
Confocal Laser Scanning Microscopy (CLSM)	Laser-based optical sectioning with fluorescent staining	Three-dimensional imaging of biofilm architecture, thickness, and cell viability
Scanning Electron Microscopy (SEM)	Electron beam imaging of sample surfaces	Visualization of microbial attachment, EPS matrix, and surface morphology
Atomic Force Microscopy (AFM)	Nano scale surface scanning using a probe	Analysis of surface roughness, adhesion forces, and biofilm topography
Polymerase Chain Reaction (PCR)	Amplification of target DNA sequences	Detection of specific biofilm-forming microorganisms
Quantitative PCR (qPCR)	Real-time amplification and quantification of DNA	Rapid quantification of microbial load and targeted pathogens
Digital PCR (dPCR)	Partitioning of DNA for absolute quantification	Detection of low-abundance microorganisms and resistant populations
Next-Generation Sequencing (NGS)	High-throughput sequencing of microbial DNA	Comprehensive profiling of biofilm microbial communities
Fluorescence In Situ Hybridization (FISH)	Fluorescent probes targeting microbial RNA/DNA	Localization and identification of specific microorganisms within biofilms
Raman Spectroscopy / Surface-Enhanced Raman Spectroscopy (SERS)	Molecular fingerprinting based on vibrational spectra	Rapid, label-free detection of microorganisms and EPS composition

Hyperspectral Imaging (HSI)	Spectral imaging across multiple wavelengths	Non-destructive detection of biofilms on processing equipment surfaces
Electrochemical Biosensors	Measurement of electrical signal changes caused by microbial activity	Real-time monitoring of biofilm development in processing systems
Optical Fiber Biosensors	Detection through optical signal variations	Continuous in-line monitoring of biofilm formation in pipelines and tanks
Quartz Crystal Microbalance (QCM)	Measurement of resonance frequency changes due to mass deposition	Early detection of bacterial adhesion and biofilm initiation
Microfluidic Lab-on-a-Chip Systems	Miniaturized platforms for microbial cultivation and analysis	Rapid biofilm screening and evaluation of cleaning and sanitizing agents
Artificial Intelligence (AI)-Based Image Analysis	Automated interpretation of microscopy and sensor data	Real-time biofilm detection, quantification, and predictive hygiene monitoring
IoT-Integrated Smart Sensors	Connected sensors with cloud-based data analytics	Continuous online monitoring and predictive maintenance of dairy processing equipment

Comparative studies highlight the need for standardized protocols to ensure consistency across the dairy industry (Bowers, 2024; Kulshrestha & Gupta, 2026).

Control Strategies

Novel methods for biofilm prevention and removal cleaning procedures in dairy manufacturing plants have traditionally relied on cost-effective chemicals, such as caustic soda, acids, and chlorine. Most sanitization protocols have remained unchanged since the early 1900s. A significant advancement in cleaning technology was the introduction of clean-in-place (CIP) systems in the 1950s, when manufacturing plants were smaller, processes were simpler, and regulatory requirements were less stringent. Over time, modifications to these systems have mainly focused on reducing cleaning costs and protecting sensitive equipment such as ultrafiltration membranes. However, current cleaning methods require reassessment to effectively control biofilms in dairy-processing environments. Although preventing biofilm formation is ideal, there is currently no universally effective method that can completely prevent or eliminate biofilms without causing undesirable side effects (Simoes *et al.*, 2010). The primary strategy for biofilm prevention is regular cleaning and disinfection before bacteria firmly adhere to surfaces (Midelet & Carpentier, 2004; Simoes *et al.*, 2006). Common disinfectants used in dairy processing include acidic compounds, aldehyde-based biocides, caustic solutions, chlorine, isothiazolinones, hydrogen ozone, peracetic peroxide, acids, iodine, phenolic, biguanidines, and surfactants (Bremer *et al.*, 2006; Dosti *et al.*, 2005).

Biological methods: Bacteriophages, enzymes, and quorum-sensing inhibitors show promise in disrupting biofilm integrity.

Innovative technologies: Nonthermal methods, such as ultrasound and plasma treatments are emerging as eco-friendly alternatives. A combination of these strategies is often necessary to achieve effective biofilm control in aquaculture (Bowers, 2024; Kulshrestha & Gupta, 2024).

Conclusion

Biofilm formation in dairy processing environments is a multifaceted challenge that requires multidisciplinary solutions. Advances in detection and control strategies offer promising avenues; however, widespread implementation demands standardization and innovation. A holistic approach combining microbiology, engineering, and industrial hygiene is essential to ensure dairy product safety and quality.

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Synthetic Seed Technology for Quality Planting Material in Vegetable Crops

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Introduction

Synthetic seed technology represents a significant breakthrough in modern plant biotechnology, offering an innovative approach to the propagation, conservation and large-scale distribution of elite genotypes. The concept involves encapsulating somatic embryos, shoot tips or other vegetative propagules in an artificial coating that mimics the function of a true seed. This encapsulated structure can be stored, handled and sown like a natural seed, facilitating the propagation of plants that are otherwise difficult to reproduce by conventional methods (Saiprasad, 2001).

In vegetable crops, artificial seed technology provides a reliable means of propagating elite genotypes while maintaining genetic uniformity. It supports rapid multiplication, conservation, and the continuous supply of quality planting material for sustainable cultivation (Faisal and Alatar, 2019).

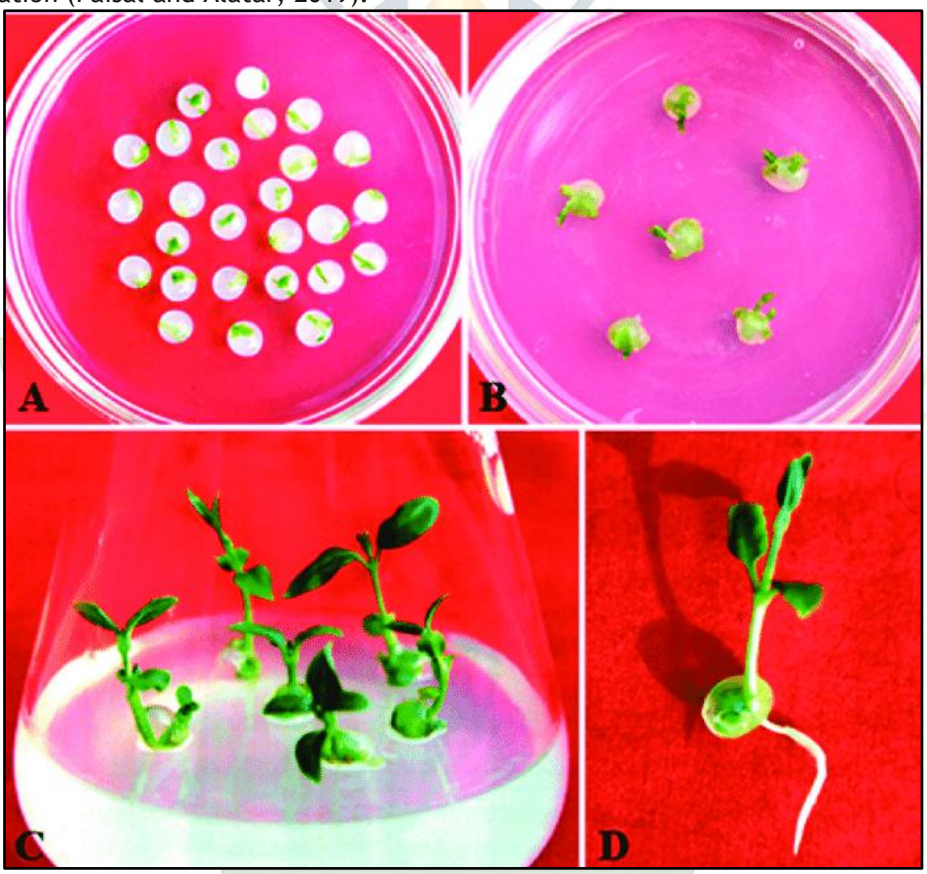


Fig 1. Different stages of synthetic seed technology in vegetable crops

Concept and Components of Synthetic Seeds

Synthetic seeds, also known as artificial seeds, are encapsulated somatic embryos or other tissue culture-derived propagules capable of developing into complete plants under in vitro or ex vitro conditions (Rihan *et al.*, 2017). The artificial coating provides protection and supplies nutrients required for survival, germination and plantlet development.

The major components of synthetic seeds include: (i) propagules such as somatic embryos, shoot tips, axillary buds, microshoots, nodal segments, or embryogenic callus, with shoot tips and nodal segments being commonly used in vegetable crops. (ii) an encapsulation matrix, usually sodium alginate, which forms calcium alginate beads upon treatment with calcium chloride ($CaCl_2$), although carrageenan, agar and polyacrylamide can also be used; (iii) nutrient and growth additives including essential nutrients, vitamins, plant growth regulators and antifungal agents to promote early establishment and (iv) an artificial coating designed to improve mechanical strength, permeability, storage, handling and controlled hydration of the encapsulated propagules.

Methods of Synthetic Seed Production

Synthetic seeds are produced by two methods. The first is the somatic embryo-based approach, in which embryogenic callus is induced on auxin-rich media such as 2,4-D. The somatic embryos develop through the globular, heart, torpedo, and cotyledonary stages before being encapsulated in sodium alginate and hardened in calcium chloride ($CaCl_2$).

The second is the non-embryogenic propagule-based approach, where shoot tips or nodal segments are encapsulated in sodium alginate. This method is widely used in vegetatively propagated vegetable crops such as potato, garlic and onion. The encapsulated propagules are stored under sterile, low-temperature conditions and later regenerated into complete plants under suitable in vitro or ex vitro conditions (Abbas *et al.*, 2022).

Applications in Vegetable Crops

Synthetic seed technology has been successfully applied in several vegetable crops for clonal propagation, hybrid multiplication and germplasm conservation. In potato, encapsulated shoot tips and nodal segments are widely used for the production of disease-free planting material and microtubers. In tomato, synthetic seeds facilitate the uniform propagation of hybrid and transgenic lines with high germination potential. In onion and garlic, encapsulated shoot tips enable rapid clonal multiplication and short-term storage despite poor seed viability and dormancy. In chilli and capsicum, shoot tip encapsulation is preferred for maintaining elite hybrid and transgenic lines. Carrot serves as a model crop for studies on somatic embryogenesis, encapsulation, and synthetic seed germination (Ghosh *et al.*, 2026; Shallal *et al.*, 2020).

Advantages of Synthetic Seed Technology

1. Clonal uniformity: Produces genetically identical and true-to-type plants.

2. Year-round availability: Ensures continuous production of quality planting material irrespective of the growing season.

3. Easy handling and transport: Facilitates cost-effective storage, handling and transportation compared with tissue culture plantlets.

4. Disease-free propagation: Minimizes pathogen transmission through in vitro-derived propagules.

5. Germplasm conservation: Supports the short and medium-term preservation of elite genotypes.

6. Ease of sowing: Encapsulated propagules can be sown directly in nurseries or greenhouses like natural seeds.

Recent Advances

Recent research has focused on improving the efficiency and practicality of synthetic seeds through:

1. Cryopreservation and encapsulation-dehydration techniques for long-term storage.
2. Nanoencapsulation and polymer-based coatings for controlled release of nutrients.
3. Automation of encapsulation using droplet-forming devices for large-scale production.
4. Ex vitro germination systems that bypass the need for tissue culture recovery stages.

Future Prospects

Synthetic seed technology holds immense promise for revolutionizing the propagation of vegetable crops, particularly those lacking viable seeds or relying on clonal propagation. The integration of plant tissue culture, cryobiology and polymer science will further enhance its commercial feasibility.

In future, the technology could enable:

a. Large-scale production of elite hybrids and transgenic vegetable plants.
b. On-farm sowing of encapsulated propagules.
c. Long-distance germplasm exchange without quarantine risks.
d. Sustainable and rapid supply chains for quality planting material.

Conclusion

Synthetic seed technology stands as a powerful tool bridging conventional and modern propagation systems in vegetable crops. By mimicking natural seeds, it enables clonal propagation, germplasm conservation and genetic stability in valuable varieties. Continued research on improving encapsulation materials, storage stability and ex vitro conversion rates will pave the way for its large-scale application in commercial vegetable production systems.

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Innovative Extension Approaches for Climate-Smart Agriculture: Building Farmer Resilience to Environmental Change

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Introduction

Agriculture directly and absolutely assisting billions of people worldwide (Agarwal, 2008). It is broadly acknowledge that climate change will set one of the most important tasks to humankind due to of the global nature of the problem, its probable devastatic impacts and the unspecified nature and unpredictability of its inception. To improve some of the complicated challenges of climate change, agriculture (both fisheries and forestry) which become "Climate Smart" i.e., sustainably rise agricultural productivity as well as incomes, adapt and create resilience to climate change, and bring down and/or remove greenhouse gases secretion, where possible (Chakraborty *et al.*, 2023). However, it is gradually impervious to the effects of climate change, which create complicated and manifold challenges to agricultural productivity. Increasing different precipitation patterns, global temperatures as well as the enhanced frequency of excessive weather events like storms, droughts and floods are extensively interrupting farming systems (Altieri and Nicholls, 2021).Conventionally, agricultural extension has performed as the bridge between farming communities and research institutions, transforming scientific innovations into practical, on-the-ground implementation (Faaij and Jager, 2020). This includes guidance on agronomic practices, pest and disease management, soil conservation, and water use. However, as climate-related challenges intensify, the need for innovative, climate-smart solutions within extension services has become more urgent.

Reason of Extension Matters in CSA

1. **Reducing risk:** Many climate smart agricultural practices include direct investment or unknown methods. Demonstrations as well as peer learning can create confidence and diminish risk of adoption.

2. **Bridging the knowledge gap:** Most of the farmers remain unaware of certain CSA practices appropriate to the crops as well as regions. These systems can do the gap filling through tailored data and training.

3. **Managing complexity:** CSA include joint practices viz, protected cultivation, developed varieties, effective water and nutrient practice and varied cropping which need guidance of expert.

4. **Scaling innovation:** Extension systems combined farmers, research institutions, various government schemes by ensuring that innovations are reformed and scaled efficiently across different regions.

5. Tailoring to diversity: Crops generally differs in their management requirements and market orientation. Extension must acclimatise suggestions to local microclimates and farming systems.

Need of Climate Smart Agriculture

Climate change perform a big role to the degradation of resources from nature *viz.*, water pollution, deforestation, soil erosion, reducing ground water levels, burning of fossil fuels, hole of ozone layer and ignition from automobiles creating excessive air pollution that leads to a negative effect on food production as well as food system. In India, reduce in main crop yields due to climate change that between 2010 and 2039 which could be as high as nine percent (Mani *et al.*, 2017). It enriched the requirement to adopt the concept of Climate Smart Agriculture (CSA) to diminish the adverse impacts of climate change on agricultural systems (Panda *et al.*, 2024).

The Role of Agricultural Extension in Climate-Smart Agriculture

Agricultural extension services plays essential association between farmer and research institutions providing farmers with the knowledge, skills, and technologies required to improve agricultural productivity. Moreover, as climate change continues to unsettle traditional farming systems, where extension services must grow to meet the needs of farmers in gradually volatile environments. Climate-smart agriculture (CSA) has arisen as a prime approach for addressing the connected tasks of sustainability of environment, food security as well as climate resilience. To accomplish CSA proficiently, agricultural extension systems must involve new methods which associate with its main objectives *viz.*, diminishing greenhouse gas emissions, sustainably increasing productivity and developing resilience to climate change. One of the main objective of CSA is to enhance agricultural productivity in a sustainable manner. Farmers has to learn about effective water-use methods like rainwater harvesting, drip irrigation to cope with water scarcity and also soil management approaches which increase fertility by reducing environmental degradation. Extension services can assist adaptation by giving early indication systems, local climate information, and different decision-support tools. Different

Participatory approaches like foster peer learning, farmer field schools and assist farmers to research with adaptation strategies that fit their particular contexts. CSA focuses on diminishing greenhouse gas emissions from different agricultural practices. On the other hand, extension services play an important role in encouraging low-emission farming techniques which assist to mitigate climate change. By including such practices into extension programs, extension agents provide global efforts to reduce agriculture's carbon footprint while maintaining productivity, agricultural extension services are vital to the success of climate-smart agriculture.

Characteristics of Climate-smart Agriculture

Adaptability: Climate-smart Agriculture aims on adapting different agricultural practices to the changing climate conditions (Wakweya, 2023). It include executing different approaches and technologies which increase the extreme weather events, crop resilience, livestock, and farming systems to climate variability. Examples include the use of advanced water management techniques, drought-resistant crops and various agroforestry practices which give both adaptation benefits and carbon sequestration.

Emission Reduction: CSA takes to degrade the agriculture sector's contribution to greenhouse gas emissions (Chakraborty et al.,2023). This include adopting practices which endorse carbon sequestration, reduce emissions from agricultural activities, and increase overall carbon efficiency. Practices such as improved livestock management, conservation agriculture, cover cropping and contribute to mitigating climate change by reducing emissions and increasing carbon sinks (Panda et al., 2024).

Sustainability: CSA objective is to enhance agricultural productivity in a sustainable manner (Panda et al., 2024). It include increasing production while reducing negative environmental impacts and confirming the effective executions of resources. Sustainable intensification involve the adoption of improved crop varieties, precision agriculture and integrated pest management to improve yields during reducing the ecological footprint of agriculture (Das and Ansari, 2021).

Resiliency: CSA places a strong importance on building the resilience of farmers and rural communities (Das and Ansari,2021). It include providing them with the tools, knowledge and resources to cope with climate-related challenges. Activities like the variation of income sources, access to climate data and social safety nets provide to encouraging the resilience of farming communities in the face of climate change (Sulaiman et al., 2019).

Pillars of Climate Smart Agriculture

Climate smart agriculture is an strategy which assist actions to convert agri-food systems towards green and climate resilient practices (Wakweya, 2023; Panda et al., 2024).

Productivity: Sustainable growth in agricultural productivity with regards to energy, food, eco-system services, fiber, feed and ecosystem services that support in completing food and nutritional security along with better incomes and livelihood standards.

Adaptation: Adoption of practices which can encourage the resilience of agriculture to climate change. Under climate difficulties, the adoption of integrated pest, conservation agriculture, crop rotation, water- efficient technologies and diversification, disease, and nutrient management practices, cultivating climate resilient crops and varieties, weather smart practices that can mitigate environmental impacts that can assist to adapt in erratic weather condition.

Mitigation: It recognises various possible ways to absorb carbon out of the atmosphere. Reducing greenhouse gas by avoiding deforestation and promotion agro-forestry as well as afforestation which can contribute to carbon sinks. Adopting innovative technologies and farming policies which help alleviate environmental pollution can help in mitigating climate change in long term.

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Beyond Harvest: Value Addition in Date Palm

Article ID: 74209

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Abstract
Date palm (*Phoenix dactylifera L.*) is an economically important fruit crop well suited to the arid and semi-arid regions of Gujarat due to its tolerance to drought and salinity. The recent GI recognition of Kutchi Kharek has created new opportunities for domestic and export markets, highlighting the need for scientific post-harvest management and value addition. This article discusses maturity stage-specific utilization of dates, modern harvesting and processing technologies, and the production of value-added products such as date powder, paste, syrup, stuffed dates, and date seed coffee. It also emphasizes zero-waste processing, quality assurance, and compliance with APEDA export standards through appropriate packaging and cold-chain management. Adoption of these technologies can reduce post-harvest losses, enhance product quality, diversify market opportunities, and transform date palm cultivation into a sustainable, high-value agribusiness, thereby improving farmers' income and strengthening the competitiveness of Gujarat's date industry.

Introduction
The agricultural landscape of arid and semi-arid regions is rapidly evolving. In areas characterized by high soil salinity and acute water scarcity, the date palm (*Phoenix dactylifera*) has emerged as a resilient, highly lucrative horticultural cornerstone. The recent assignment of the Geographical Indication (GI) tag to 'Kutchi Kharek' has elevated this regional treasure to a globally recognized brand, driving substantial market demand. However, achieving maximum profitability requires shifting focus from raw fruit cultivation to technologically advanced post-harvest processing (Zaid and de Wet, 2002). Raw date sales yield seasonal, highly volatile returns. Conversely, integration of precise harvesting workflows and industrial value-addition technologies introduces a year-round, diversified revenue model capable of scaling farm incomes.

The Maturity Stages of Date Development: Industrial Utilities
Effective value addition requires a clear understanding of the biochemical changes occurring during date fruit ripening. Each developmental stage offers distinct physical and chemical characteristics suitable for specific industrial applications. The Kimri stage is rich in phenolic compounds and bioactive constituents, making it suitable for nutraceuticals. The Khalal stage, characterized by maximum sucrose content, is ideal for fresh consumption. During the Rutab stage, sugar inversion and fruit softening make it suitable for date paste and syrup production, while the low-moisture Tamar stage is preferred for manufacturing date powder, diced dates, energy bars, and other shelf-stable value-added products. Proper stage-specific processing maximizes product quality, minimizes post-harvest losses, and enhances economic returns. Mechanized harvesting using hydraulic lifts or tractor-mounted platforms improves worker safety and minimizes fruit damage in tall date palms. Harvesting should be carried out at the Khalal stage to ensure optimum fruit quality, while delays may lead to skin cracking and fungal infections due to rainfall. Selective harvesting of only mature fruits ensures uniform size, color, and quality, resulting in higher market value. Additionally, protective mesh bags can be used to shield fruit clusters from birds, dust, and other environmental contaminants before harvest.



Fig.1 Maturation Stages of Date Fruits and Their Potential End-Use Products

Systematic Primary Processing Protocols

Modern post-harvest processing of dates involves several advanced operations to improve hygiene, quality, and market value:

1. Automated fluidized cleaning (Bubble Washer Technology): Dates are cleaned using pressurized air bubbles in a water bath to remove dust, dirt, and residues without damaging the delicate skin, ensuring hygienic produce that meets export standards.

2. Optical sorting and sensor-driven grading: Electronic grading systems with optical sensors classify dates based on size, colour uniformity, and firmness, ensuring consistent quality for premium markets.

3. Dehydration using solar tunnel dryers: Dates are dried in solar tunnel dryers to reduce moisture content while protecting them from contamination, preserving nutrients, and maintaining uniform colour and quality.

4. Precision de-seeding (pitting) and fortification: Mechanical or pneumatic pitting machines remove seeds without damaging the fruit, and the resulting cavity can be filled with premium nuts such as almonds, cashews, or walnuts to produce high-value value-added products.

Diversified Secondary Value-Added Products

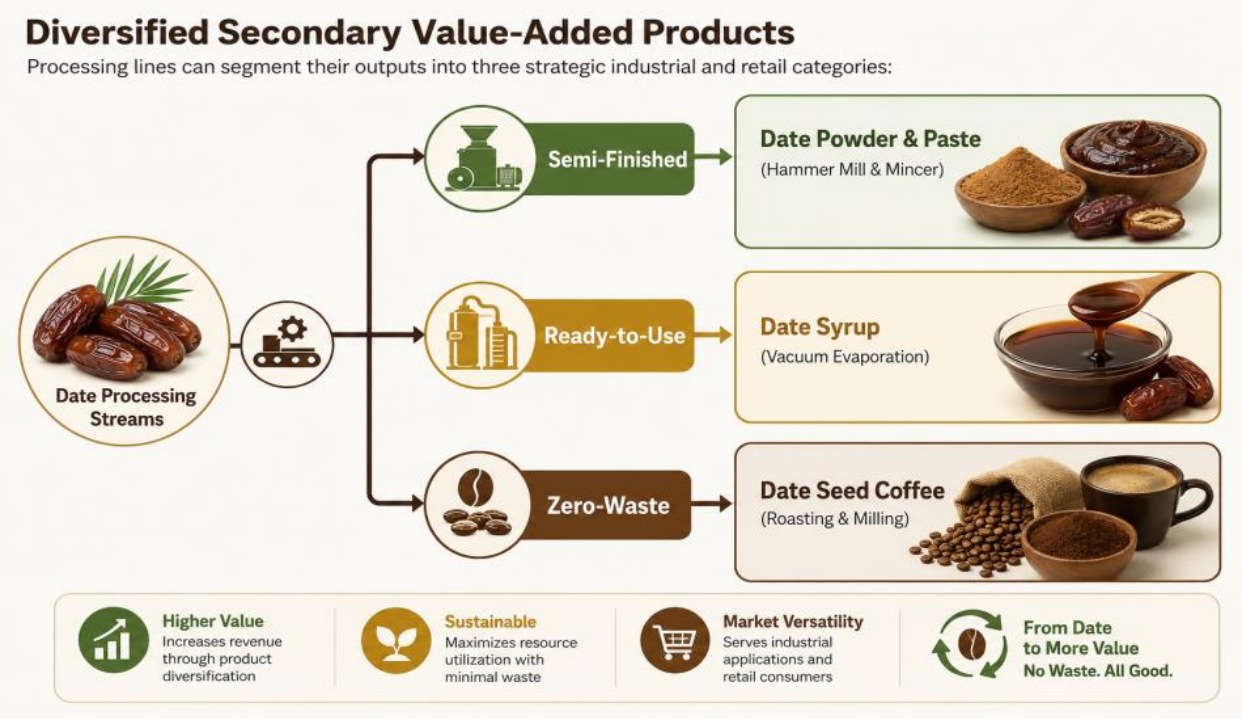


Fig. 2 Diversified Secondary Value-Added Products from date palm

Date processing industries produce a range of value-added products to maximize profitability and sustainability. Date powder is prepared by milling dehydrated Tamar-stage dates into a fine natural sweetener, while date paste is produced by mincing soft dates into a smooth binder and texturizer for bakery and confectionery products. Date syrup is manufactured using vacuum evaporation, which concentrates date juice at low temperatures to preserve its natural flavour and nutrients. Adopting a zero-waste approach, date seeds are cleaned, roasted, and milled to produce date seed coffee, a caffeine-free, antioxidant-rich beverage, ensuring efficient utilization of processing by-products (Jain *et al.*, 2015).

Conclusion

Date palm cultivation has become a profitable and climate-resilient enterprise for the arid and semi-arid regions of Gujarat, particularly with the growing recognition of GI-tagged Kutchi Kharek. Scientific post-harvest management, stage-specific harvesting, and modern processing technologies enable the production of high-value products such as fresh dates, date paste, syrup, powder, stuffed dates, and date seed coffee. Advanced operations including bubble washing, optical grading, solar drying, mechanical pitting, and zero-waste utilization improve product quality, reduce post-harvest losses, and increase profitability. Compliance with APEDA export standards, adoption of Modified Atmosphere Packaging (MAP), maintenance of the cold chain, and GI-based branding further enhance export potential. Together with government support, these innovations can transform date palm cultivation into a sustainable, year-round, value-added agribusiness that significantly improves farmers' income.



Plate 1. Unripen stage of date palm fruit

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Advanced Applications of Plant Tissue Culture

Article ID: 74210

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Introduction

In 1902, Gottlieb Haberlandt proposed the concept of growing isolated plant cells on artificial media. Although he did not achieve this experimentally, his idea laid the foundation for plant tissue culture technology. Plant tissue culture involves the sterile cultivation of plant cells, tissues, organs, or seeds on nutrient media. Initially developed for basic research in cell division, growth, and biochemistry, it has evolved into a widely applied and commercially important technique for the propagation of many horticultural crops. Plant tissue culture uses controlled media composition to direct plant growth, enabling shoot, root, callus, or embryo formation. Micropropagation is widely used for rapid plant multiplication. Somatic embryogenesis produces embryos from somatic cells and aids in mutation recovery, polyploidy induction, and chimera stabilization. Techniques like embryo rescue and ovule culture help overcome breeding barriers, making tissue culture an important tool in modern plant breeding.

Applications

Micropropagation: Micropropagation, also known as in vitro plant propagation, is one of the most important applications of plant tissue culture. It provides a quick and effective approach for mass multiplication and commercial production of plants compared to traditional propagation methods. For example, an efficient micropropagation protocol was developed for Hydrangea arborescens. Shoots were grown on Murashige and Skoog (MS) basal medium supplemented with 2 µM 6-benzylaminopurine (BAP). In this method, six shoots were cultured in a 180 ml jar and transferred to fresh medium every five weeks. Each subculture cycle produced an average of 21.0 ± 0.7 shoots per jar, or about 3.5 shoots per plantlet. Using this system, more than 1.5 million plants could be produced annually from an initial stock of only 50 plantlets. In addition, successful micropropagation methods have been developed for several other plant genera, including Rhododendron (azalea), Hypericum, Miscanthus, and Rudbeckia.

Polyploid Induction: The development of new polyploids through chromosome doubling can enhance ornamental traits, broaden breeding possibilities, and restore fertility in sterile hybrids, leading to improved cultivars. Polyploid induction has been widely used in ornamental plant breeding to improve plant characteristics and support breeding programs. In the genus Rudbeckia, researchers studied the effects of polyploidy on ornamental traits using embryogenic tissue culture systems to produce clonal lines. In-vitro treatments with 15–60 µM oryzalin for 3–5 days successfully induced polyploidy in different taxa. As a result, new tetraploids of R. maxima, R. subtomentosa, and a novel interspecific hybrid were developed for evaluation of their ornamental value.

Mutation Breeding: Induced mutations through irradiation or chemical mutagens are important biotechnological tools for developing sterile plants, dwarf varieties, and unique foliage traits such as variegation. Mutation breeding also helps increase genetic variability in species with limited diversity, such as Hypericum frondosum. Gamma irradiation has long been used on seeds and whole plants, and is now increasingly applied to tissue cultures to induce mutations. Treating callus cultures and regenerating plants from single cells helps avoid chimeric tissues. Researchers have also developed embryogenic systems in Hypericum to study the effects of gamma rays and chemical mutagens.

Stabilising Chimaeras: Chimaeras occur when a plant contains genetically different cell layers, often leading to leaf variegation. Through somatic embryogenesis, whole plants can be regenerated from single cells, allowing the production of plants with different genetic compositions from the same leaf or flower tissue. For example, in Rhododendron 'Little John', leaf variegation is caused by a mutation in the L1(outer) cell layer that produces red pigments. Using embryogenic techniques, both red and green plants were regenerated from the same leaf tissue.

Wide Crosses: Wide crosses involve hybridization between species from the same or different genera. These crosses are valuable in crop improvement because they combine diverse genes and desirable traits. However, differences in genomes and ploidy levels often create post-fertilization barriers, causing seeds to abort before development. Techniques such as embryo rescue and ovule culture help recover progeny from these crosses, as demonstrated in hybrids between *Derivilla* and *Weigela*.

Wide hybrids are often sterile because improper chromosome pairing disrupts meiosis. Fertility can be restored through chromosome doubling, which provides homologous chromosome sets for proper pairing. Tissue culture methods, especially somatic embryogenesis, are useful for inducing and recovering polyploids. For instance, embryogenesis was

induced in the sterile hybrid *Rhododendron* 'Fragrantissimum Improved' using thidiazuron (TDZ) and indole acetic acid (IAA), followed by oryzalin treatment to produce polyploids.

Developing Sterile Cultivars: One major goal of this research is the development of improved, non-invasive, seedless nursery crops. A common method for producing seedless plants is the creation of triploids, which contain three sets of chromosomes. Triploid plants usually grow normally but are sterile because their chromosomes cannot divide evenly during meiosis, preventing viable seed formation. Triploids are commonly produced by crossing tetraploid and diploid plants.

In *Miscanthus*, tissue culture techniques were used to produce triploid plants. Somatic embryos were developed from callus cultures derived from seeds or shoot tips. The callus was treated with oryzalin, a mitotic inhibitor, which produced about 60% tetraploid plants. These tetraploids were then crossed with diploids to generate triploids.

A major challenge was the "triploid block," where imbalance between embryo and endosperm ploidy caused embryo abortion. To overcome this, embryo rescue techniques were used by excising immature embryos from aborting seeds and culturing them *in vitro*. Although successful, efficiency was low, with about 600 plantlets recovered from more than 10,000 seeds.

Conclusion

Plant tissue culture is a biotechnological technique in which small plant parts (explants) are grown on a nutrient medium under sterile conditions to produce large numbers of plants throughout the year. The concept was introduced by the German botanist Gottlieb Haberlandt, known as the father of plant tissue culture. This technique is widely used for micropropagation, crop improvement, genetic transformation, virus-free plant production, and germplasm conservation. Compared with conventional propagation methods, it enables rapid and large-scale multiplication of plants. However, plant tissue culture has limitations such as somaclonal variation, low yield, and difficulty in regenerating some plants, especially monocotyledons. Despite these challenges, it remains an important tool in modern biotechnology and plays a significant role in improving global food security.

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Aromatherapy: The Culture of Fragrance

Article ID: 74211

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Introduction

The art of using fragrances with the science of healing is called aromatherapy. The National Association for Holistic Aromatherapy defines it as "the art and science of utilizing naturally extracted aromatic essences from plants to balance, harmonize, and promote the health of body, mind, and spirit." The benefits of aromatherapy goods for human health include physical and mental relaxation, enhancing emotional state and as a placebo to treat physiological related disorders. For at least 6000 years, this has been a reliable technique used by numerous ancient cultures, including Egypt, China, and India. Essential oils have grown in value due to their applications in spiritual purpose, cosmetics, therapy, and fragrances. These oils are the key therapeutic agents in aromatherapy. They are highly concentrated extracts derived from many parts of plants, including flowers, leaves, stems, fruits, and roots, also by the distillation of resins. A vast range of applications of essential oils and their constituents including food manufacturing, medicine, cosmetics, hygiene products and agriculture (Sharma and Sharma, 2025). During 1910, Rene-Maurice Gatte Fosse, a French chemist, discovered that his burn hand had recovered after accidentally spilling lavender oil on it, leaving only a tiny scar. This led him to create the word Aromatherapy. Subsequently aromatherapy become a complementary therapy in world wide. Every year, Americans spend around $30.2 billion on this therapy, according to the National Institutes of Health's National Centre for Complementary and Integrative Health. It is anticipated the worldwide market will expand in spending to $5 trillion by 2050.



Figure 1. Importance of Aromatherapy

Aromatherapy and Healing

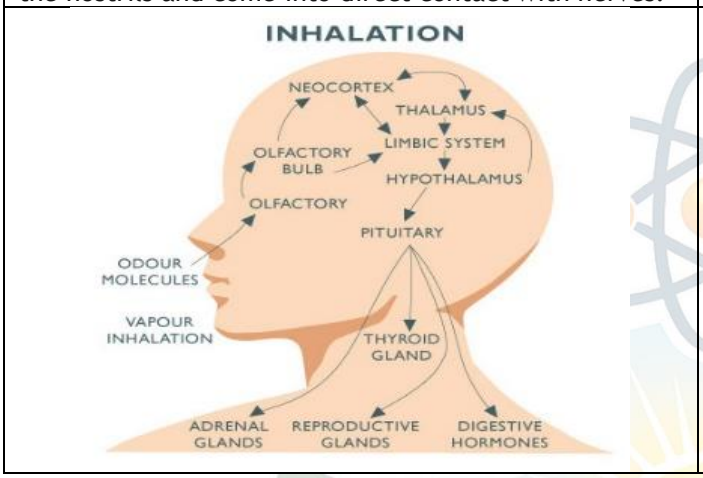
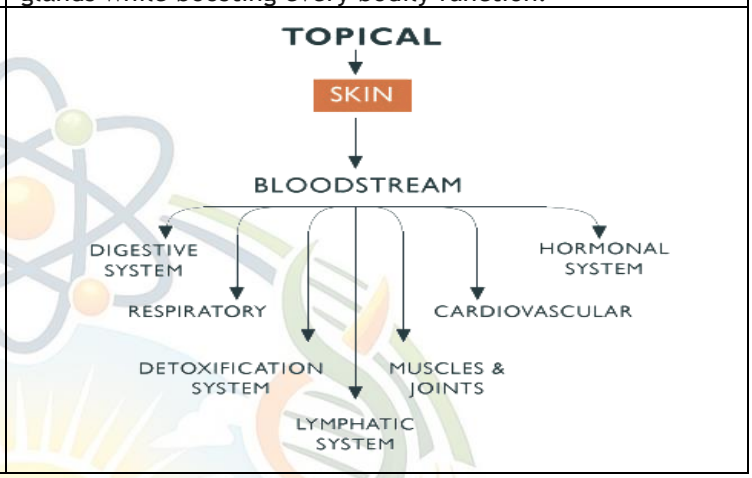
Essential oil solely plays crucial role in aromatherapy. It is very compulsory to use 100% unadulterated essential oils and totally pesticide-free. The limbic system is the region of the brain that senses and reacts to emotions, memories, and

pleasure. Aromas activate the limbic system and releases neurochemicals that enhance brain function and reduce pain. It also promotes calmness and peace.

How Aromatherapy Works?

Inhalation and topical application (Table.1) are the methods to use of essential oil (Sameer *et al.*, 2019).It was recorded that essential oil possess antiviral, antibacterial, and anti-inflammatory qualities along with immune-stimulating, hormonal, glandular, emotional, circulatory, calming, memory, and alertness-boosting abilities.

Table 1. Mechanism of Essential oil:

1. Inhalation: Essential oils stimulate the strong sense of smell, subsequently humans can distinguish 10,000 different scents. The brain responds to scents that enter the nostrils and come into direct contact with nerves.	**2. Topical Application:** Applying essential oils topically causes them to be absorbed via the skin and enter the body, revitalizing and calming the skin, muscles, nerves, and glands while boosting every bodily function.
	

Classification of Aromatherapy

1. Cosmetic aromatherapy: Beautification often invigorated by aromatherapy. This therapy uses specific essential oils religiously for facial, body as well as hair . Healthier skin can be attained by using essential oils as massage cosmetics.

2. Massage aromatherapy: In this therapy, the patient is massaged by a qualified masseuse who blends various essential oils. The goal of this type of therapy is to reduce discomfort. It helps the joints heal by calming them.

3. Clinical aromatherapy: Medical aromatherapy and massage aromatherapy are closely related since essential oils can be administered topically. It entails applying essential oils with caution to enhance mental, emotional, and physical health.

4. Olfactory aromatherapy: This type of therapy uses diffusers and vaporizers to evaporate the essential oil in the surrounding air. The air molecules are quickly absorbed by the bloodstream and then start to function. A few drops on a handkerchief, a room spray, or an aromatherapy candle can all be used as therapeutic tools.

5. Psycho-aromatherapy: These oils can be used in psycho-aromatherapy to elicit particular emotions and moods, such as relaxation, energy, or a profound memory. In this therapy, the oils are infused in the patient's room and inhaled directly.

Table 2. Examples of essential oils used for massages and skin care:

Kind of treatment/indications	Essential oils
Harmonising	Geranium, Rose Tree, Grapefruit, Neroli, Roman Chamomile
Stimulating	Lemon, Ginger, Rosemary
Relaxing	Sandalwood, Rose Tree, Geranium, Neroli
Calming	Lavender, Roman Chamomile, Sandalwood
Toning	Colander, Pepper, Grapefruit, Clary Sage, Ylang-Ylang
Anti-cellulite	Juniper, Rosemary, Patchouli, Cedar, Grapefruit, Cypress, Geranium
Slimming	Rosemary, Cypress, Geranium, Lemon, Ginger
Dry skin	Geranium, Neroli, Rose, Roman Chamomile, Sandalwood, Jasmine
Oily skin, acne skin	Lemon, Cypress, Tea Tree, Lavender, Roman Chamomile, Bergamot, Sandalwood, Copaiba

Combination skin	Geranium, Ylang-Ylang
Sensitive skin	Rose ,Lemon, Lavender, Roman Chamomile, Sandalwood
Couperose skin	Neroli, Rose, Roman Chamomile, Cypress, Sandalwood
Mature skin	Rose, Lemon, Rosemary, Neroli, Geranium, Sandalwood

Conclusion

Aromatherapy is an exceptionally wonderful technique to maintain a healthy quality life especially in this 21st century where people dealing with various issues. There is no adverse side effect which makes it more notable. Even anyone with basic knowledge of fragrances can use essential oil for betterment. Synthetic essential oil is the major drawback of this industries so there is demand for authentic organic essential oil and their constituents used in aromatherapy purpose.

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Beyond the Field: Transforming Agricultural Waste into Valuable Products

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Summary
What if the crop debris, fruit peels, onion skins, and rice husks often throw away could be used as raw materials for the food, packaging, and energy sectors of the future? Agricultural waste is a hidden trove of useful bioactive chemicals, fibres, and industrial resources—far more than just a problem for disposal. These neglected by-products can be turned into high-value goods using cutting-edge technology and value addition, generating revenue, lowering pollution levels, and promoting sustainable rural development. This article examines the ways in which agricultural waste might generate income and support a more environmentally friendly, circular bioeconomy.

Introduction
Millions of Indians rely on agriculture for their livelihood, making it one of the main drivers of the country's economy. The agricultural industry produces large amounts of waste throughout the harvesting, processing, shipping, and storage processes in addition to food production. Crop leftovers, fruit peels, vegetable trimmings, rice husk, bran, seeds, stalks, and processing byproducts are some examples of these wastes. A significant amount of this waste is typically thrown away or burned in open areas, which results in greenhouse gas emissions, environmental pollution, and the loss of potentially useful resources. Every year, around one-third of the food produced for human consumption is lost or wasted worldwide. Over 500 million tonnes of leftovers are produced annually in India by agricultural and agro-industrial operations. For every 100 kg of pomegranate processed, approximately 50 kg peel waste is generated. Similarly, rice milling produces nearly 200 kg husk per tonne of paddy processed. These by-products represent a significant untapped resource.

Recent scholarly research studies have suggested that many agricultural wastes are valuable sources of dietary fibers, polyphenols, flavonoids, pigments, cellulose, proteins, and essential oils. Such compounds have substantial industrial, medicinal, and nutritional value. The idea of "waste to wealth" is to recover these precious components and turn them into goods that can be commercialized. The circular economy, sustainable agriculture, and resource efficiency are all in line with this strategy. It is feasible to lessen the effects on the environment, create jobs in rural areas, increase farmers' income, and promote the growth of sustainable agri-enterprises by turning agricultural waste into high-value products.

Types of Agricultural Waste and Their Utilization Potential
Agricultural waste includes crop residues such as straw, leaves, husks, and bran, along with food processing by-products like fruit peels, vegetable wastes, pomace, and seeds. Biogas, bioethanol, biochar, biodegradable polymers, bio-based chemicals, and complex biomaterials are capable of being produced from these valuable leftovers, promoting sustainable resource use and lessening the impact on the environment (as shown in Table 1).

Table 1: Agro waste, bioactive compounds and their utilisation potential:

Agricultural Waste	Major Extractable Components	Potential Applications
Pomegranate Peel	Punicalagin, ellagic acid, polyphenols, flavonoids, anthocyanins, dietary fiber	Natural antioxidants, antimicrobial agents, edible coatings, active packaging films, functional foods, nutraceuticals
Rice Husk	Cellulose, hemicellulose, lignin, silica	Carboxymethyl cellulose (CMC), biodegradable films, biochar, adsorbents, silica nanoparticles, biofuel production
Rice Bran	Rice bran oil, γ-oryzanol, tocopherols, tocotrienols, dietary fiber	Functional foods, nutraceuticals, edible oils, antioxidant formulations
Onion Skin	Quercetin, flavonoids, phenolic compounds	Functional foods, pharmaceuticals, dietary supplements, natural preservatives, UV-protective packaging
Citrus Peel (Orange/Lemon)	Pectin, essential oils, flavonoids (hesperidin, naringin)	Jam and jelly production, edible films, pharmaceuticals, cosmetics, food stabilizers
Mango Peel and Seed Kernel	Pectin, carotenoids, polyphenols, starch, oil	Functional foods, edible coatings, antioxidants, cosmetic products
Banana Peel	Starch, pectin, dietary fiber, phenolic compounds	Animal feed, bioethanol, biodegradable packaging, functional food ingredients

Potato Peel	Starch, phenolic compounds, dietary fiber	Bioethanol production, antioxidant extracts, biodegradable films, livestock feed
Sugarcane Bagasse	Cellulose, hemicellulose, lignin	Paper and pulp industry, bioethanol, biodegradable composites, particle boards
Corn Cob	Cellulose, hemicellulose, xylan	Xylitol production, bioethanol, activated carbon, biodegradable composites
Butterfly Pea Flower Residues	Anthocyanins (ternatins), flavonoids	Natural food colorants, intelligent packaging, functional beverages

Challenges in Agricultural Waste Recovery

One significant limitation is the sporadic and seasonal availability of raw materials, which makes transportation and collecting challenging and costly. Crop variety, climate, cultivation methods, and storage time greatly affect the quality and composition of agricultural wastes, which leads to inconsistent final products. Agricultural residuals contain a number of bioactive chemicals that are sensitive to light, moisture, heat, and oxygen. Product quality and monetary value may be impaired by their deterioration during processing and storage. Technologies for extraction and recovery demands high cost specialized tools and technical know-how, which boosts manufacturing costs. It could be challenging for small business owners to invest in cutting-edge processing facilities. Additional difficulties include quality control and regulatory approval, especially for goods meant for food, pharmaceutical, and packaging uses. It can be costly as well as laborious to comply with safety standards, toxicity rules, and labeling requirements. Consumer acceptability may be limited since market awareness of items made from agricultural waste is still in infant stage. Therefore, the commercialization of waste-derived goods depends on overcoming these technological, financial, and market-related constraints.

Future Line of Work

Future studies should concentrate on creating economical and eco-friendly methods for extracting useful substances from agricultural waste. Supercritical fluid extraction, microwave-assisted extraction, and ultrasound-assisted extraction are examples of advanced extraction methods that provide greater recovery efficiency while using less solvent. The combination of biotechnology and nanotechnology can improve the stability and functionality of waste-derived products and open new rural as well as commercial opportunities in the agriculture industry (Fig. 1).

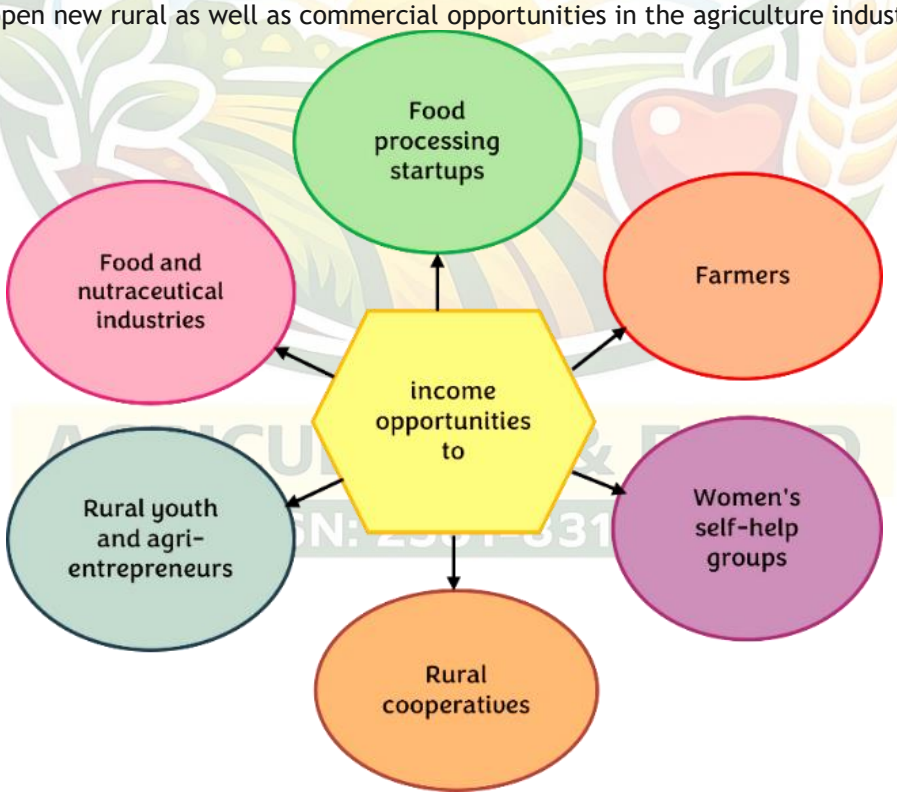


Figure 1: Income opportunities from agro-waste sector

Additionally, there should be more focus on creating bio-based chemicals from agricultural residues, functional food ingredients, and biodegradable packaging materials. Decentralized processing facilities can lower transportation expenses and generate jobs regionally. Establishment of agribusiness incubation centres, government supported start-ups, public private partnerships can boost technology transfer and its commercialization to its optimum level. To

maximize resource usage and achieve sustainable agricultural development, it will be essential to promote circular bioeconomy models and raise farmer awareness.

Conclusion

The waste once acted as a burden or ended up in landfills is now grooming and becoming a resource for sustainable growth and providing circular economy. The agricultural residues such as rice husk, fruit and vegetable peels, seeds, skins are now being used as functional foods, base material for bioactive compounds extraction, reusable packaging material and bioethanol production etc. This conversion is utmost important in current scenario to minimize pollution, GHG emissions and open new startups and rural enterprenuership. This can be a promising pathway for building sustainable and resource optimization agriculture with creation of a circular economy ecosystem with technological advancement, policy regulations and increased awareness among the consumers.

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Effect of Zinc and Bio NPK on Nutrient Content and Uptake by Summer Pearl Millet

Article ID: 74213

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Abstract
The field experiment was carried out at the Agronomy Instructional Farm, Bio Science Research Centre, S.D. Agricultural University, Sardarkrushinagar, Dantiwada during the period of March 2019- 2021 to study the effect of zinc and bio NPK on nutrient content and uptake by summer pearlmillet. The experiment was laid out in randomized block design in three replications. The experimental treatment comprised of different nine treatments asT_1: RDF (120:60:00 kg N:P_2O_5:K_2O ha^{-1}), T_2: RDF + Soil application of Zn @ 2.5 kg ha^{-1}, T_3: RDF + Soil application of Zn @ 5.0 kg ha^{-1},T_4: RDF + Foliar spray of $ZnSO_47H_2O$ @ 0.5 % at 30 and 45 DAS, T_5: RDF + Foliar spray of $ZnSO_47H_2O$ @ 1.0 % at 30 and 45 DAS, T_6:RDF + Soil application of Zn @ 2.5 kg ha^{-1} + Bio NPK (1 lit. ha^{-1}), T_7: RDF + Soil application of Zn @ 5.0 kg ha^{-1} + Bio NPK (1 lit. ha^{-1}),T_8:RDF + Seed priming with 1% Zn solution and T_9: RDF + Seed priming with 2% Zn solution. (Seed priming: Seeds will be soaked for 16 hrs. in respective solution keeping seed solution ratio of 1:5 (w/v) at 25° C). In light of the results obtained from this investigation, it is indicated that among the different treatments, an application of RDF + Soil application of Zn @ 5.0 kg ha^{-1} + Bio NPK(1 lit. ha^{-1}) (T_7) recorded significantly higher grain and straw yield of pearlmillet over rest of treatments.

Keywords: Pearlmillet, Zinc, Bio NPK.

Introduction
Bajra (Pearlmillet) the world's hardiest warm season cereal crop (Reddy *et al.*, 2011), is an indispensable arid and semi arid crop of India (Ramesh *et al.*, 2006) cultivated as dual purpose (food and feed) crop in over 8.3 m ha ranking fourth among total cereals. Further, the nutritional value of Bajra offers much scope to development of value added products in new health conscious consumer segments (Yadav *et al.*, 2011) as it contains more fiber and is good for diabetic and heart patients. It is the richest sources of nutrition, especially iron, calcium and zinc among cereals and hence can provide all the nutrients at least cost compared to wheat and rice (Parthasarathy *et al.*, 2006).

Materials and Methods
Experimental site: The field experiment was carried out during *summer* season of 2019 - 21 at Agronomy Instructional Farm, Department of Agronomy, Chimanbhai Patel College of Agriculture, Sardarkrushinagar Dantiwada Agricultural University, Sardarkrushinagar, District: Banaskantha (North Gujarat).

Results and Discussions
1. Effect on nutrient content: The pooled data (Table 1) indicated that different zinc application methods significantly influenced the nutrient composition of pearl millet. Nitrogen content in grain (1.62–1.69%) and straw (1.19–1.28%) showed numerical improvement under zinc treatments; however, the differences were statistically non-significant. This may be attributed to the role of zinc in enhancing nitrogen metabolism, chlorophyll synthesis, and protein formation (Alloway, 2008; Marschner, 2012). Grain phosphorus content increased significantly, with the highest value (0.329%) recorded under T_3 (RDF + soil application of Zn @ 5.0 kg ha^{-1}) and T_6 (RDF + soil application of Zn @ 2.5 kg ha^{-1} + Bio-NPK), while straw phosphorus was highest in T_7 (0.129%). The increase may be due to improved root growth and phosphorus solubilization by Bio-NPK microorganisms (Richardson *et al.*, 2009). Grain potassium content was significantly higher under T_3 (0.486%), whereas straw potassium content was maximum under T_8 (0.959%). Zinc application improves membrane stability and root activity, resulting in better potassium uptake (Marschner, 2012). Iron concentration in grain (68.00–71.91 ppm) and straw (332–360 ppm) showed numerical increases but remained statistically non-significant. Zinc concentration responded significantly to the treatments, with the highest grain (48.35 ppm) and straw (15.53 ppm) zinc contents recorded under T_7 (RDF + soil application of Zn @ 5.0 kg ha^{-1} + Bio-NPK). The combined application of zinc and Bio-NPK enhanced zinc availability, uptake, and translocation through improved microbial activity and root growth, leading to higher zinc accumulation in grain (Cakmak, 2008; Alloway, 2008). Overall, integrated application of 5.0 kg Zn ha^{-1} along with Bio-NPK proved to be the most effective treatment for improving the nutritional quality and zinc biofortification of pearl millet.

Table 1: Effect of different treatments on nutrient content of pearlmillet crop (Pooled data)

Treatments	N content (%)		P content (%)		K content (%)		Fe content (ppm)		Zn content (ppm)	
	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw
T_1 : RDF (120:60:00 kg NPK ha^{-1})	1.62	1.19	0.310	0.125	0.453	0.953	68.00	333	43.97	12.75
T_2 : RDF + Soil application of Zn @ 2.5 kg ha^{-1}	1.69	1.25	0.327	0.126	0.481	0.951	68.39	360	45.53	13.28
T_3 : RDF + Soil application of Zn @ 5.0 kg ha^{-1}	1.68	1.20	0.329	0.128	0.486	0.943	70.69	332	47.18	14.53
T_4 : RDF + Foliar spray of $ZnSO_4$ @ 0.5 % at 30 and 45 DAS	1.66	1.28	0.325	0.123	0.467	0.949	71.67	346	44.99	14.22
T_5 : RDF + Foliar spray of $ZnSO_4$ @ 1.0 % at 30 and 45 DAS	1.68	1.24	0.321	0.122	0.464	0.957	71.84	347	43.96	14.39
T_6 : RDF + Soil application of Zn @ 2.5 kg ha^{-1} + Bio NPK (1 lit. ha^{-1})	1.64	1.26	0.329	0.127	0.474	0.955	69.56	356	46.44	15.07
T_7 : RDF + Soil application of Zn @ 5.0 kg ha^{-1} + Bio NPK (1 lit. ha^{-1})	1.66	1.25	0.312	0.129	0.472	0.958	71.91	348	48.35	15.53
T_8 : RDF + Seed priming with 1% Zn solution	1.65	1.24	0.327	0.123	0.447	0.959	71.72	346	42.57	13.73
T_9 : RDF + Seed priming with 2% Zn solution	1.68	1.23	0.321	0.126	0.448	0.945	68.81	340	44.61	13.77
S.Em. ±	0.040	0.020	0.005	0.004	0.008	0.011	1.79	6.93	0.74	0.24
C.D. (P=0.05)	NS	NS	0.01	NS	0.023	NS	NS	NS	2.11	0.68
C.V. %	4.41	4.93	4.74	5.18	4.98	4.05	5.35	5.48	4.83	5.60
Y x T S.Em. ±	0.042	0.035	0.009	0.004	0.013	0.022	2.17	10.92	1.26	0.45
C.D. (P=0.05)	0.12	NS	NS	0.01	NS	NS	6.17	NS	NS	NS

Table 2: Effect of different treatments on nutrient uptake by pearlmillet crop (Pooled data)

Treatments	N uptake (kg ha^{-1})		P uptake (kg ha^{-1})		K uptake (kg ha^{-1})		Fe uptake (g ha^{-1})		Zn uptake (g ha^{-1})	
	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw
T_1 : RDF (120:60:00 kg NPK ha^{-1})	37.65	44.16	7.11	4.56	10.40	35.28	156.8	1240	102.9	47.18
T_2 : RDF + Soil application of Zn @ 2.5 kg ha^{-1}	43.19	53.57	8.43	5.27	12.33	40.07	174.8	1542	118.0	56.54
T_3 : RDF + Soil application of Zn @ 5.0 kg ha^{-1}	45.46	52.69	8.99	5.56	13.17	41.27	191.4	1447	129.9	63.95
T_4 : RDF + Foliar spray of $ZnSO_4$ @ 0.5 % at 30 and 45 DAS	38.85	50.89	7.67	4.81	10.94	37.45	169.4	1364	107.1	56.52
T_5 : RDF + Foliar spray of $ZnSO_4$ @ 1.0 % at 30 and 45 DAS	40.93	50.94	7.79	5.01	11.14	39.32	174.9	1447	108.7	59.85
T_6 : RDF + Soil application of Zn @ 2.5 kg ha^{-1} + Bio NPK (1 lit. ha^{-1})	45.89	58.45	9.28	5.96	13.26	44.50	196.8	1675	133.7	70.34
T_7 : RDF + Soil application of Zn @ 5.0 kg ha^{-1} + Bio NPK (1 lit. ha^{-1})	47.92	60.42	9.12	6.25	13.67	46.48	210.1	1699	143.7	75.50
T_8 : RDF + Seed priming with 1% Zn solution	39.14	46.80	7.76	4.60	10.62	36.15	170.7	1311	102.5	52.00
T_9 : RDF + Seed priming with 2% Zn solution	39.10	46.18	7.53	4.69	10.37	35.44	159.7	1289	105.0	52.02
S.Em. ±	1.50	2.06	0.27	0.20	0.42	1.39	6.45	58.75	4.31	2.12
C.D. (P=0.05)	4.26	5.83	0.77	0.58	1.20	3.95	18.30	165.9	12.20	6.03
C.V. %	11.49	13.21	10.72	12.49	11.78	11.52	11.35	13.03	11.08	11.05
Y x T S.Em. ±	2.78	3.93	0.50	0.37	0.80	2.63	11.68	109	7.47	3.78
C.D. (P=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

2. Effect on nutrient uptake: The pooled data (Table 2) revealed that different zinc management practices significantly influenced the uptake of major nutrients (N, P, and K) and micronutrients (Fe and Zn) by pearl millet. The nutrient uptake was consistently higher with integrated application of zinc and Bio-NPK compared with RDF alone. Nitrogen uptake by grain and straw ranged from 37.65–47.92 kg ha^{-1} and 44.16–60.42 kg ha^{-1}, respectively. The highest grain nitrogen uptake (47.92 kg ha^{-1}) and straw nitrogen uptake (60.42 kg ha^{-1}) were recorded under T_7 (RDF + soil application

of Zn @ 5.0 kg ha^{-1} + Bio-NPK), followed by T_6. The increased nitrogen uptake may be attributed to improved root growth, enhanced nutrient absorption, and the role of zinc in nitrogen metabolism and enzyme activation (Alloway, 2008; Marschner, 2012).

Phosphorus uptake showed a similar trend, with grain and straw phosphorus uptake ranging from 7.11–9.28 kg ha^{-1} and 4.56–6.25 kg ha^{-1}, respectively. The maximum phosphorus uptake in grain (9.28 kg ha^{-1}) and straw (6.25 kg ha^{-1}) was observed under T_6 and T_7, respectively. Enhanced phosphorus uptake under integrated zinc and Bio-NPK application may be due to improved phosphorus solubilization, increased root proliferation, and microbial activity in the rhizosphere (Richardson *et al.*, 2009).

Potassium uptake in grain ranged from 10.37–13.67 kg ha^{-1}, whereas straw potassium uptake varied from 35.28–46.48 kg ha^{-1}. The highest potassium uptake was recorded under T_7 (13.67 and 46.48 kg ha^{-1} in grain and straw, respectively). Improved potassium uptake under zinc application may be related to better root development, enhanced membrane functioning, and increased nutrient transport efficiency (Marschner, 2012).

Micronutrient uptake also showed significant improvement with zinc fertilization. Iron uptake in grain ranged from 156.8–210.1 g ha^{-1} and straw from 1240–1699 g ha^{-1}. The highest iron uptake was recorded under T_7, followed by T_6, which may be due to enhanced root activity and improved availability of micronutrients through microbial interactions. Zinc uptake showed a pronounced response, with grain and straw zinc uptake ranging from 102.5–143.7 g ha^{-1} and 47.18–75.50 g ha^{-1}, respectively. The highest zinc uptake in both grain (143.7 g ha^{-1}) and straw (75.50 g ha^{-1}) was observed under T_7, followed by T_6. The higher zinc uptake under integrated zinc and Bio-NPK application may be attributed to continuous zinc availability, microbial-mediated zinc solubilization, improved root growth, and efficient translocation of zinc from vegetative parts to grains (Cakmak, 2008; Alloway, 2008).

Summary and Conclusion

Integrated zinc management significantly improved nutrient content and uptake in pearl millet. Among all treatments, T_7 (RDF + Zn @ 5.0 kg ha^{-1} + Bio-NPK) was most effective, recording higher N, P, K, Fe, and Zn uptake, especially grain and straw zinc accumulation. The combined use of zinc and Bio-NPK enhanced nutrient availability, uptake efficiency, and grain nutritional quality. Therefore, Zn @ 5.0 kg ha^{-1} with Bio-NPK along with recommended NPK can be recommended for improving pearl millet productivity and zinc bio fortification.

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Recent Advances in Packaging Technologies for Postharvest Management of Fruits and Vegetables: A Review

Article ID: 74214

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Introduction

Fruits and vegetables are highly perishable agricultural commodities whose quality deteriorates rapidly after harvest. Improper storage, transportation, and packaging lead to significant postharvest losses, resulting in economic loss. Modern packaging technologies play a vital role in enhancing the freshness, nutritional quality, and shelf life of fruits and vegetables. This review discusses advanced technologies such as Modified Atmosphere Packaging (MAP), Active Packaging, Intelligent Packaging, Biodegradable Packaging, and Nano-Packaging.

Keywords: Postharvest management, packaging technology, fruits, vegetables, shelf life, active packaging.

Introduction

India is one of the major producers of fruits and vegetables in the world. However, postharvest losses account for a significant portion of total production. To reduce these losses, advanced packaging technologies have been developed to maintain product quality and ensure safe delivery to the market.

Major Causes of Postharvest Losses

1. High Respiration Rate: After harvest, fruits and vegetables continue to respire as living tissues. During respiration, they consume oxygen (O_2) and convert stored carbohydrates and nutrients into energy, releasing carbon dioxide (CO_2), water, and heat.

A high respiration rate leads to rapid depletion of nutrients, resulting in loss of freshness, flavor, texture, and nutritional value. This causes faster ripening, softening, and reduced shelf life. Mango, banana, papaya, tomato, and leafy vegetables are examples of high-respiration products.

Control measures:

a. Cold storage
b. Modified Atmosphere Packaging (MAP)
c. Controlled Atmosphere Storage
d. Proper humidity maintenance
e. Quick transportation and marketing

2. Moisture Loss: After harvest, fruits and vegetables continuously lose water through transpiration. Excess moisture loss leads to wilting, weight reduction, and decreased market value.

Moisture loss affects texture, causing shrinkage and quality deterioration. Leafy vegetables, carrots, radish, cucumber, grapes, and strawberries are highly sensitive to moisture loss.

Factors affecting moisture loss:

a. High temperature
b. Low relative humidity
c. Air movement
d. Long storage duration
e. Improper packaging

Control measures:

a. High relative humidity storage
b. Proper packaging materials
c. Plastic films or edible coatings
d. Cold storage
e. Careful handling and transport

3. Microbial Infection: After harvest, fruits and vegetables are susceptible to microbial contamination by bacteria, fungi, and yeast. These microorganisms enter through wounds, cuts, or natural openings and cause rapid spoilage.

Microbial infection affects color, taste, odor, and texture. Severe infection renders products unfit for consumption. Mango, grapes, tomato, strawberry, and leafy vegetables are highly affected.

Causes:

a. Mechanical damage during handling
b. Poor sanitation
c. High temperature and humidity
d. Contaminated water or equipment
e. Improper packaging

Control measures:

a. Sanitation practices
b. Cold storage
c. Antimicrobial packaging
d. Hygienic handling
e. Clean water and equipment

4. Mechanical Damage: Mechanical damage refers to physical injuries such as bruising, cuts, abrasion, and breakage during harvesting, sorting, packaging, transportation, and storage.

Such damage increases moisture loss and microbial infection, leading to faster spoilage and reduced shelf life.

Causes:

a. Improper harvesting and handling
b. Dropping from height
c. Excessive stacking pressure
d. Poor packaging materials
e. Vibration during transport

Effects:

a. Loss of color, texture, and flavor
b. Increased moisture loss
c. Higher microbial susceptibility
d. Reduced market value

Control measures:

a. Careful handling
b. Cushioning materials (foam, paper trays)
c. Strong ventilated packaging
d. Cold storage and transport
e. Trained workers

5. Variation in Temperature and Humidity: Temperature and relative humidity greatly influence postharvest quality. Uncontrolled variations accelerate physiological and biological processes, leading to rapid deterioration.

Higher temperature increases respiration and transpiration, speeding up ripening and reducing shelf life. Low humidity increases moisture loss, causing wilting and shrinkage.

Effects:

a. Increased respiration rate
b. Higher moisture loss
c. Faster ripening and softening
d. Enhanced microbial growth
e. Reduced quality and market value

Control measures:

a. Cold chain system
b. Controlled atmosphere storage
c. Proper packaging
d. High relative humidity maintenance
e. Continuous monitoring

Modern Packaging Technologies

Modern packaging technologies refer to advanced and innovative packaging systems designed to improve the shelf life, safety, quality, and sustainability of food products, especially perishable commodities such as fruits and vegetables. These technologies go beyond traditional packaging by actively controlling or monitoring the internal environment of packaged foods.

Modern packaging technologies are scientific and technology-driven packaging systems that use advanced materials, sensors, and functional components to enhance food preservation, reduce postharvest losses, and improve supply chain efficiency.

1. Modified Atmosphere Packaging (MAP): This technology controls the balance of oxygen, carbon dioxide, and nitrogen inside packaging to reduce respiration rate and extend freshness.

2. Active Packaging- Active packaging is an advanced food packaging system that not only provides a protective barrier to food but also interacts with the internal environment of the package to improve product quality and extend shelf life, especially for perishable foods like fruits and vegetables.
Involves the use of oxygen absorbers, moisture regulators, and antimicrobial agents to enhance shelf life.

3. Intelligent Packaging- Intelligent packaging is an advanced packaging system that is designed to monitor and provide information about the condition of food products during storage, transportation, and marketing. It does not only protect the food but also communicates the quality status of the packaged product in real time. Uses sensors and indicators to monitor quality, temperature, and freshness in real time.

4. Biodegradable Packaging- Biodegradable packaging refers to packaging materials that can be naturally broken down by microorganisms (such as bacteria and fungi) into harmless substances like water, carbon dioxide, and biomass within a reasonable period of time, without leaving toxic residues in the environment. Uses starch, cellulose, chitosan, and other bio-based materials for environmental sustainability.

5. Nano-Packaging- is an advanced food packaging technology in which nanomaterials (1–100 nm size range) are incorporated into packaging systems to improve the protection, preservation, and shelf life of food products, especially perishable items like fruits and vegetables.

Recent Research and Development

Recent developments include IoT, artificial intelligence (AI), and smart sensor-based packaging systems that monitor product conditions and predict shelf life in real time.

Advantages

1. Reduction in postharvest losses
2. Extended shelf life
3. Preservation of quality and nutrition
4. Safe transportation and marketing
5. Reduction in food waste

Challenges

1. High cost
2. Need for technical expertise
3. Limited adoption by small farmers
4. Environmental and regulatory issues

Conclusion

Advanced packaging technologies play a crucial role in postharvest management of fruits and vegetables. Technologies such as MAP, active, intelligent, and biodegradable packaging significantly improve product quality and shelf life. Future developments using smart sensors, AI, and IoT will further enhance efficiency and sustainability in this field.

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Biocontrol Potential of Bacteriophage Against Plant Pathogenic Bacteria

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Abstract

Plant pathogenic bacteria significantly reduce crop yields and threaten global food security. Bacteriophages (phages), viruses that specifically infect and kill bacteria, have emerged as promising eco-friendly biocontrol agents due to their high specificity and safety for humans and the environment. Phage therapy offers a sustainable alternative for managing bacterial plant diseases, with studies demonstrating its effectiveness under both greenhouse and field conditions. Phages can be applied individually or as phage cocktails to improve disease control. This review highlights the potential of bacteriophages in sustainable agriculture, focusing on their life cycle, application methods, and role in controlling bacterial plant pathogens.

Keywords: Bacteriophages, Phage therapy, Cocktail, Plant pathogenic bacteria, Biocontrol.

Introduction

Plants are continuously exposed to a wide range of pests and diseases in natural environments. Among these, pathogenic bacteria are important disease causing agents that infect numerous plant species, adversely affecting plant growth, productivity, and overall crop yield. These bacterial pathogens contribute significantly to agricultural losses and threaten global food security as the demand for food increases with the growing human population. Ensuring sustainable crop production requires the development of effective and environmentally responsible disease management strategies. Conventional approaches for controlling bacterial infections, particularly the use of antibiotics, have raised concerns due to their harmful effects on the environment and human health, as well as the increasing emergence of antibiotic-resistant bacterial strains. In this context, bacteriophages have gained considerable attention as a promising and eco-friendly alternative for the biological control of plant bacterial diseases (Korniienko *et al.*, 2022).

Bacteriophages, commonly known as phages, are viruses that specifically infect prokaryotic cells. They exhibit considerable diversity in morphology and size, with most measuring less than 100 nm. The majority of identified bacteriophages possess double-stranded DNA genomes, while a smaller proportion contain either single-stranded DNA or RNA as their genetic material. Phages are widely distributed across various environments, particularly in aquatic habitats where they are highly abundant. The application of bacteriophages for the treatment of bacterial diseases dates back to the period before the discovery and widespread use of antibiotics (Tesfaye Kassa, 2021). Through long-term coevolution with their bacterial hosts, bacteriophages have developed important ecological functions by regulating bacterial populations in diverse ecosystems, including soil, water, and even the human body. Since their discovery over a century ago, bacteriophages have been recognized for their potential as biological control agents against bacterial pathogens. In addition to biocontrol, they have found diverse applications in areas such as phage therapy, phage display, phage typing, and molecular cloning. Although the use of bacteriophages for managing bacterial diseases in plants has been explored, their application in agriculture remains relatively limited and is still considered an emerging approach. Similar to other biological control methods, phage-based disease management offers the advantage of reducing dependence on chemical pesticides, thereby minimizing environmental concerns such as habitat degradation, deforestation, and pesticide residues on agricultural produce. Bacteriophages targeting important plant pathogens, including *Ralstonia solanacearum, Xanthomonas oryzae* pv. *oryzae*, *X. axonopodis* pv. *punicae*, and *X. campestris* pv. *campestris*, have been successfully isolated and characterized for their physical and physiological properties (Bairwa and Jambagi, 2021).

Historical Background

Bacteriophages were first discovered independently by Twort and d'Herelle in the early twentieth century and were initially recognized for their potential in treating bacterial diseases in humans and animals. Their association with plant-pathogenic bacteria was identified soon afterward, leading to their consideration as biological agents for the management of plant diseases. Among the earliest studies, Mallman and Hemstreet (1924) reported that filtrates obtained from decomposing cabbage inhibited the growth of *Xanthomonas campestris* pv. *campestris*, the bacterium responsible for black rot of cabbage (Holtappels *et al.*, 2021). Subsequently, in 1925, Kotila and Coons demonstrated

that bacteriophages isolated from soil effectively suppressed the growth of *Pectobacterium carotovorum* subsp. *atrosepticum*, the causal organism of potato blackleg disease.

General Characteristics and Life Cycle

Bacteriophages are viruses that specifically infect bacterial cells and are considered the most abundant biological entities on Earth. They depend on bacterial hosts for their replication and consist of a protein capsid enclosing either DNA or RNA as their genetic material. Among the phages identified to date, more than 97% possess double-stranded DNA genomes. Bacteriophages exhibit considerable diversity in morphology and size, although most display a characteristic tadpole-like structure comprising an icosahedral or isometric head attached to a tail with terminal fiber-like appendages. Members of the order *Caudovirales* typically possess isometric heads ranging from 20 to 200 nm in diameter, with tails of varying lengths and associated tail fibers. Due to their widespread distribution in nature, bacteriophages are readily isolated from diverse environments and can be purified, cultured, and manipulated using relatively simple laboratory techniques. Their environmentally friendly nature is attributed to their high specificity toward bacterial hosts, lack of toxicity to eukaryotic organisms, and minimal impact on the surrounding microbial community. Furthermore, because they are naturally occurring, biodegradable, and leave no harmful residues, bacteriophages represent a sustainable alternative to conventional agrochemicals for plant disease management.

Phages are classified as either lytic or lysogenic (temperate), depending on their lifestyle. Lysogenic viruses infect bacterial cells followed by integration of their DNA information into the DNA of bacteria. Therefore, the bacteria reproduce asexually in conjunction with the integrated bacteriophage information. The viral genome replicates together with the bacterial DNA and as a result, all the bacterial progeny reproduced will carry the virus information. The lysogenic cycle continues endlessly unless exposed to adverse conditions that can terminate the lysogenic phase. Lytic viruses interact, enter and complete their life cycle in the bacterial cell and finally lyse the host cell. Lytic phages, unlike lysogenic groups, do not integrate their DNA material into the DNA of the bacteria.

Bacteriophage Biocontrol – The Art of Controlling

Phage therapy, which involves the use of bacteriophages to specifically infect and eliminate bacterial pathogens, has re-emerged as a promising strategy for the management of bacterial diseases in plants (Vu and Oh, 2020). A key factor in selecting bacteriophages for biological control is determining whether they exhibit a lytic or lysogenic life cycle. Identifying the replication strategy of a phage is essential to ensure its safety and effectiveness as a biocontrol agent. Lytic bacteriophages are particularly suitable because they actively infect susceptible bacterial cells, replicate within them, and cause cell lysis to release numerous progeny phages. This rapid bactericidal activity has led to their widespread use in phage therapy for controlling bacterial diseases affecting both plants and animals.

The development of commercial phage-based products, often referred to as phage-derived bactericides, generally involves a series of systematic steps to ensure their safety, efficacy, and practical application (Moye *et al.*, 2018). These steps include:

1. Phage isolation from the natural environment, likely from the material where the host bacteria actively grow, (i.e., rotten vegetables or waste water)

2. Phage characterisation (morphology, biochemical properties, host range, genome sequencing, proteome analysis, phylogeny)

3. Antibacterial tests *in vitro* and *in vivo*

4. Optimisation of the phage cocktail for the biocontrol (i.e., field trials)

5. Patenting.

The application of a single type of phage (monophage therapy) makes it easier for bacteria to develop resistance to that phage. However, the simultaneous use of more than one phage type (polyphage therapy or phage cocktail method) may prevent the development of phage-resistant bacterial mutants. Using a mixture of lytic bacteriophages known as a bacteriophage cocktail is also a potential approach to compensate for the limitation of host-range of a single bacteriophage as well as prevention of the development of bacteriophage-resistant bacteria. The phage mixtures were used to control a variety of bacterial plant pathogens such as *R. solanacearum* (Ramirez *et al.*, 2020), *Xanthomonas* spp. (Chae *et al.*, 2014). Although there are some bacteriophages attacking one or more bacterial genera, most bacteriophages can infect restrictively some strains within a single bacterial species. The restriction is mainly derived from the highly specific interaction between host cell surface receptors and phage attachment structures.

Bacteriophages can be administered in both greenhouse and field environments through different application methods, including soil drenching, foliar spraying, infiltration, and seed treatment by immersion. These methods enable effective delivery of phages to the target site for disease management. For instance, soil drenching of the rhizosphere with bacteriophages has been reported to significantly reduce bacterial wilt caused by *Ralstonia solanacearum* in tomato plants (Elhalag *et al.*, 2018). Likewise, foliar spraying of bacteriophages has proven effective in lowering disease incidence caused by *Xanthomonas campestris* pv. *campestris* (Nagai *et al.*, 2017) and *Pectobacterium carotovorum* subsp.

carotovorum, highlighting the potential of phage application as an eco-friendly strategy for controlling bacterial diseases in crops.

Phages as Part of Integrated Management Strategy

Effective management of bacterial plant diseases requires an integrated approach rather than relying on a single control method. Conventional strategies such as pathogen-free planting material, resistant cultivars, and good cultural practices provide partial disease control but are more effective when combined within an Integrated Pest Management (IPM) system. Recent studies have shown that integrating bacteriophage therapy with chemical treatments, systemic acquired resistance (SAR) inducers, or biological control agents such as plant growth-promoting rhizobacteria (PGPR) enhances disease suppression. These findings highlight the potential of phage-based integrated strategies for achieving more reliable and sustainable management of bacterial plant diseases.

Conclusion and Future Perspectives

Bacteriophages are promising biological agents for controlling plant pathogenic bacteria and can reduce reliance on copper-based bactericides and antibiotics. Their high specificity, safety to humans and other eukaryotes, and minimal impact on beneficial microorganisms make them an environmentally friendly and sustainable disease management option. Several commercial phage products, such as AgriPhages, Erwiphage, and Biolyse, are already available for controlling bacterial diseases in crops. However, their field performance can be affected by environmental factors including UV radiation, temperature, humidity, and rainfall. Therefore, improved formulations, efficient delivery methods, standardized phage selection, and extensive field trials are essential to ensure consistent performance and support the broader adoption of phage therapy in sustainable agriculture.

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Microbacterium meiriae: As a Climate Resilient New Spp.

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Abstract

One of the biggest threats to global food security is climate change, which makes it necessary to find and use new stress-tolerant microorganisms. The recently identified bacterial species *Microbacterium meiriae* sp. nov., which was first isolated from the International Space Station (ISS), has an amazing array of stress-adaptive genetic traits that make it a potentially useful organism for climate-resilient agriculture. In order to place *M. meiriae* importances within the larger context of climate-smart microbiology, this study examines its taxonomic and genetic characterization, physiological resilience and potential agricultural uses. *M. meiriae* is a strong contender for future bioinoculant development under changing climatic conditions because of its broad temperature tolerance, salinity resistance, heavy metal adaption and secondary metabolites production.

Keywords: *Microbacterium meiriae*, climate resilient bacteria, climate smart agriculture, stress adaptation, ISS microbiology, secondary metabolites.

Introduction

The dynamics of agricultural ecosystems are being significantly altered by global climate change, which is characterized by rising temperatures, unpredictable precipitation, increased salt intrusion and soil degradation. High yielding cultivars, chemical herbicides and synthetic fertilizers are examples of conventional approaches that are becoming less and less effective in addressing the dual challenges of environmental sustainability and food production (FAO, 2021). In this regard, a new area of study in sustainable agriculture is the investigation and use of climate resilient microorganisms. Because they mediate nutrient cycling, promote plant development and biologically manage diseases, soil microbiota is essential to the functioning of ecosystems. Plant growth promoting rhizobacteria (PGPR) are particularly important because they can increase crop yield by producing phytohormones, fixing nitrogen, solubilizing phosphate and inducing systemic resistance (Glick, 2012). However, under climate extremes like heat, drought, salinity and heavy metal stress, the effectiveness of many known PGPR strains is reduced, highlighting the critical need to identify novel, stress tolerant bacterial species (Meena *et al.*, 2017; Kumari *et al.*, 2022). Outer space represents one of the most extreme environments for life, characterized by intense ionizing radiation, high vacuum, microgravity, and severe temperature fluctuations. These conditions impose significant physiological stress on living organisms. Nevertheless, numerous microorganisms have evolved mechanisms that enable them to withstand and adapt to such hostile environments. Extremophilic organisms, including bacterial genera such as *Bacillus* and *Microbacterium*, fungi, tardigrades, bdelloid rotifers, and other resilient taxa, have demonstrated remarkable survival under simulated or actual space conditions, highlighting their exceptional resistance to multiple environmental stresses (Szydlowski *et al.*, 2024). A surprising source of microbial variety has been discovered on the International Space Station (ISS). The International Space Station (ISS) is a closed environment that houses a diverse range of microorganisms, including potential pathogens. *Microbacterium meiriae* sp. Nov. was recently isolated and thoroughly characterized from this harsh environment (Karouia *et al.*, 2025). A thorough analysis of *M. meiriae*, its climate resilient genomic architecture and its potential contribution to agricultural systems that are future proof are presented in this paper.

General Characteristics of *Microbacterium meiriae* Sp. Nov

The genus *Microbacterium* belongs to the family *Microbacteriaceae* within the order *Micrococcales*. Due to similarities in morphological characteristics, members of this genus were initially classified under the genus *Corynebacterium*. The species *meiriae* was named in honor of NASA astronaut Jessica U. Meir who is a marine biologist from USA. Gram staining positive, non spore forming rods and possess high degree of physiological and biochemical diversity. Thy are chemoheterotrophic and mesophilic rods with pale yellow pigmentation. Cells are non-flagellated, slender rods with rounded ends measuring around 1.5µm in length and 1µm in width (Karouia *et al.*, 2025). The changes in amino acid

composition reflect the adaptations to the lifestyle of *M. meiriae*, with enrichment of arginine(s) and methionine(s), with the subsequent reduction of lysine and asparagine. Arginine is known to provide more stability to the structure than lysine (Sokalingam *et al.*, 2012). There is also evidence of plasmid in *M. meiriae*, due to the presence of relaxosome encoding genes, such as MobC/L family relaxase.

Microbacterium meiriae in the Context of Climate Smart Agriculture

Microbacterium meiriae has emerged as a promising microbial resource for climate-smart agriculture due to its potential to enhance crop productivity while improving resilience to climate-induced stresses. As a plant associated bacterium, it can promote plant growth by improving nutrient availability, producing phytohormones, and supporting root development, thereby enabling crops to better withstand drought, salinity, and other abiotic stresses. Its use as a bioinoculant can reduce dependence on synthetic fertilizers and other agrochemicals, contributing to environmentally sustainable farming practices. By enhancing plant health, resource-use efficiency, and stress tolerance, represents a valuable component of climate-smart agricultural strategies aimed at ensuring sustainable crop production under changing climatic conditions.

It exhibits remarkable physiological resilience, enabling it to survive and grow under a broad range of environmental conditions. This wide physiological tolerance indicates that it is a truly eurytolerant organism, making it a promising candidate for agricultural applications in diverse and changing environments. The bacterium is capable of growing across a temperature range of 4 - 40°C, reflecting an overlap between psychrotolerant and mesophilic characteristics. It also tolerates salinity levels ranging from 0.5% to 8% NaCl, demonstrating substantial resistance to salt stress. Furthermore, *M. meiriae* grows within a pH range of 6.0–9.0, indicating adaptability to both slightly acidic and alkaline soils. As a strictly aerobic microorganism, it requires oxygen for growth and metabolism, supporting efficient physiological activity under well-aerated conditions.

Climate Smart Agriculture and the Microbial Imperative

Strategies that concurrently boost resistance to climate change, lower greenhouse gas emissions and increase production are collectively referred to as climate-smart agriculture (CSA) (FAO, 2013). According to Meena *et al.* (2017), microorganisms are essential to the CSA toolset. Beneficial microorganisms and endophytes show adaptive amplifications under changing climate scenarios to mitigate the detrimental effects on plant physiology, metabolic processes and health (Mishra *et al.*, 2020). In light of climate variability, this broad temperature range (4-40°C) is especially important. From chilly highland farms to parched lowland fields, agricultural soils are more subject to temperature changes brought on by climate change. As a bioinoculant, a microorganism that can function across this spectrum would provide significant adaptive advantages (Basu *et al.*, 2021).

The Role of Soil Microbiota Extends Across All Three Pillars of CSA: Productivity, Resilience and Mitigation

Soil microbiota play a fundamental role in achieving the three core pillars of climate-smart agriculture (CSA), namely productivity, resilience, and climate change mitigation. As a member of the beneficial soil microbiota, *M. meiriae* has the potential to contribute to these objectives through its physiological adaptability and ecological functions. Its ability to tolerate a wide range of environmental conditions suggests that it may enhance agricultural productivity by supporting nutrient cycling and promoting plant growth, improve crop resilience by helping plants withstand abiotic stresses, and contribute to climate change mitigation through its involvement in soil carbon and nitrogen dynamics. Although further functional studies are needed to fully characterize its plant growth-promoting and ecological attributes. The drawbacks of traditional PGPR bioinoculants, which often lose effectiveness in harsh weather conditions, are directly addressed by *M. meiriae* stress tolerance profile.

Table 1. Physiological and genomic characteristics of *M. meiriae* and their potential significance for climate resilient agriculture:

Climate-Related Stress	Characteristic of *Microbacterium meiriae*	Potential Agricultural Significance
Temperature fluctuations	Growth over a broad temperature range (4-40°C)	Adaptation to diverse agro-climatic conditions and variable seasonal temperatures
Drought / Water deficit	Presence of toxin-antitoxin (TA) systems and stress-response regulatory genes	Enhanced bacterial survival under desiccation and water-limited conditions
Soil salinity	Growth in the presence of up to 8% NaCl	Potential application in saline and salt-affected agricultural soils
Heavy metal contamination	Presence of genes associated with heavy metal resistance	Potential use in contaminated soils and bioremediation of polluted agricultural lands
Reduced plant growth	Presence of auxin (IAA) biosynthesis-related genes	Potential to stimulate root development and improve plant growth

Soil-borne pathogen pressure	Presence of biosynthetic gene clusters (BGCs) for secondary metabolite production	Potential source of antimicrobial compounds for biological control of soil-borne pathogens

Comparison with Established Climate Resilient PGPR

M. meiriae functions similarly to a number of well-known climate-resilient bacteria. *Acidovorax radicis* N35 inhibits insect pests and encourages barley growth; this impact is highest when ozone stress levels are high (Stenberg *et al.*, 2021). TA-equipped *Bacillus* and *Pseudomonas* strains exhibit improved resistance to heat and osmotic stress. *M. meiriae* is a member of the phylum Actinobacteria, which is a prolific generator of secondary metabolites used in agriculture (Van Der Meij *et al.*, 2017). But unlike the majority of PGPR that have been investigated, *M. meiriae* was developed in the ISS, which is the ultimate stress environment. As a result, it has a stress-adaptation toolkit that is distinct from that of soil-origin strains.

M. meiriae benefits from the well-established metabolic adaptability of the phylum Actinobacteria. According to Barka *et al.* (2016), actinobacteria are among the most abundant makers of bioactive secondary metabolites, such as plant growth promoters, antibiotics and antifungals. The ability of the *Microbacterium* genus to produce a variety of secondary metabolites, resist heavy metals and improve phytoremediation has already been shown by comparative genomics (Schneider *et al.*, 2020).

Challenges and Future Research Directions

Although *Microbacterium meiriae* exhibits a promising genomic and physiological profile, several critical challenges must be addressed before its widespread agricultural application can be realized. First, its plant growth promoting (PGPR) traits require experimental validation. The predicted auxin biosynthesis genes should be confirmed through indole-3-acetic acid (IAA) quantification using the Salkowski reagent method, followed by pot experiments under abiotic stress conditions to evaluate plant growth promotion and studies investigating rhizosphere colonization efficiency. Another important consideration is biosafety. The presence of the tetracycline resistance gene tet (42), which shares 82% sequence identity with that of *Microbacterium paraoxydans*, raises concerns regarding the potential horizontal gene transfer (HGT) of antibiotic resistance genes in soil ecosystems (Karouia *et al.*, 2025). Therefore, future studies should assess the transferability of tet (42) under field conditions, ensure compliance with regulatory guidelines for bioinoculant development, and explore alternative antibiotic-sensitive strains of the species. Furthermore, despite its remarkable stress tolerance, *M. meiriae* has not naturally evolved within terrestrial soil ecosystems, making its ecological integration an important area of investigation. Future research should evaluate its competitiveness with native soil microbiota, root colonization efficiency, rhizosphere competence, effects on beneficial mycorrhizal associations, and its influence on the composition and diversity of soil microbial communities following inoculation. Additionally, the approximately 76% uncharacterized portion of the *M. meiriae* genome represents a valuable reservoir of unexplored genetic potential. Functional genomics approaches, including CRISPR-Cas9 mediated mutagenesis, heterologous expression of biosynthetic gene clusters (BGCs), and functional metagenomics, may facilitate the discovery of novel bioproducts and stress tolerance mechanisms with applications in biotechnology and sustainable agriculture. Finally, comprehensive field evaluations are essential to determine the practical performance of *M. meiriae* as a bioinoculant. Controlled environment agriculture (CEA) studies simulating future climate conditions, including elevated atmospheric CO_2, increased temperatures, and variable precipitation patterns projected by the IPCC, would provide valuable insights into its effectiveness under climate change scenarios.

Conclusion

A promising climate-resilient bacterium, *Microbacterium meiriae* sp. nov., can withstand a variety of environmental stressors, such as severe temperatures, salt and heavy metal pollution. Its genetic capacity for auxin synthesis, stress adaptability and secondary metabolite biosynthesis points to potential uses in sustainable agriculture and plant growth promotion. *M. meiriae* shows great potential as a future bioinoculant for climate-smart agriculture and enhancing crop resilience under changing environmental conditions, but more research is required to confirm its efficacy and biosafety in field settings. Its ability to survive in an extreme environment like the ISS makes it particularly interesting for future space missions.

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Forgotten Crops for Future Food Security: Why Millets, Pulses, and Underutilized Crops Matter?

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Introduction

Feeding a planet that will carry close to ten billion people by mid-century was never going to be simple, but the arithmetic has grown harder in the last few years. Three crops -rice, wheat, and maize -supply roughly half of humanity's calories, a concentration that has delivered impressive yield gains since the Green Revolution but has also left global food systems dangerously narrow. When a drought, a pest outbreak, or a war disrupts even one of these staples, the shock reverberates through markets on the other side of the world. Meanwhile, hunger has not been retreating the way development planners once hoped; conflict, economic stress, and increasingly erratic weather have combined to push food insecurity back onto the agenda after years of steady progress.

Climate change compounds the problem in a second, quieter way. It is not only shrinking yields in some regions; it is also eroding the nutritional density of the food that is still being produced, since elevated carbon dioxide levels are associated with lower protein, iron, and zinc concentrations in several major cereals. So the challenge facing agriculture today is not simply “grow more food” -it is “grow more food that keeps people adequately nourished, on land and water that are becoming less predictable by the season.”

Diversification is the obvious, if underused, answer. A food system anchored in a wider basket of crops is more resilient to any single shock, more capable of supplying a fuller spread of nutrients, and generally kinder to the soils and ecosystems that have to keep producing, year after year. That is precisely where forgotten and underutilized crops re-enter the conversation -not as a nostalgic throwback to pre-Green Revolution farming, but as a genuinely practical strategy for building sturdier food systems.

What are Forgotten and Underutilized Crops?

Forgotten or underutilized crops -sometimes called neglected and underutilized species (NUS), orphan crops, or minor crops -are plant species that were once cultivated widely, or still are in specific regions, but have slipped out of mainstream agricultural research, breeding investment, and formal markets. Millets, minor pulses, amaranth, buckwheat, and a long list of indigenous vegetables and tubers fall into this category. They are not “wild” in the sense of being unimproved by human selection; farming communities bred and refined many of them over centuries. What they lack is institutional attention: certified seed systems, dedicated breeding programmes, processing infrastructure, and consumer visibility, all of which flowed disproportionately toward rice, wheat, and maize after the 1960s.

Their relevance to sustainable agriculture follows directly from that neglect. Because these crops were never pushed through the high-input breeding pipeline that shaped modern rice and wheat varieties, most retain traits suited to marginal, rainfed, or otherwise difficult growing conditions -traits that today's breeders are scrambling to reintroduce into mainstream crops through more expensive means. Reviving them is, in a sense, a shortcut back to resilience that agriculture spent the last sixty years breeding away from.

Why they Matter?

Nutritional Benefits: The nutritional case for forgotten crops is arguably the strongest of all. Finger millet carries roughly ten times the calcium of rice or wheat, an advantage so pronounced that nutritionists routinely recommend it for growing children and pregnant women whose micronutrient needs are especially high; millets more broadly are rich in calcium, iron, zinc, and phosphorus alongside B-vitamins that are comparatively scarce in rice and wheat (Jacob et al., 2024). Systematic reviews pooling data across dozens of published studies confirm that finger millet consistently records the highest calcium and iron levels among the millets, while pearl millet stands out for zinc (Anitha et al., 2024), and that pearl millet's protein content is comparable to wheat and distinctly higher than rice or maize. Pulses tell a complementary story: chickpea and pigeon pea both deliver a fifth or more of their weight as protein in raw form, along

with the dietary fibre that refined cereals lack almost entirely. Put a millet and a pulse on the same plate and the combination approaches a genuinely complete amino acid profile -something neither achieves alone.

Climate Resilience: Millets and most indigenous pulses evolved, or were domesticated, in semi-arid and marginal tracts, and it shows in their physiology. They typically need a fraction of the water that rice demands, tolerate poor and saline soils, and mature quickly enough to dodge terminal drought -the kind that arrives just as a crop is filling grain. This is precisely the profile that climate projections say more of India's, and the world's, farmland will need in coming decades. Reviews of neglected and underutilized species make the point directly: these are frequently the crops that smallholders have quietly relied on for generations, specifically because they survive when better-known staples fail, and researchers now argue that NUS deserve far more research investment precisely because they remain neglected relative to their real potential for building sustainable food systems (Ali & Bhattacharjee, 2023).

Soil Health and Ecosystem Services: Pulses fix atmospheric nitrogen through their root nodules, quietly replenishing soil fertility that cereal monocultures steadily deplete. Including them in rotation reduces the synthetic fertiliser bill for the following crop and improves soil structure and microbial activity in the process. Millets, for their part, tend to have deep, fibrous root systems that improve water infiltration and reduce erosion on sloping or degraded land -exactly the terrain where many of them are traditionally grown. Diversified cropping built around these species also supports pollinators and beneficial insects far better than cereal monocultures, an ecosystem service that is easy to overlook until it is gone.

Economic Opportunities for Farmers: For smallholders on marginal land, these crops often represent the difference between a harvest and a failed season, since they can be grown profitably where rice or wheat simply will not perform. Growing consumer interest in "superfoods," gluten-free diets, and diabetic-friendly grains has also opened new, higher-value market segments, particularly for millets, which increasingly move beyond subsistence use into branded, packaged, and export-oriented products. That shift matters for farm incomes in a way that subsistence cultivation alone never could.

TABLE 1: Comparison of Major Food Crops and Forgotten Crops:

Crop Group	Examples	Major Nutritional Advantage	Climate Resilience	Major Uses
Millets	Finger millet, pearl millet, foxtail millet, sorghum	Very high calcium (finger millet) and iron; balanced amino acid profile; low glycaemic index	High -drought-tolerant, short duration, thrive on marginal and rainfed soils	Staple flours, porridge, malted foods, biofortified snacks, fodder
Pulses	Chickpea, pigeon pea, black gram, green gram, lentil	High protein (20–25%), dietary fibre, folate; nitrogen-fixing	Moderate-High - many varieties suited to rainfed, residual-moisture conditions	Dal, flour (besan), sprouts, processed protein products, green manure
Pseudo-cereals	Amaranth, buckwheat, quinoa	Complete protein with lysine; gluten-free; rich in antioxidants	High -tolerant of poor soils, cold, and short growing seasons	Flour, popped grain, health foods, festival and fasting foods
Minor tubers & legumes	Taro, yam, winged bean, moth bean	Resistant starch, micronutrients, region-specific protein sources	High -suited to hill, tribal, and flood-prone agro-ecologies	Subsistence staple, traditional medicine, local markets
Major cereals (for comparison)	Rice, wheat, maize	High energy density; lower micronutrient density relative to millets	Low-Moderate - generally input- and water-intensive	Staple food, processed foods, global commodity trade

Sources: Synthesised from Ali & Bhattacharjee (2023), Jacob et al. (2024), Anitha et al. (2024), and Mudau et al. (2022).

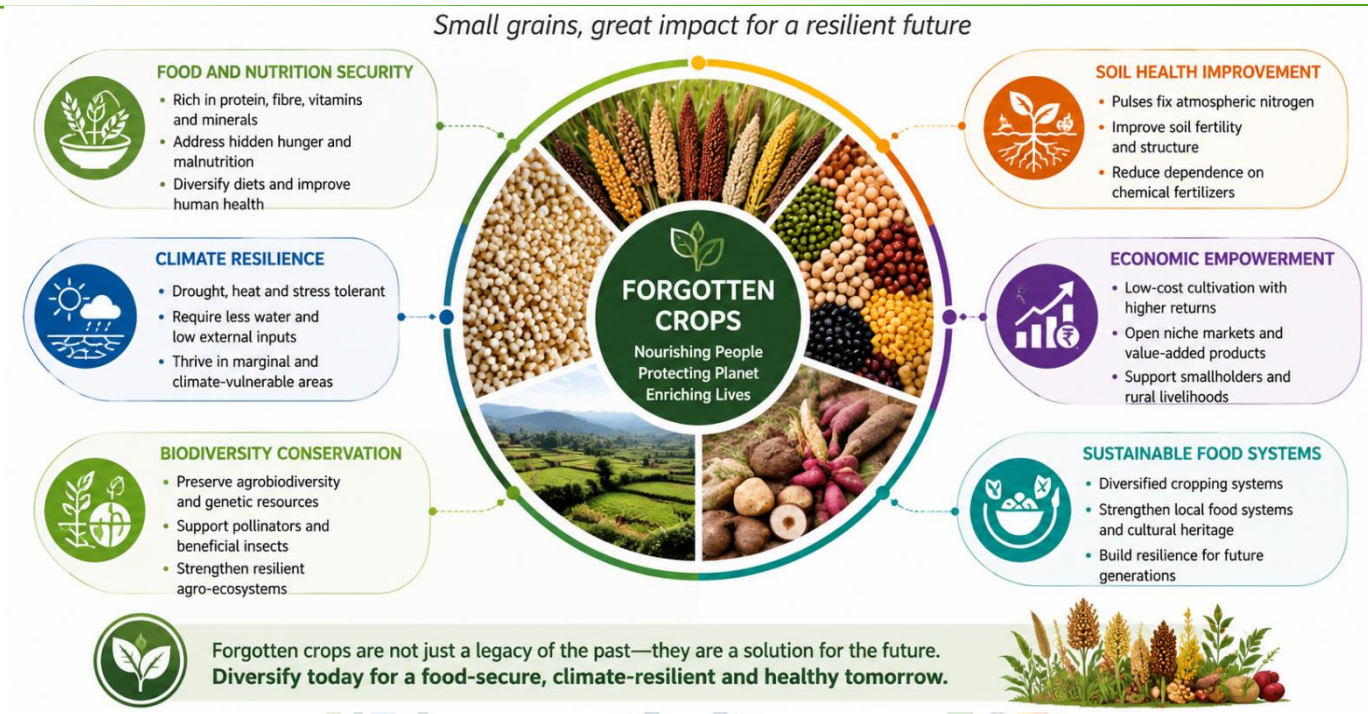


Figure 1. Role of Forgotten Crops in Sustainable Food Systems

Current Status in India and the World

Millets: India occupies a central place in the modern millet story, both as producer and as advocate. India is currently the largest millet producer in the world, contributing well over a third of global production, and as of mid-2025 the country's annual millet output stood above 18 million tonnes, a steady rise reflecting sustained efforts to promote cultivation across diverse agro-climatic regions (Press Information Bureau, 2025). That prominence was not accidental. India proposed the idea to the United Nations, and the UN General Assembly duly declared 2023 the International Year of Millets at its 75th session in 2021, following endorsement from more than seventy countries, with the goal of building global demand while raising awareness of millets' nutritional, environmental, and economic benefits (National Bank for Agriculture and Rural Development, 2023). The closing ceremony, fittingly, was held at FAO headquarters in Rome, signalling that the millet revival campaign had genuinely gone global rather than remaining an Indian domestic exercise.

Pulses: Pulses present a more complicated picture -genuine progress shadowed by persistent supply gaps. India remains, by a wide margin, the world's largest producer, consumer, and importer of pulses all at once, an unusual combination that reflects both the crop's central place in Indian diets and the country's continuing struggle to close the demand-supply gap. Chickpea production alone reached 13.75 million tonnes in 2021-22, contributing nearly half of total Indian pulse output, an achievement widely credited to sustained breeding effort within the national agricultural research system (ICAR-Indian Institute of Pulses Research, 2024). Even so, national pulse production has hovered in the 24-26 million tonne range against a domestic requirement well above that figure, and imports touched an all-time high of 7.3 million tonnes worth roughly USD 5.5 billion in 2024-25, a level surpassing even the previous record set in 2016-17. Recognising the strain, the Union Budget 2025-26 announced a dedicated six-year mission targeting self-reliance in pulses, with particular emphasis on pigeon pea, black gram, and lentil -the three pulses where import dependence remains highest (Murugananthi et al., 2024).

Other Neglected Indigenous Crops: Beyond the headline millets and pulses, a broader constellation of indigenous species is quietly attracting renewed research interest: amaranth and buckwheat as pseudo-cereals valued for their protein quality; taro, yam, and other minor tubers as climate-buffer staples in eastern and northeastern India; and a range of underused legumes and leafy vegetables that remain deeply embedded in regional diets even without formal market recognition. Global reviews of these species describe a common pattern: a lack of improved high-yielding varieties, limited modernised processing, poor input access, and constrained market linkages, even as research interest in this category has grown markedly since around 2015, tracking rising international attention to the Sustainable Development Goals (Mudau et al., 2022; Purba & Krishnaswamy, 2025).

Government Initiatives and Recent Developments: Policy momentum has followed the research interest. Millets were officially rebranded “Shree Anna” (roughly, “divine grain”) in 2023, a branding exercise meant to shed the older, somewhat dismissive “coarse cereal” label. The rebranding built on 2018's designation of millets as “Nutri-Cereals” and their inclusion in the POSHAN Mission Abhiyan, part of a longer effort by India's agriculture ministry to reposition millets -once relegated to just six percent of the national food-grain basket -back into mainstream diets. On the institutional side, ICAR's Indian Institute of Millets Research in Hyderabad was formally recognised as the Global Centre of Excellence

on Millets, and the government has backed the sector with a dedicated production-linked incentive scheme for millet-based food processing worth roughly Rs 800 crore, alongside a sub-mission on nutri-cereals under the National Food Security Mission (Chandra et al., 2024). On the pulses side, expanded procurement guarantees for tur, urad, and masoor, along with a new national mission on high-yielding seeds, aim to replicate for pulses something like the self-sufficiency story millets are now enjoying (Government of India, Directorate of Pulses Development, 2025).

TABLE 2: Nutritional Comparison of Selected Cereals, Millets, and Pulses:

Crop (per 100 g edible portion)	Protein (g)	Dietary Fibre (g)	Iron (mg)	Calcium (mg)	Zinc (mg)
Rice (milled, raw)	6.8	1.3	0.8	10	1.2
Wheat (whole, atta)	11.8	11.2	3.5	34	2.7
Finger millet (Ragi)	7.3	11.5	3.9	344	2.3
Pearl millet (Bajra)	11.6	11.3	8.0	42	3.1
Chickpea (desi, raw)	20.5	12.2	4.7	57	3.4
Pigeon pea (Tur, raw)	21.7	15.0	5.2	130	2.8

Sources: Longvah et al. (2017), Jacob et al. (2024), and Anitha et al. (2024). Values are typical figures reported per 100 g edible portion; actual composition varies with genotype, soil, and processing method.

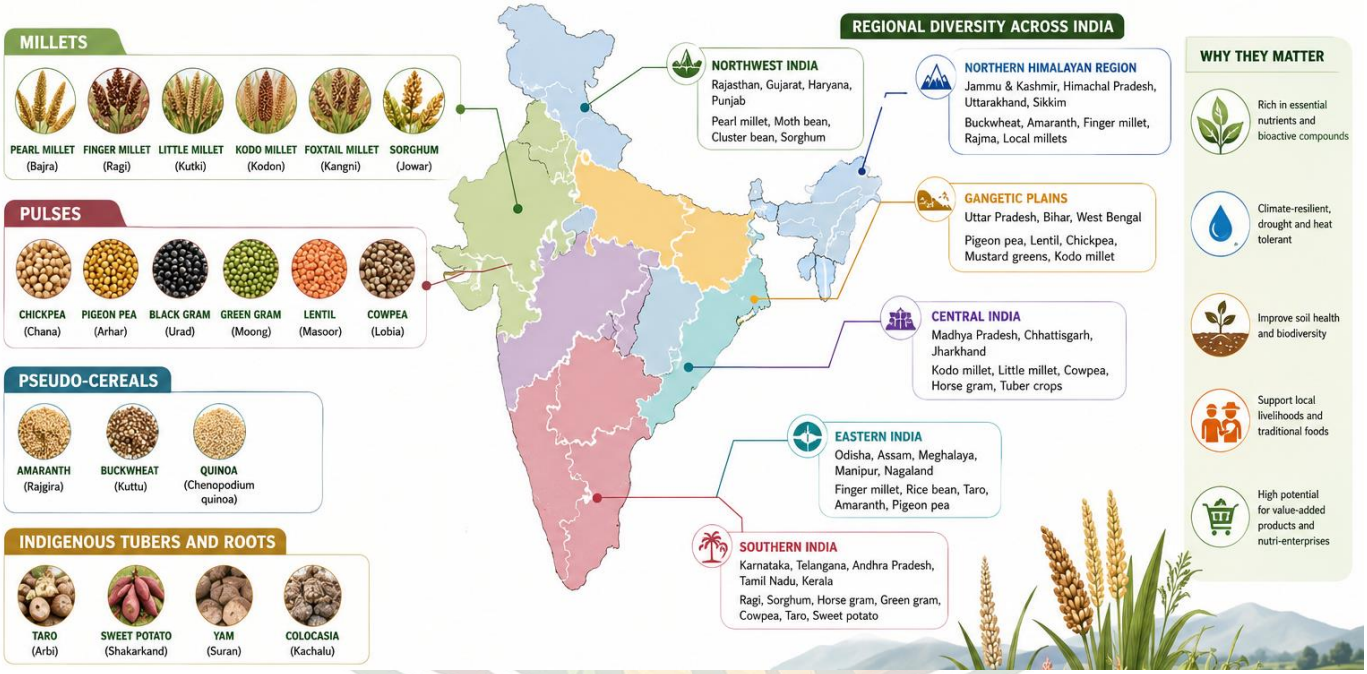


Figure 2. Major Underutilized Crops of India

Future Prospects

Plant Breeding: Conventional breeding still has plenty of headroom in these crops, precisely because they were bypassed by decades of intensive selection that transformed rice and wheat. Programmes at ICAR institutes and international centres such as ICRISAT continue to release higher-yielding, disease-resistant millet and pulse varieties, but the germplasm pool for most underutilized species remains only lightly explored compared with the major cereals -which is as much an opportunity as a constraint. Newer tools are also compressing breeding timelines dramatically; rapid, speed-breeding protocols recently developed for finger millet are shortening what once took years of field seasons into a fraction of the time (Kudapa et al., 2023), a development with obvious implications for how quickly improved varieties can reach farmers.

Genomics: Genomic tools have moved these once-neglected crops from a data desert into a genuinely well-characterised space in barely a decade. Publicly available genome sequences for sorghum and other millets have enabled genome-wide association studies covering drought tolerance, disease resistance, grain quality, and yield-related traits (Kasule et al., 2024), while comprehensive reviews note that genome-wide association studies in large pearl millet germplasm panels have already identified hundreds of significant marker-trait associations for protein and amino acid composition alone. That density of genomic information is precisely what plant breeders need to move from broad, slow phenotypic selection toward targeted, marker-assisted gains.

Biofortification: Because iron and zinc deficiencies remain so widespread globally, breeding for higher grain micronutrient density has become a priority research thread in its own right. Reviews of genetic and genomic approaches to millet biofortification highlight recent advances in high-throughput phenotyping for accurately measuring grain

micronutrient content, alongside efforts to map the genetic diversity in global millet germplasm collections that breeders can draw on to develop nutrient-dense, high-yielding varieties (Kudapa et al., 2023). Given that millets already carry a natural micronutrient advantage over rice and wheat, biofortification here is less about creating something new than about concentrating an existing strength.

Digital Agriculture: Precision agriculture tools -soil sensors, satellite-based advisories, mobile-based extension platforms -have so far been deployed mostly on high-value or high-acreage commercial crops. Extending them to millet- and pulse-growing regions, many of which are rainfed and resource-poor, could meaningfully close the yield gap between research-station potential and what farmers actually harvest, a gap that studies of Indian pulse cultivation put at 45-50 percent for crops like pigeon pea and green gram. Digital advisory systems tailored to these crops' shorter, more climate-sensitive growth windows would be a natural next step for extension services already working in millet- and pulse-growing tracts.

Conservation of Genetic Resources: None of the breeding or genomic progress described above is possible without well-curated germplasm to draw on, which makes genebank conservation the unglamorous but essential foundation of the entire effort. National and international collections -held by ICAR-NBPGR in India and by ICRISAT's genebank regionally - safeguard the landrace diversity that underpins future variety development. Expanding participatory conservation, where farming communities themselves maintain and exchange traditional varieties, complements formal genebanks by keeping genetic diversity alive and adapting under real farming conditions, not just in cold storage (Li & Siddique, 2020).

Conclusion

The case for forgotten crops rests on a fairly simple observation: the food system that concentrated itself around three or four staples over the past sixty years bought impressive short-term productivity at the cost of long-term resilience, nutritional breadth, and ecological balance. Millets and pulses, along with the wider family of underutilized indigenous crops, are not a rejection of that achievement so much as a necessary correction to it -a way of rebuilding the redundancy and diversity that any genuinely secure food system needs.

The roadmap ahead is reasonably clear, even if the execution will take sustained effort. It calls for continued breeding and genomic investment to close the productivity gap between these crops and mainstream cereals; deliberate policy support of the kind millets have recently received, extended more evenly to pulses and other neglected species; stronger processing and market infrastructure so that farmers are rewarded for growing what the climate actually favours; and genetic conservation robust enough to keep options open for breeders decades from now. For students, researchers, and extension professionals entering agricultural careers today, forgotten crops are not a niche specialisation -they may well be one of the more consequential frontiers in the discipline, precisely because so much of the foundational work still remains to be done.

Comparison with Established Climate Resilient PGPR

M. meiriae functions similarly to a number of well-known climate-resilient bacteria. *Acidovorax radicis* N35 inhibits insect pests and encourages barley growth; this impact is highest when ozone stress levels are high (Stenberg *et al.*, 2021). TA-equipped *Bacillus* and *Pseudomonas* strains exhibit improved resistance to heat and osmotic stress. *M. meiriae* is a member of the phylum Actinobacteria, which is a prolific generator of secondary metabolites used in agriculture (Van Der Meij *et al.*, 2017). But unlike the majority of PGPR that have been investigated, *M. meiriae* was developed in the ISS, which is the ultimate stress environment. As a result, it has a stress-adaptation toolkit that is distinct from that of soil-origin strains.

M. meiriae benefits from the well-established metabolic adaptability of the phylum Actinobacteria. According to Barka *et al.* (2016), actinobacteria are among the most abundant makers of bioactive secondary metabolites, such as plant growth promoters, antibiotics and antifungals. The ability of the *Microbacterium* genus to produce a variety of secondary metabolites, resist heavy metals and improve phytoremediation has already been shown by comparative genomics (Schneider *et al.*, 2020).

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Barhi Dates: Emerging Opportunities in Biotechnology Assisted Date Palm Cultivation

Article ID: 74218

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Introduction

Among the many cultivars of date palm, Barhi also spelled Barhee has a special place because of its golden yellow colour, crisp texture and fresh eating quality (Fig.1). Unlike the commonly available brown, soft or semi-dry dates consumed at the fully ripe Tamar stage, Barhi is highly preferred at the Khalal or Bisr stage, when the fruit is physiologically mature but still firm, crunchy and attractive. This unique quality makes Barhi a premium fresh date rather than only a dry fruit. The date palm, *Phoenix dactylifera* L., belongs to the family Arecaceae and is one of the oldest cultivated fruit crops of arid and semi-arid regions. It is closely linked with desert agriculture, oasis farming, food security and traditional food systems. The crop is naturally adapted to hot and dry environments, but successful commercial production requires scientific management of irrigation, nutrition, pollination, bunch load, harvesting and post-harvest handling (Chao and Krueger, 2007).

Barhi is commercially attractive because it offers consumers something different from conventional dates: a fresh, golden, mildly sweet and crunchy fruit. However, the same high moisture content that gives Barhi its freshness also makes it highly perishable. Fresh Khalal-stage dates are prone to rapid softening, browning, microbial spoilage and conversion to the Rutab stage if not properly handled (Alqahtani et al., 2025). Therefore, Barhi cultivation and marketing require a strong connection between production technology, post-harvest management and market linkage. In India, Barhi has relevance because date palm cultivation is gaining attention in hot arid and semi-arid regions, particularly Gujarat and Rajasthan. Varietal evaluation in Kachchh, Gujarat, reported Barhee as a promising cultivar for commercial cultivation under local conditions (Sharma et al., 2019). With scientific cultivation, quality planting material and proper cold-chain facilities, Barhi can become an important high-value fruit for dryland horticulture.



Fig.1 Fresh Barhi date fruits (*Phoenix dactylifera* L. cv. Barhi)

Botanical Identity and Crop Biology

Barhi is a cultivar of *Phoenix dactylifera* L. it is a perennial, monocotyledonous and dioecious palm. The term dioecious means that male and female flowers are borne on separate plants. Female palms produce fruits, but they require viable pollen from male palms for proper fruit set. Therefore, pollination is a critical process in date palm cultivation. The date palm is well adapted to arid environments and can tolerate high temperatures. However, commercial productivity depends on irrigation, soil fertility, nutrient management, pollination, bunch thinning and pest management. In Barhi, fruit quality is especially important because consumers expect uniform golden yellow, crisp fruits at the Khalal stage. Hence, true-to-type planting material is essential. Seed propagation is not suitable for commercial Barhi orchards because seedlings are genetically variable and their sex cannot be identified at the early stage. Some seedlings may become male and even female seedlings may not produce fruits identical to Barhi. Therefore, commercial multiplication depends mainly on offshoots or tissue-culture-raised plants.

Fruit Development and Ripening Stages

Date fruits pass through a series of developmental stages known as Kimri, Khalal/Bisr, Rutab and Tamar. These stages differ in colour, moisture, sugar content, texture and eating quality. For Barhi, the most important stage is the Khalal or Bisr stage, when the fruit is mature, firm, bright yellow and crunchy. At the Kimri stage, fruits are green, immature and generally not consumed. At the Khalal stage, the fruit reaches full size and develops its characteristic colour. This is the premium fresh eating stage of Barhi. As ripening continues, fruits enter the Rutab stage, where they soften and turn brownish. Finally, at the Tamar stage, fruits become fully ripe, darker, sweeter and dried. In recent research abscisic acid has been reported to play an important role in date fruit ripening, especially in sugar accumulation and colour change (Elbar et al., 2023). For Barhi, harvesting at the right stage is very important because delay in harvest may reduce crispness and market value.

Nutritional and Functional Importance

Dates are naturally energy rich fruits. Their major nutritional component is carbohydrate, mainly in the form of natural sugars such as glucose and fructose. Apart from sugars, dates contain dietary fibre, minerals and bioactive compounds (Al-Farsi and Lee, 2008; Tang et al. 2013). Barhi fruits at the Khalal stage are especially considered because they are consumed fresh. Studies on Barhi have shown that fruit flesh and seeds contain important nutritive and bioactive constituents, including phenolic compounds, flavonoids and carotenoids (Hinkaew et al., 2021). This indicates that Barhi is not only a pleasant fresh fruit but also a source of plant based bioactive compounds. Another important scientific point is the importance of date seeds. Date seeds are usually discarded, or other by-products may have potential for value addition, with subject to proper safety testing and regulatory approval. This supports the concept of waste-to-wealth and circular bioeconomy in date processing.

Pollination Biology and Metaxenia

Pollination is one of the most important processes in Barhi cultivation. Since date palm is dioecious, female palms require pollen from male palms for fruit development. In commercial orchards, natural wind pollination is usually not sufficient, so manual or assisted pollination is commonly practiced. A scientifically important phenomenon in date palm is metaxenia, where the pollen source influences fruit characters such as fruit set, fruit size, weight, maturity and quality. This means the male palm does not merely provide pollen for fertilization; it can also influence the economic quality of the fruit. Rezazadeh et al. (2013) reported that pollen source significantly influenced fruit production and quality traits in Barhi date palm under humid coastal regions of southern Iran. Mohammadi et al. (2017) also showed that pollen source and pollination time strongly affected fruit set and yield of tissue culture derived Barhi trees. Therefore, farmers cultivating Barhi should use good quality pollen from suitable male palms and perform pollination at the correct receptive stage.

Propagation and Tissue Culture

Commercial Barhi cultivation requires uniform and true-to-type planting material. Seed propagation is not recommended because seedlings are variable and their sex is unknown. Offshoot propagation is true-to-type and traditional, but the number of offshoots produced by a palm is limited. This makes large scale multiplication slow. Tissue culture has therefore become an important tool for rapid multiplication of elite date palm cultivars, including Barhi. *In vitro* propagation of date palm is mainly achieved through somatic embryogenesis and organogenesis. Somatic embryogenesis involves the formation of embryo-like structures from somatic cells, while organogenesis involves the development of shoots and roots from cultured tissues. Early research by Bhaskaran and Smith (1992) demonstrated somatic embryogenesis from shoot tip and immature inflorescence explants of *Phoenix dactylifera* cv. Barhee. More recently, Solangi et al. (2023) developed micropropagation protocols for date palm cv. Barhi using shoot tip explants and reported successful field performance of regenerated plants. These studies show that tissue culture can support commercial expansion of Barhi when protocols are properly standardized.

However, tissue culture must be used carefully because somaclonal variation may occur during *in vitro* culture. Somaclonal variation refers to genetic or epigenetic changes that may affect plant growth, flowering, yield or fruit quality. Therefore, clonal fidelity testing is essential before tissue cultured Barhi plants are supplied to farmers. Kumar et al. (2010) used RAPD and ISSR markers to assess genetic fidelity in micropropagated date palm, while Mirani et al. (2020) used transposable element-based markers to detect somaclonal variation. In India, tissue culture raised date palm plants have been promoted in arid regions. However, large scale use of tissue cultured Barhi should be supported by reliable laboratories, nursery certification, molecular fidelity testing, proper hardening and field evaluation.

Barhi Dates in India: Scope and Commercial Relevance

India has considerable scope for date palm cultivation in selected arid and semi-arid regions. At present, date palm is mainly associated with Gujarat and Rajasthan, while its cultivation is also emerging to a lesser extent in Maharashtra and Tamil Nadu (Singh et al., 2025). The Kachchh region of Gujarat is one of the most important date growing areas of the country. Sharma et al. (2019) evaluated date palm cultivars in Kachchh and reported Barhee as a promising cultivar for commercial cultivation. Rajasthan, particularly the western districts such as Barmer, Jaisalmer, Bikaner, Jodhpur and Jalore, also has strong potential because of its hot arid climate, sufficient heat units, availability of saline water in some areas and ongoing promotion of tissue culture raised date palm plants. ICAR has also reported successful expansion of date palm cultivation in Barmer, Rajasthan, where tissue cultured plants of varieties such as Barahi, Khuneizi, Khalas and Medjool were introduced for farmers.

In Bihar, the scope of Barhi date cultivation should be considered as an emerging and experimental opportunity, rather than as an immediately large scale commercial crop. Bihar has hot summers, with temperatures rising up to 44 - 45°C during March to mid-June, but the state also receives substantial monsoon rainfall and high humidity from mid-June to September. The Bihar Agriculture Department reports average annual rainfall of about 1100-1250 mm, with Zone III receiving comparatively lower rainfall than other zones. Therefore, in Bihar, Barhi may be explored initially through pilot-scale trials in comparatively drier, well drained and upland areas, especially in parts of South Bihar agro-climatic Zone III, where rainfall is relatively lower and drought prone conditions are more frequent than in the northern flood prone zones. Potential exploratory areas may include suitable upland pockets of districts such as Bhagalpur, Banka, Munger, Jamui, Gaya, Aurangabad, Nawada, Rohtas and Kaimur, provided that the sites have good drainage, assured irrigation, sufficient summer heat, protection from waterlogging and access to post-harvest facilities. Low lying, flood prone and high humidity areas should be avoided because rainfall and humidity during fruit maturity may cause fruit cracking, microbial spoilage and rapid quality deterioration. Thus, Barhi promotion in India should not be based only on its high market value. It should be planned as a complete value-chain crop involving quality planting material, scientific pollination, suitable agro-climatic selection, post-harvest handling, cold-chain infrastructure, processing facilities and assured market linkage.

Post-Harvest Management and Value Addition

The major limitation of Barhi is its short shelf life. At the Khalal stage, the fruit has high moisture and high water activity. These features maintain freshness and crispness but also increase the risk of rapid quality loss and microbial spoilage. Alhamdan (2024) reported that Barhi fruits at the Khalal stage require careful quality monitoring during storage. Visible and Near-Infrared (VIS-NIR) technology has also been studied as a non-destructive method for assessing Barhi fruit quality. Several post-harvest technologies have been studied for maintaining Barhi quality. Alhamdan et al. (2018) showed that rapid freezing methods such as cryogenic freezing and individual quick freezing can preserve fresh Barhi quality better than slow freezing. Ahmed et al. (2021) reported that natural elicitors such as chitosan, salicylic acid and calcium chloride can improve fruit quality, bioactive compounds and storage life of Barhi. Abdelkarim et al. (2022) studied optimized ultrasound treatment for fresh Khalal Barhi dates and reported its potential for extending shelf life. Barakat et al. (2025) evaluated freeze-dried Barhi dates and showed that freeze drying can help reduce losses and create shelf-stable products.

Food Safety and Handling

Since Barhi is consumed fresh at the Khalal stage, food safety is extremely important. Fruits should be harvested carefully and should not come into contact with soil or contaminated surfaces. Damaged, cracked, infected or overripe fruits should be removed during grading. Clean crates, food-grade packaging and cold-chain maintenance are essential. Fresh Barhi should be harvested at uniform maturity, handled gently and cooled quickly. Workers involved in harvesting and packaging should be trained in hygiene. For premium marketing, fruits should be uniform in colour, size and maturity. Proper branding and packaging can help introduce Barhi as a high value fresh fruit to Indian consumers.

Climate Change and Future Research Needs

Date palm is known for heat tolerance, but climate change can still affect Barhi cultivation. Unseasonal rainfall, high humidity during maturity, heat waves and changes in flowering behaviour may influence fruit set, fruit quality and post-harvest losses. Fresh date cultivars such as Barhi are especially sensitive because they are harvested at a high-moisture

stage. Rainfall during maturity can cause cracking, microbial spoilage and rapid quality deterioration. High humidity can increase fungal contamination. Extreme heat may affect pollen viability and fruit development. Therefore, climate smart Barhi cultivation should focus on suitable site selection, reliable pollen sources, bunch protection, irrigation management, cold chain support and processing facilities. Under Indian conditions, more research is required on Barhi performance across different agro-climatic zones, comparison of tissue cultured and offshoot-derived plants, suitable pollinizers, biochemical profiling, shelf-life studies, low cost cold chain models, processing technology and consumer preference. Such research will help convert Barhi from a specialty fruit into a scientifically managed premium horticultural crop.

Conclusion

Barhi date is one of the most attractive fresh date cultivars of *Phoenix dactylifera* L. Its golden yellow colour, crisp texture, mild sweetness and fresh eating quality distinguish it from conventional dry dates. Scientifically, Barhi is important because it connects fruit physiology, plant biotechnology, pollination biology, nutrition, post-harvest technology and value addition. The greatest strength of Barhi is its premium fresh fruit quality. The greatest challenge is its short shelf life. Therefore, Barhi should not be treated like an ordinary dry date. It requires true-to-type planting material, scientific pollination, proper orchard management, timely harvesting, cold-chain support and suitable value-addition strategies. In India, Barhi has strong potential in arid and semi-arid regions, especially where date palm cultivation is already emerging. However, large-scale promotion should be supported by reliable tissue culture plants, local field evaluation, farmer training, post harvest infrastructure and market linkage.

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Kalijiri (Bitter Cumin): A Promising Herbal Resource for Sustainable Livestock Health Management

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Introduction

The livestock sector plays a vital role in ensuring food security, nutritional security, and rural livelihoods. However, the increasing prevalence of antimicrobial resistance (AMR), concerns regarding chemical residues in animal-derived products, and the escalating cost of conventional veterinary medicines have prompted researchers and livestock producers to explore safer and sustainable alternatives for animal healthcare (WHO, 2023). In recent years, medicinal plants have gained considerable attention as natural feed additives and therapeutic agents because of their wide range of biological activities, low toxicity, environmental safety, and reduced risk of developing antimicrobial resistance (FAO, 2023). Among the numerous medicinal plants used in traditional veterinary medicine, Kalijiri (*Centratherum anthelminticum* (Willd.) Kuntze), commonly known as Bitter Cumin, has emerged as an important ethnoveterinary herb with remarkable medicinal potential. Belonging to the family Asteraceae, Kalijiri has been widely used in Ayurveda, Siddha, and indigenous healthcare systems for centuries to treat digestive disorders, intestinal parasitic infections, fever, skin ailments, and general debility in both humans and animals (Kirtikar and Basu, 2005). The seeds of Kalijiri are the principal medicinal part of the plant and are valued for their characteristic bitter taste and rich phytochemical composition.

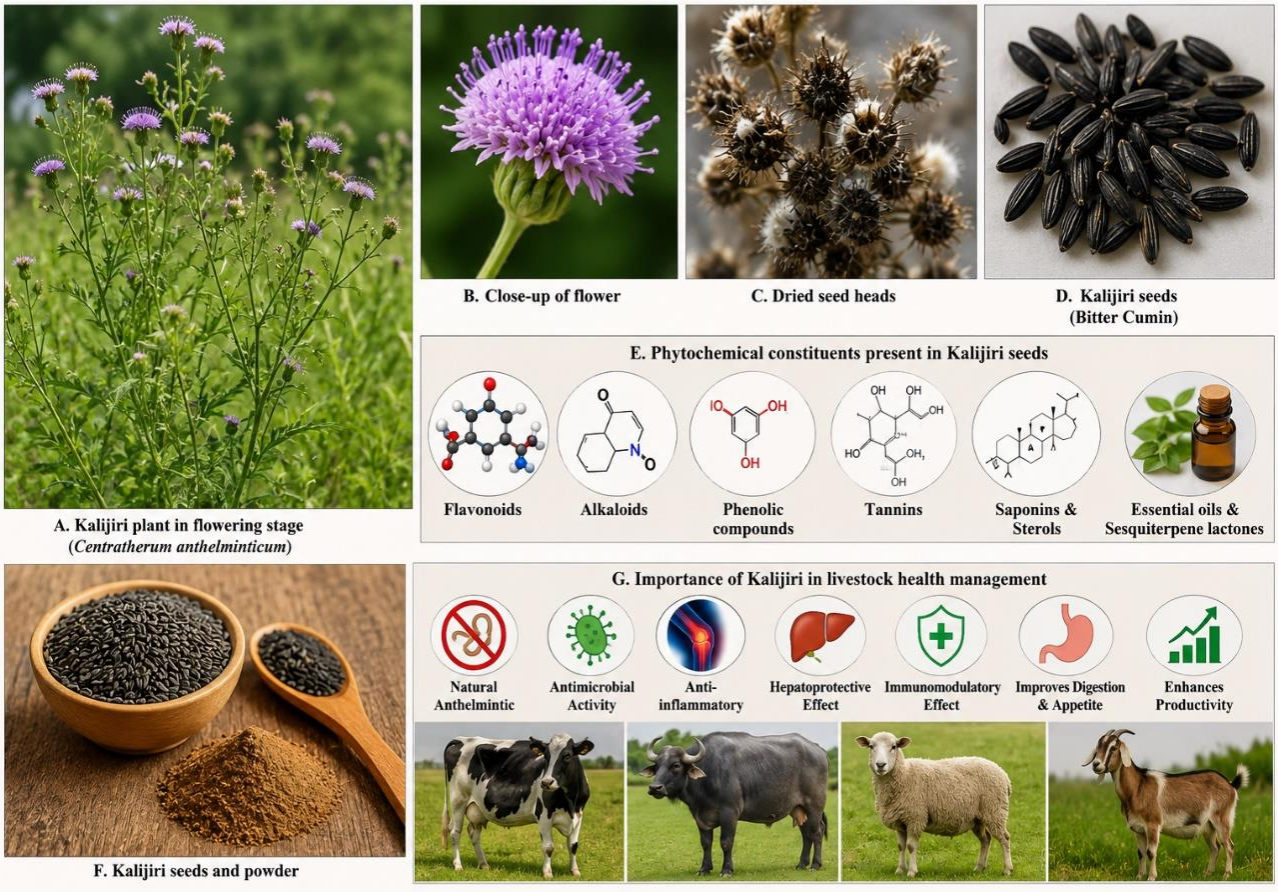


Figure. Kalijiri (*Centratherum anthelminticum*): Plant, seeds, phytoconstituents and its importance in livestock health management.

Scientific investigations have revealed that Kalijiri seeds are a rich source of flavonoids, alkaloids, phenolic compounds, tannins, saponins, essential oils, sterols, and sesquiterpene lactones, which collectively contribute to their antioxidant, antimicrobial, anti-inflammatory, immunomodulatory, hepatoprotective, and anthelmintic activities (Kokate et al., 2018). These bioactive compounds help improve digestive efficiency, stimulate appetite, enhance immune responses,

protect tissues against oxidative stress, and inhibit the growth of pathogenic microorganisms. In livestock production, Kalijiri has traditionally been incorporated into herbal formulations to improve rumen function, control gastrointestinal parasites, support liver health, promote wound healing, and enhance the overall productivity and well-being of cattle, buffaloes, sheep, and goats (Ghosh et al., 2020). Its natural therapeutic properties have attracted considerable scientific interest as a potential alternative to synthetic antibiotics and chemical dewormers, particularly in organic and low-input livestock production systems.

With the global emphasis on sustainable agriculture and reduced dependence on synthetic veterinary drugs, Kalijiri offers significant opportunities for developing eco-friendly livestock healthcare strategies. The integration of traditional ethnoveterinary knowledge with modern scientific research can facilitate the development of standardized herbal formulations that are safe, effective, and economically viable for farmers. Although several experimental studies have demonstrated the therapeutic potential of Kalijiri, further research is required to establish optimum dosage, long-term safety, and species-specific efficacy under field conditions. Considering its broad spectrum of pharmacological activities and long history of traditional use, Kalijiri represents a promising herbal resource for improving livestock health, enhancing production efficiency, and supporting sustainable animal husbandry practices.

Botanical Characteristics

Kalijiri (*Centratherum anthelminticum* (Willd.) Kuntze), commonly known as Bitter Cumin, is an annual medicinal herb belonging to the family Asteraceae. The plant is widely distributed throughout tropical and subtropical regions of India, Sri Lanka, and Southeast Asia, where it naturally thrives in dry wastelands, grasslands, and open scrub habitats. It prefers well-drained sandy to loamy soils and performs well under warm climatic conditions, making it well adapted to semi-arid agro-ecological regions. Morphologically, the plant attains a height of approximately 30–100 cm, with an erect, branched stem bearing simple, lanceolate leaves arranged alternately. It produces characteristic purple to violet terminal flower heads, followed by small, oblong, black seeds possessing a distinctly bitter taste. These seeds constitute the principal medicinal part of the plant and are extensively utilized in traditional medicine as well as ethnoveterinary practices. The seeds are a rich reservoir of bioactive phytochemicals, including flavonoids, alkaloids, phenolic compounds, tannins, saponins, sesquiterpene lactones, phytosterols, and volatile (essential) oils. These secondary metabolites exhibit a wide spectrum of pharmacological activities, such as antioxidant, antimicrobial, anti-inflammatory, anthelmintic, hepatoprotective, immunomodulatory, and gastroprotective effects. Owing to this diverse phytochemical profile, Kalijiri has attracted increasing scientific interest as a potential natural feed additive and herbal therapeutic agent for improving livestock health and productivity (Kirtikar and Basu, 2005; Kokate et al., 2018; Ghosh et al., 2020).

Importance of Kalijiri in Livestock Health Management

Kalijiri possesses several pharmacological properties that make it an important medicinal plant for sustainable livestock production. Its major benefits include:

Natural Anthelmintic Activity: Kalijiri seeds exhibit potent anthelmintic properties that help control gastrointestinal nematodes and other intestinal parasites, thereby improving nutrient utilization, body weight gain, and overall animal performance (Ghosh et al., 2020).

Enhances Digestive Function: The bitter phytoconstituents stimulate appetite, increase digestive enzyme secretion, improve rumen activity, and promote efficient digestion and nutrient absorption, particularly in ruminants (Kokate et al., 2018).

Powerful Antioxidant Properties: Rich in flavonoids and phenolic compounds, Kalijiri scavenges reactive oxygen species (ROS), reduces oxidative stress, and protects cellular components from oxidative damage caused by disease, heat stress, and metabolic disorders.

Immunomodulatory Effects: Bioactive compounds present in Kalijiri enhance innate and adaptive immune responses, improving the animal's natural resistance against bacterial, viral, and parasitic infections.

Broad-Spectrum Antimicrobial Activity: Extracts of Kalijiri possess antibacterial and antifungal activities against several pathogenic microorganisms, contributing to improved gut health and reduced incidence of infectious diseases.

Anti-inflammatory Action: The plant contains natural anti-inflammatory compounds that help reduce tissue inflammation associated with infections, injuries, and metabolic disturbances, thereby supporting faster recovery.

Hepatoprotective Potential: Kalijiri protects liver cells from oxidative damage, supports detoxification processes, and improves metabolic efficiency, which is particularly beneficial during periods of physiological stress.

Supports Skin and Wound Healing: Traditional herbal formulations containing Kalijiri are widely used for the management of wounds, dermatitis, eczema, and external parasitic infestations because of their antimicrobial and tissue-repair properties.

Improves Feed Efficiency and Productivity: By enhancing digestion, reducing parasite burden, and improving metabolic health, Kalijiri may contribute to better feed conversion efficiency, growth rate, milk production, and reproductive performance.

Eco-friendly Alternative to Synthetic Drugs: Kalijiri has considerable potential as a phytogenic feed additive that can reduce dependence on antibiotics and chemical anthelmintics, thereby minimizing antimicrobial resistance and drug residues in animal-derived food products (WHO, 2023).

Compatible with Organic Livestock Farming: Being a plant-based natural product, Kalijiri fits well within organic and sustainable livestock production systems, where the use of synthetic chemicals is minimized.

Cost-effective Herbal Resource: Kalijiri is locally available in many regions of India and can serve as an economical healthcare option for smallholder and resource-poor livestock farmers.

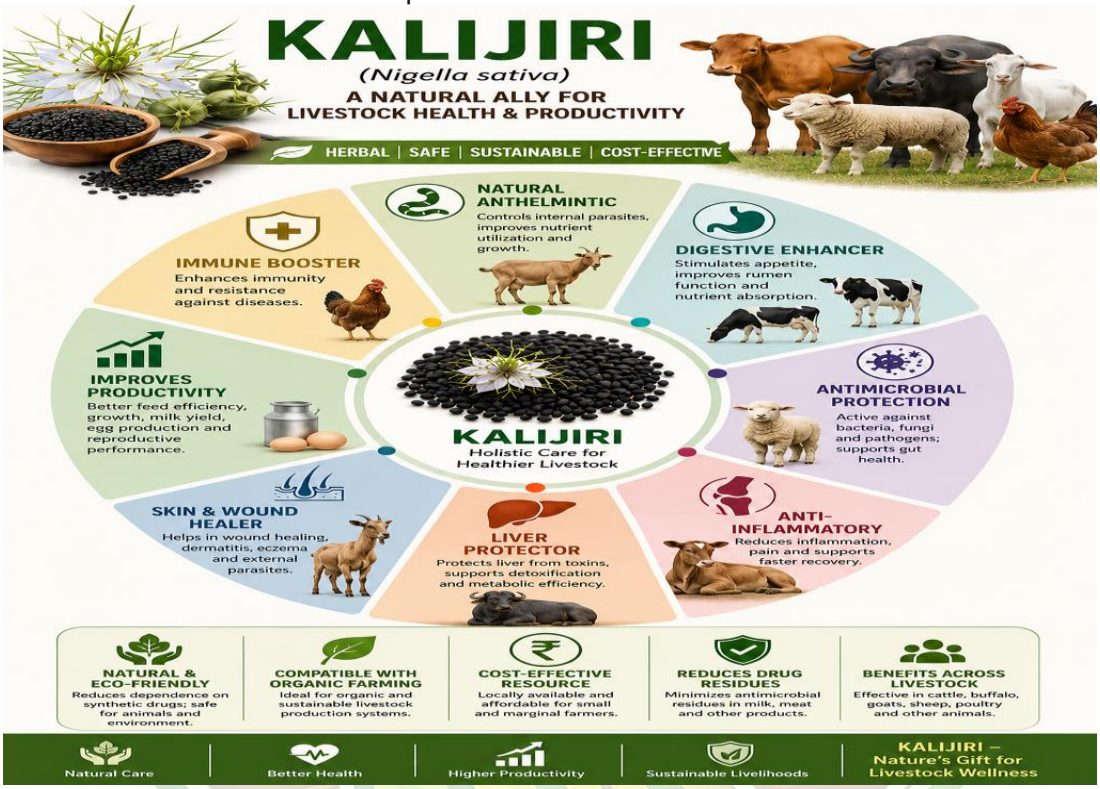


Figure 1. Role of Kalijiri in Livestock Health Management

Recommendations for Farmers

1. Use authenticated Kalijiri seeds from trusted sources.
2. Follow the recommended dosage for each animal species.
3. Administer herbal preparations under hygienic conditions.
4. Combine Kalijiri use with balanced feeding and proper farm management.
5. Continue routine vaccination and parasite control programs.
6. Consult a veterinarian before use in pregnant or seriously ill animals.
7. Observe animals for their response after supplementation.
8. Store seeds and herbal products in a cool, dry place to preserve quality.

Conclusion

Kalijiri is a promising medicinal plant with considerable potential to support sustainable livestock production. Its anthelmintic, antimicrobial, antioxidant, anti-inflammatory, and immunomodulatory properties make it a valuable natural supplement for improving animal health and productivity. In addition to enhancing disease resistance and digestive health, Kalijiri may reduce dependence on synthetic drugs and contribute to environmentally friendly livestock management. However, standardized dosage, quality assurance, and scientific validation through well-designed in vivo studies are essential for its wider adoption. Integrating traditional knowledge with modern research will facilitate the safe and effective use of Kalijiri as a component of integrated livestock health management.

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Indigenous Livestock Breeds: A Key to Sustainable and Climate-Resilient Livestock Farming

Article ID: 74220

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Introduction

Indigenous livestock breeds represent an invaluable component of global animal genetic resources and have supported human societies for centuries under diverse production environments (Figure 1). Unlike highly selected commercial breeds that depend on intensive management, these native populations have evolved through prolonged natural selection and traditional farmer-led breeding practices. Continuous exposure to harsh climatic conditions, seasonal feed scarcity, endemic diseases, and extensive grazing systems has enabled them to acquire unique adaptive characteristics that enhance survival and productivity under low-input farming conditions (Mwai et al., 2015; Ahmad et al., 2021). In many developing countries, particularly India, indigenous breeds of cattle, buffalo, sheep, goats, pigs, and poultry remain fundamental to the livelihoods of millions of smallholder farmers. Beyond their contribution to the production of milk, meat, eggs, fibre, manure, and draught power, these breeds provide an important source of income, nutritional security, and social stability for resource-poor households. Their ability to thrive with limited feed resources, minimal healthcare interventions, and fluctuating environmental conditions makes them especially valuable in regions where livestock production is constrained by climate and resource availability (FAO, 2015). The increasing impact of climate chang e has further highlighted the importance of locally adapted livestock populations. Rising temperatures, erratic rainfall, prolonged droughts, and the emergence of new disease challenges have reduced the suitability of many high-producing exotic breeds, which often require intensive feeding, cooling facilities, and continuous veterinary support. In contrast, indigenous breeds generally maintain better reproductive efficiency, health, and longevity under environmental stress because of their superior thermotolerance, efficient utilization of poor-quality feed, and natural resistance to many endemic diseases and parasites (Khan et al., 2022; Sejian et al., 2018). These adaptive traits position native breeds as key biological resources for building climate-resilient livestock production systems.

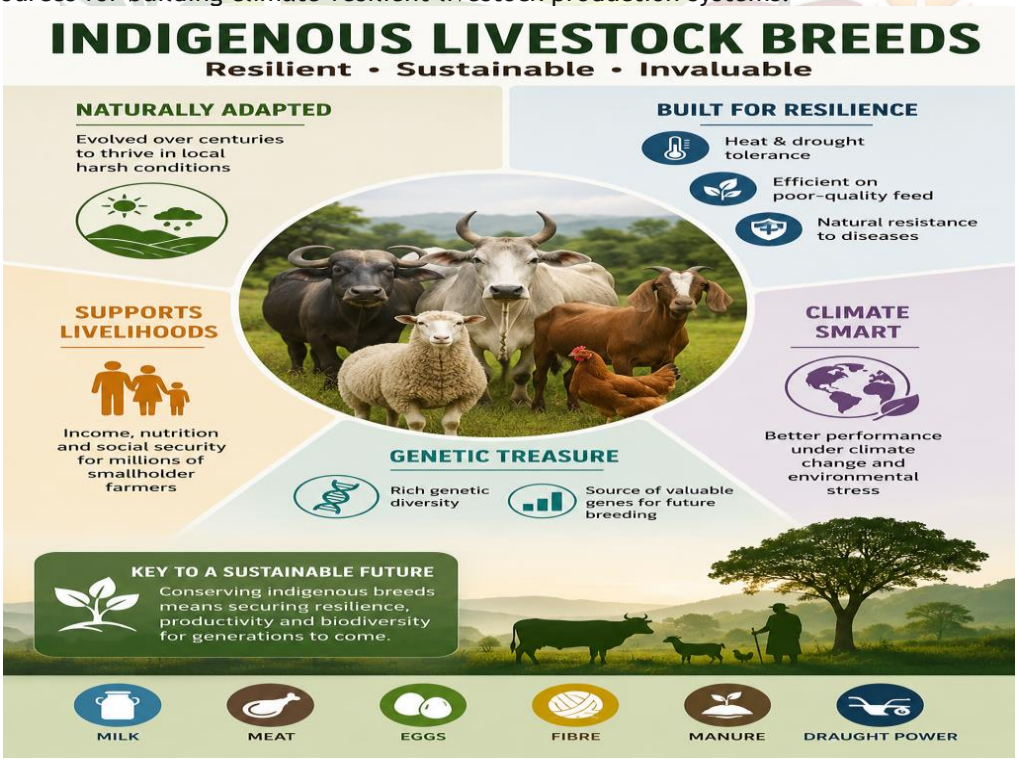


Figure 1. Key Characteristics and Importance of Indigenous Livestock Breeds for Sustainable Livestock Production

Recent developments in molecular genetics and genomic technologies have transformed our understanding of indigenous animal populations. Techniques such as whole-genome sequencing, single nucleotide polymorphism (SNP) genotyping, and population genomic analyses have revealed extensive genetic variation within native breeds and identified genomic

regions associated with heat tolerance, immune competence, metabolic efficiency, and environmental adaptation (Sharma et al., 2023; Muthusamy et al., 2025). These discoveries demonstrate that indigenous breeds possess valuable genetic resources that can be utilized in conservation programmes and future breeding strategies aimed at improving resilience without compromising productivity. Consequently, the perception of indigenous livestock has shifted considerably over the past decade. Once regarded primarily as low-producing genetic resources, they are now recognized as strategic assets for sustainable livestock development, biodiversity conservation, and climate adaptation. Their conservation, scientific characterization, and systematic genetic improvement are increasingly viewed as essential components of future livestock breeding programmes that seek to balance productivity with resilience, environmental sustainability, and rural livelihood security.

Why Indigenous Breeds Matter?

Genetic Diversity: Indigenous breeds possess rich genetic variability developed through long-term natural and farmer-led selection. This diversity provides a valuable genetic reservoir for improving adaptation, productivity, and resilience under changing production environments (Mwai et al., 2015).

Climate Adaptation: Native livestock are well adapted to heat stress, feed scarcity, water limitation, and endemic diseases. Their superior thermotolerance and efficient resource utilization enable sustained production under low-input and climate-vulnerable farming systems (Sejian et al., 2018).

Disease and Parasite Resistance: Many indigenous breeds exhibit enhanced resistance to infectious diseases and gastrointestinal parasites, reducing dependence on veterinary interventions and improving herd health. These traits contribute significantly to sustainable livestock production (Kim et al., 2019).

Genomic Potential: Recent advances in genomics have identified adaptive genes associated with heat tolerance, immune competence, metabolic efficiency, and environmental resilience in indigenous breeds. These discoveries provide opportunities for conservation and climate-smart breeding programmes (Sharma et al., 2023; Muthusamy et al., 2025).

Livelihood Security: Indigenous livestock support millions of smallholder farmers by providing milk, meat, fibre, manure, draught power, and regular household income. Their low maintenance requirements make them particularly suitable for resource-constrained production systems (Ahmad et al., 2021).

Conservation Priorities: Despite their adaptive advantages, many indigenous breeds are threatened by indiscriminate crossbreeding and declining population sizes. Scientific characterization, genetic conservation, and sustainable utilization are essential to preserve these valuable animal genetic resources for future generations (FAO, 2015).

Modern Science Meets Traditional Breeds

Genomic Innovations: Recent advances in molecular genetics have transformed the characterization and utilization of indigenous livestock breeds. Modern genomic approaches are revealing adaptive genetic variants that remained unexplored using conventional breeding methods.

Key applications include:

a. Whole-genome sequencing (WGS): Comprehensive identification of adaptive genetic variation across the genome.
b. SNP genotyping: Detection of polymorphisms associated with economically important traits.
c. Population genomics: Assessment of genetic diversity, population structure, and evolutionary relationships.
d. Selection signature analysis: Identification of genomic regions associated with adaptation to specific environments.

Applications for livestock improvement:

a. Marker-assisted selection (MAS)
b. Genomic selection for adaptive traits
c. Conservation genomics
d. Development of climate-resilient breeding programmes
e. Reconstruction of breed evolutionary history

Phenotypic Characterization: Phenotypic evaluation remains an indispensable component of breed characterization and genetic improvement. Morphological and production traits complement genomic information and support breed identification, registration, and conservation (Figure 2).

Important characterization parameters:

a. Body weight and growth performance
b. Morphometric measurements
c. Coat colour and physical characteristics
d. Reproductive performance
e. Adaptation to local production systems
f. Disease resistance and survivability

Opportunities and Challenges for Harnessing Indigenous Breeds

Opportunities: The growing emphasis on sustainable livestock production has renewed interest in indigenous animal genetic resources.

Potential opportunities include:

a. Climate-smart livestock production through utilization of naturally adapted breeds.
b. Genomic-assisted conservation to preserve valuable adaptive alleles.
c. Community-based breeding programmes involving farmers in genetic improvement.
d. Development of niche products such as indigenous milk, meat, fibre, and organic livestock products.
e. Reduced dependence on intensive management due to superior adaptability.
f. Integration with precision livestock farming using genomic and digital technologies.
g. Support for biodiversity conservation and sustainable agricultural development.
h. Challenges
i. Despite their importance, several factors threaten the sustainability of indigenous breeds.

Major constraints include:

a. Uncontrolled crossbreeding leading to genetic erosion.
b. Limited genomic and phenotypic characterization of many native populations.
c. Inadequate conservation policies and financial support.
d. Weak breeding infrastructure and performance recording systems.
e. Poor market recognition and value addition for indigenous livestock products.
f. Declining population size of several native breeds.
g. Limited awareness regarding the long-term value of indigenous genetic resources (FAO, 2015).

Future Perspectives

Sustainable utilization of indigenous livestock requires integration of advanced genomic technologies with traditional breeding knowledge.

Priority Areas for Future Research and Development

1. Comprehensive genomic, phenotypic, and biochemical characterization of underexplored breeds.
2. Identification of novel adaptive genes associated with climate resilience.
3. Expansion of community-based conservation and breeding programmes.
4. Application of genomic selection and precision breeding technologies.
5. Development of national genomic databases and breed information systems.
6. Promotion of geographical indication (GI) and value-added indigenous livestock products.
7. Formulation of policies to minimize genetic dilution and strengthen in situ conservation.
8. Capacity building and awareness programmes for farmers, breeders, and policymakers.
9. These integrated approaches will facilitate the conservation, genetic improvement, and sustainable utilization of indigenous livestock breeds while strengthening climate resilience and livestock productivity.



Figure 2. Integrated Framework for Phenotypic Characterization, Conservation, and Sustainable Utilization of Indigenous Livestock Breeds

Conclusion

Indigenous livestock breeds are invaluable animal genetic resources that play a crucial role in sustainable and climate-resilient livestock production. Their inherent adaptability, disease resistance, efficient utilization of low-quality feed resources, and resilience to environmental stress make them well suited to low-input production systems. Recent advances in genomics have further highlighted their unique genetic potential for climate-smart breeding and conservation. Therefore, integrating scientific innovations with traditional breeding practices and strengthening conservation efforts will be essential to safeguard these genetic resources and enhance the sustainability of future livestock production systems.

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Usutu Virus - A New Threat?

Article ID: 74221

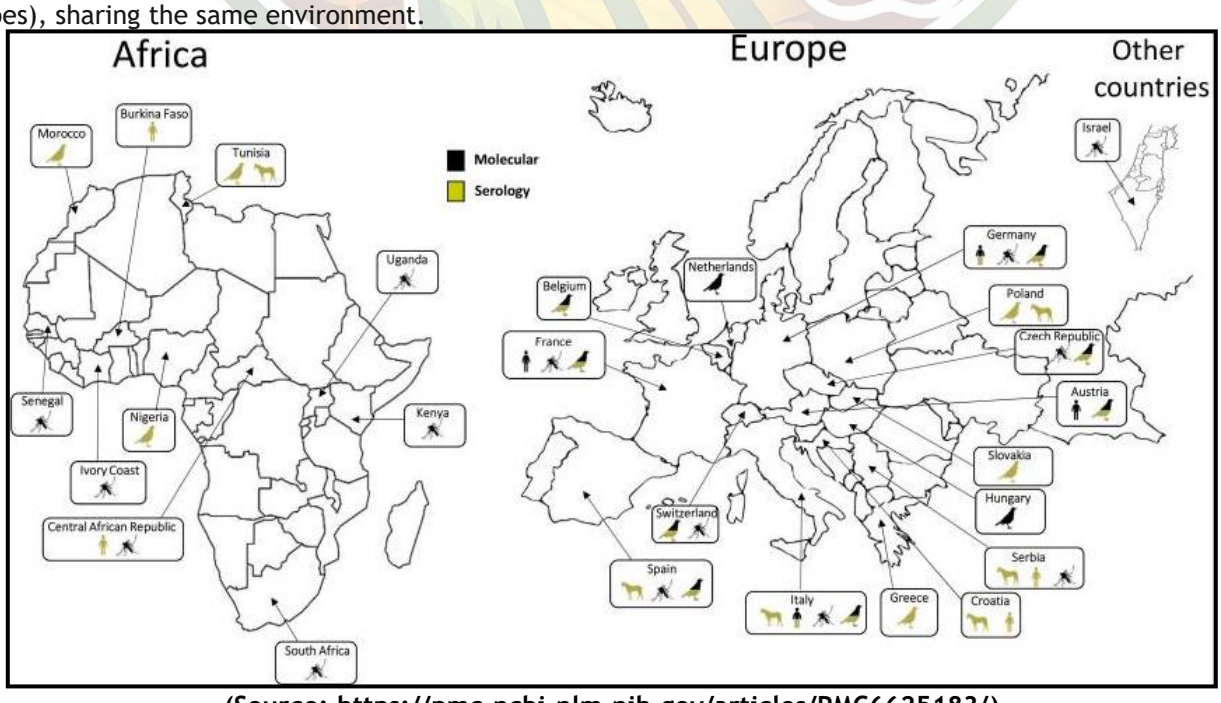
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Introduction



Usutu virus (USUV) is an emerging flavivirus of African origin transmitted mainly by mosquitoes of *Culex* species (spp.) to multiple bird species, which act as amplifying hosts. In Europe, this virus was first detected in 1996 in Italy, where it caused an outbreak among birds. Conceivably, the virus spread from Italy to the neighbouring countries and is now present in many western, southern and central European countries, where it has been detected in humans, vertebrate hosts and/or mosquitoes. Phylogenetic analyses grouped USUV strains into eight distinct lineages, i.e. Africa 1–3 and Europe 1–5, of which Europe 2 lineage is the most commonly detected in European countries. Usutu virus often co-circulates with West Nile virus (WNV) in a potentially overlapping geographic and ecological range (i.e. avian hosts and mosquitoes), sharing the same environment.



(Source: https://pmc.ncbi.nlm.nih.gov/articles/PMC6625183/)

Usutu virus causes mortality in several wild bird species, mainly in Eurasian blackbird (*Turdus merula*) and great grey owl (*Strix nebulosa*). Infected mosquitoes can transmit the virus to humans and other mammals, which represent dead-end hosts. Direct human-to-human transmission may potentially occur through infectious substances of human origin (SoHO).

Laboratory diagnosis of USUV infection in humans is based on demonstration of a specific antibody response against the virus, detection of viral RNA and virus isolation in cell culture from body fluids. The presence of USUV RNA has been demonstrated in blood, urine and cerebrospinal fluid (CSF) of patients with acute infection. Diagnosing USUV infection in humans is challenging because of the cross-reactivity of antibodies with other related flaviviruses, such as WNV. Thus, neutralisation assays against both viruses need to be run in parallel for confirmation.

Symptoms

Common symptoms include:

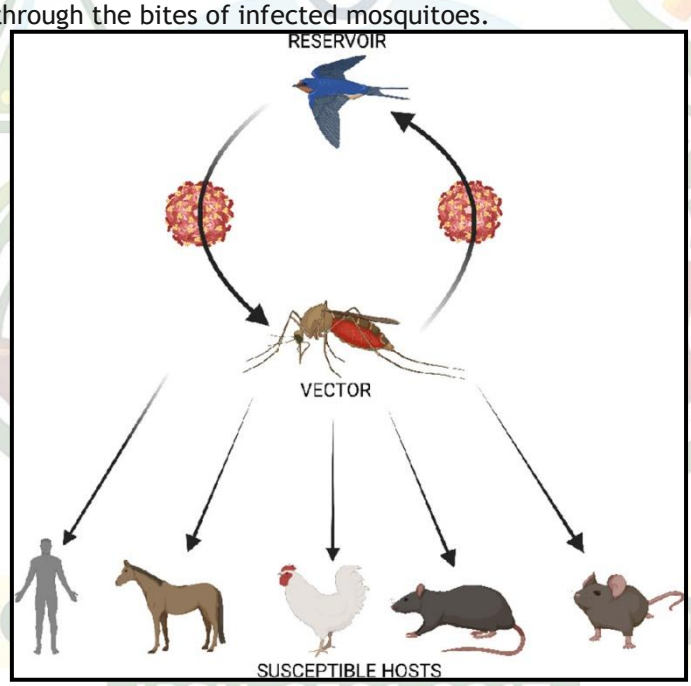
a. Rash
b. Fever
c. Yellowing of the eyes (jaundice)

Symptoms of severe illness can include:

a. High fever
b. Tremors
c. Meningitis (inflammation of the membranes that surround the brain and spinal cord)
d. Encephalitis (inflammation of the brain)

How it Spreads

Usutu virus spreads to people through the bites of infected mosquitoes.



(Source:https://www.frontiersin.org/journals/veterinaryscience/articles/10.3389/fvets.2023.1115501/full)

Infections in Animals

Fifteen EU countries (Austria, Belgium, Croatia, Czechia, France, Germany, Greece, Hungary, Italy, Luxembourg, the Netherlands, Poland, Slovakia, Slovenia and Spain) reported USUV circulation among vertebrate animals, mostly in birds by detection of the virus and/or anti-USUV antibodies and occasionally in equids using serology. Usutu virus was detected in 11 countries in resident or captive wild birds and in 10 countries in migratory birds. Specifically, the most affected wild migratory and/or resident bird species (sp.) were Passeriformes (mainly *Turdus* sp., particularly Eurasian blackbird, barn swallow, European goldfinch), Accipitriformes (common buzzard, hawk, goshawk), Strigiformes (owls) and Columbiformes (common wood pigeons, collar dove). Infection with USUV may cause outbreaks and lead to high mortality in captive zoo birds that thus can be useful sentinels for early detection of the virus circulation.

Usutu virus was detected in mosquitoes in Austria, Croatia, Czechia, France, Italy, the Netherlands and Slovakia. In these countries, the virus was mostly detected in *Culex pipiens* (Austria, Croatia, Czechia, France, Germany, Italy, Slovakia), but also in *Cx. modestus* (Czechia, Slovakia), *Aedes albopictus* (Italy), *Ae. japonicus* (Austria), *Anopheles hyrcanus* (Slovakia), *An. maculipennis* s.l. (Slovakia) and *Ochlerotatus caspius* (Italy).

Prevention

People who live in or travel to areas at risk should take steps to prevent mosquito bites. No vaccines or medicines are available to prevent Usutu virus.

Testing and Diagnosis

Talk to your healthcare provider if you have any symptoms or signs described above and recently traveled to an area where Usutu virus occurs. Your healthcare provider can order tests to look for Usutu virus or other infections that can cause similar symptoms.

Treatment

There are no specific medicines to treat Usutu. Rest, fluids and over-the-counter pain medicine might relieve some symptoms. Some patients might need to be hospitalized for intravenous fluids and supportive care for pain, fever, or other related problems.

Conclusion

In the past some years, at least half of the EU/EEA countries have found evidence of USUV infection in humans or animals. Most USUV infections in humans were asymptomatic and rarely associated with neuroinvasive disease and the impact of USUV on public health was much lower. However, this could be because of lack of testing for USUV. Further research will be required to better understand the epidemiology and the ecology of the virus. To date, USUV does not pose a major public health threat to the EU, but monitoring virus circulation and pathogenicity is important to early detect any change in the epidemiology of the disease.

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Vegetable Microgreens: Tiny Greens with Tremendous Potential

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Introduction

Microgreens are young, tender seedlings of vegetables and herbs harvested at the cotyledon stage or immediately after the emergence of the first true leaves, usually within 7-21 days after germination (Xiao *et al.*, 2012). Unlike sprouts, microgreens are harvested above the root and consumed fresh, while baby greens are harvested at a relatively later growth stage. Owing to their attractive appearance, delicate texture, intense flavour and vibrant colours, microgreens have gained immense popularity among consumers, chefs and nutritionists across the world (Naorem *et al.*, 2026).

In recent years, vegetable microgreens have emerged as an important functional food because they are rich sources of vitamins, minerals, carotenoids, phenolic compounds, flavonoids and other bioactive substances that contribute to human health (Teng *et al.*, 2023). Several studies have reported that many microgreens contain higher concentrations of these health-promoting compounds than their mature vegetable counterparts, making them a valuable component of a balanced diet. Their short production cycle, low water requirement, limited space requirement and suitability for indoor, terrace and protected cultivation further make them an ideal crop for urban agriculture and sustainable food production.

Nutritional Significance of Microgreens

Microgreens are regarded as nutrient-dense functional foods because they contain a high concentration of vitamins, minerals and bioactive compounds despite being harvested at a very early stage of growth. Studies have shown that many vegetable microgreens possess higher levels of essential nutrients than their mature counterparts, making them an excellent choice for a healthy diet. These young seedlings are rich in vitamins C, E and K, and minerals such as calcium, iron, magnesium, potassium and zinc. They also contain valuable phytochemicals, including phenolic compounds, flavonoids, carotenoids, glucosinolates and anthocyanins, which exhibit strong antioxidant properties and help protect the body against oxidative stress (Turner *et al.*, 2020).

The nutritional composition varies among species. Broccoli, kale and mustard microgreens are rich in glucosinolates, while red cabbage and amaranth contain higher levels of anthocyanins and phenolic compounds. Similarly, fenugreek and spinach microgreens are excellent sources of vitamins and essential minerals (Ghoora *et al.*, 2020; Tomas *et al.*, 2021). Regular consumption of microgreens can therefore contribute to better nutritional security and support a healthy lifestyle.

Production Technology of Microgreens

Microgreens can be grown easily in a short period using simple production techniques under both indoor and outdoor conditions. They are commonly cultivated in trays or shallow containers filled with soil, cocopeat, vermiculite, perlite or other soilless growing media. Healthy, untreated and high-quality seeds should be selected to ensure uniform germination and better yield (Kyriacou *et al.*, 2020).

Seeds are sown uniformly on a moist growing medium and lightly covered, if required. Adequate moisture, proper ventilation and sufficient light are essential for healthy seedling growth. Depending on the crop, microgreens are usually ready for harvest within 7–21 days after sowing, when the cotyledons are fully expanded and the first true leaves begin to emerge. Harvesting is done by cutting the seedlings just above the growing medium using clean scissors or a sharp knife. Modern production systems such as hydroponics, vertical farming and controlled-environment cultivation are also being adopted to produce high-quality microgreens throughout the year with efficient use of water and space.

Vegetable Crops Suitable for Microgreens

Microgreens can be produced from a wide range of vegetable, herb and legume crops, although not all plant species are suitable for consumption at the seedling stage. Members of the Brassicaceae family are the most commonly cultivated because of their rapid growth, high nutritional value and pleasant flavour (Kyriacou *et al.*, 2020). Popular vegetable crops grown as microgreens include broccoli, cabbage, kale, mustard, radish, cauliflower, kohlrabi, fenugreek, amaranth, spinach, lettuce, beetroot, carrot, green pea, sunflower and coriander. These crops differ in colour, flavour and nutritional composition, offering consumers a variety of healthy options. Among them, broccoli, kale and radish

microgreens are valued for their high glucosinolate content, while amaranth and beetroot are rich in natural pigments and antioxidants (Ghoora *et al.*, 2020).

However, certain crops such as tomato, potato, brinjal (eggplant), pepper and rhubarb are not recommended for microgreen production because their young seedlings may contain toxic compounds that are unsafe for consumption (Naorem *et al.*, 2026). Therefore, selecting suitable crop species is essential for producing safe, nutritious and high-quality microgreens.



Figure 1. Diverse vegetable microgreens cultivated in trays

Health Benefits of Microgreens

Regular consumption of microgreens offers numerous health benefits due to their high concentration of vitamins, minerals, antioxidants and other bioactive compounds. Their rich antioxidant content helps neutralize free radicals, thereby reducing oxidative stress and protecting the body from various chronic diseases. Several studies have reported that microgreens possess antioxidant, anti-inflammatory, antidiabetic, anticancer and cardioprotective properties. Bioactive compounds such as phenolics, flavonoids, carotenoids and glucosinolates contribute to strengthening the immune system, improving heart health, regulating blood glucose levels and reducing the risk of certain cancers (Mohamed *et al.*, 2022).

Incorporating a variety of vegetable microgreens into the daily diet is an easy and effective way to enhance nutritional intake and promote overall health. Their fresh flavour, attractive appearance and exceptional nutritional quality make them an ideal functional food for people of all age groups.

Commercial Potential of Microgreens

Microgreens are emerging as a high-value horticultural crop because of their short production cycle, minimal space requirement and growing consumer demand. They can be cultivated throughout the year in trays, rooftops, balconies, greenhouses and vertical farming systems, making them ideal for urban agriculture and small-scale entrepreneurship. The increasing awareness of healthy eating has created a strong market for microgreens in supermarkets, restaurants, hotels and health food outlets. Their attractive appearance, unique flavour and superior nutritional quality make them a premium product that often fetches higher prices than conventional leafy vegetables. Moreover, their low input requirement and quick harvest within 7-21 days enable farmers and entrepreneurs to obtain faster returns on investment.

With the expansion of protected cultivation, hydroponics and indoor farming, microgreens offer excellent opportunities for startups, women entrepreneurs and urban youth. Their commercial cultivation can contribute to nutritional security, income generation and sustainable horticultural production, making them one of the most promising specialty crops of the future.

Challenges and Future Prospects

Despite their immense nutritional and commercial potential, the large-scale adoption of microgreens faces several challenges. Their short shelf life, high perishability and the need for careful post-harvest handling limit long-distance transportation and storage. In addition, the use of high-quality seeds, controlled environmental conditions and maintenance of hygiene during production are essential to ensure safe and premium-quality microgreens.

With the growing demand for functional foods and sustainable agriculture, the future of microgreens appears highly promising. Advancements in hydroponics, vertical farming, LED lighting and controlled-environment agriculture are expected to enhance production efficiency and year-round cultivation. Increasing consumer awareness, coupled with opportunities for urban farming and value-added products, is likely to further expand the microgreen industry in the coming years. Therefore, microgreens have the potential to play an important role in improving nutritional security, promoting healthy lifestyles and creating profitable entrepreneurial opportunities in the horticultural sector.

Conclusion

Vegetable microgreens represent a new generation of nutrient-rich horticultural crops that combine exceptional nutritional value with ease of cultivation and commercial potential. Microgreens produced from vegetables such as broccoli, radish, cabbage, kale, mustard, fenugreek and amaranth are rich in vitamins, minerals, antioxidants and other bioactive compounds, making them valuable functional foods for promoting human health. Their short production cycle, low resource requirement and adaptability to urban and protected cultivation systems make them a promising option for sustainable vegetable production. With increasing consumer awareness and demand for healthy foods, vegetable microgreens are expected to play a significant role in improving nutritional security while creating new income opportunities for farmers, entrepreneurs and urban growers.

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Biochar in Forestry: A Sustainable Approach for Forest Ecosystem Management

Article ID: 74223

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Abstract
Biochar is a stable, carbon-rich material produced through the thermochemical conversion of biomass under oxygen-limited conditions. In recent years, biochar has gained considerable attention in forestry due to its potential to improve soil properties, enhance tree growth, restore degraded lands, and mitigate climate change through carbon sequestration (Lehmann and Joseph, 2015). Biochar offers a sustainable solution by improving soil fertility, increasing water retention, enhancing microbial activity, and reducing greenhouse gas emissions (Sohi *et al.*, 2010). Furthermore, biochar can be produced from forestry residues such as sawdust, bark, wood chips, and logging wastes, thereby promoting efficient biomass utilization and circular bioeconomy principles.

Introduction
Forests are essential for maintaining biodiversity, regulating hydrological cycles, conserving soil, and mitigating climate change through carbon storage. However, unsustainable land-use practices, deforestation, forest degradation, and climate variability have negatively affected forest productivity worldwide (Lal, 2004). Consequently, innovative approaches are required to improve forest ecosystem resilience and sustainability. Biochar has emerged as a promising soil amendment and carbon management tool. It is produced through pyrolysis, a process involving the thermal decomposition of organic biomass in the absence or limited presence of oxygen (Lehmann and Joseph, 2015). Unlike charcoal, which is mainly used as fuel, biochar is intended for environmental applications, particularly soil improvement and carbon sequestration. The application of biochar in forestry contributes to sustainable forest management by enhancing soil quality, improving nutrient cycling, increasing water retention, and supporting forest restoration efforts (Glaser *et al.*, 2002).

Production and Characteristics of Biochar
Biochar can be produced from a variety of forestry biomass feedstocks, including logging residues, sawdust, wood chips, bark, branches, and bamboo residues (McHenry, 2009).

Table 1. Major Biochar Production Technologies and their Characteristics:

Production Method	Temperature Range (°C)	Main Product	Biochar Yield	Characteristics
Slow Pyrolysis	300–700	Biochar	High (30–50%)	Most suitable for soil amendment
Fast Pyrolysis	400–700	Bio-oil	Moderate (10–20%)	Produces more liquid products
Gasification	600–900	Syngas	Low (5–15%)	Mainly used for energy generation
Hydrothermal Carbonization	180–250	Hydrochar	Moderate	Suitable for wet biomass

The physical and chemical properties of biochar depend on feedstock type and production conditions. Generally, biochar possesses high carbon content, a porous structure, large surface area, high water-holding capacity, and significant cation exchange capacity (Sohi *et al.*, 2010). These characteristics make biochar particularly beneficial for forest soil management.

Significance and Applications of Biochar in Forestry
1. Improvement of Soil Fertility: Forest soils often suffer from nutrient deficiencies and poor organic matter content, particularly in degraded landscapes. Biochar improves soil fertility by increasing nutrient retention and reducing nutrient leaching (Glaser et al., 2002). It enhances cation exchange capacity (CEC), allowing soils to retain essential nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium (Lehmann and Joseph, 2015). It provides favorable habitats for beneficial microorganisms involved in nutrient cycling, thereby improving soil biological activity (Sohi *et al.*, 2010).

2. Enhancement of Tree Growth: Biochar application has been reported to improve seedling establishment and growth in numerous forest species. Enhanced nutrient availability, improved soil aeration, and increased moisture retention contribute to better root development and overall plant performance (Jeffery *et al.*, 2011).

3. Soil Water Conservation: Water availability is one of the major factors limiting forest productivity. Due to its porous structure, biochar increases the soil's capacity to retain water and reduces evaporation losses (Sohi *et al.*, 2010). This property is particularly important in arid and semi-arid regions where drought stress affects tree survival and growth. Improved water retention enhances seedling establishment and resilience during dry periods.

4. Carbon Sequestration: Biochar is highly resistant to microbial decomposition and can remain stable in soils for hundreds to thousands of years (Lehmann, 2007). This characteristic enables long-term carbon storage and contributes to climate change mitigation. By converting biomass into biochar and incorporating it into soils, atmospheric carbon dioxide absorbed by trees is effectively locked away, reducing greenhouse gas concentrations (Woolf *et al.*, 2010).

5. Restoration of Degraded Forest Lands: Land degradation resulting from mining, erosion, deforestation, and intensive land use has become a serious concern. Biochar improves soil structure, increases organic carbon content, and supports vegetation establishment on degraded sites (Glaser *et al.*, 2002).

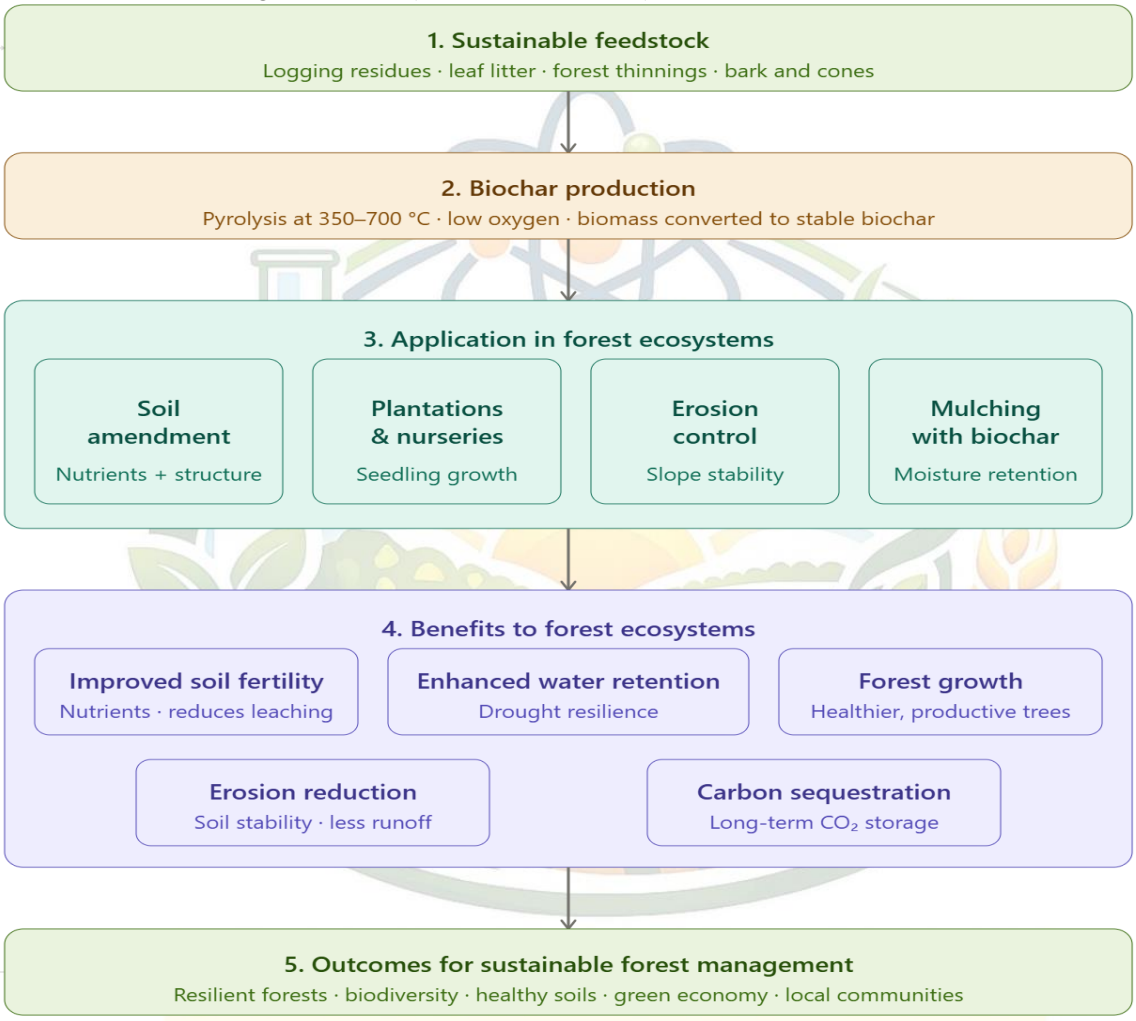


Fig 1: Applications of Biochar in Forestry

6. Application in Forest Nurseries: Biochar is increasingly used as a component of nursery growing media. It improves seed germination, root development, nutrient retention, and seedling quality (Dalei *et. al.*, 2026).

7. Afforestation and Reforestation: The incorporation of biochar during planting operations improves soil conditions and enhances establishment success in afforestation and reforestation projects (Agegnehu *et al.*, 2016).

8. Agroforestry Systems: Biochar contributes to improved soil fertility, increased crop productivity, and enhanced tree growth in agroforestry systems (Lehmann and Joseph, 2015).

Challenges in Biochar Adoption

Despite its numerous advantages, biochar application in forestry faces several constraints. High production costs, transportation expenses, lack of standardized production methods, variability in biochar quality, and limited long-term field studies hinder widespread adoption. Furthermore, inadequate awareness among forest managers and stakeholders limits its practical implementation.

Conclusion

Biochar represents a promising tool for sustainable forestry due to its multifunctional benefits. It improves soil fertility, enhances water retention, promotes tree growth, restores degraded lands, and sequesters carbon for long periods (Lehmann and Joseph, 2015). Additionally, biochar provides an environmentally sound method for utilizing forestry residues while contributing to climate change mitigation (Woolf *et al.*, 2010). Although challenges related to production costs and standardization remain, continued research and technological advancements are expected to expand the role of biochar in forestry. The integration of biochar into forest management practices can support healthier, more productive, and climate-resilient forest ecosystems.

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Rugositalea oryzae: A Novel Rice Rhizopheric Bacteria

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Abstract

Rice (*Oryza sativa* L.) rhizosphere hosts a diverse and dynamic microbial community that plays a key role in nutrient cycling and plant health. *Rugositalea oryzae* is a recently identified gram-negative, aerobic, motile bacterium isolated from rice rhizosphere soil in Korea. It belongs to the family Bradyrhizobiaceae and represents a novel genus within the order Rhizobiales. A distinctive feature of this bacterium is its ability to undergo reversible morphological changes, shifting from smooth rod shaped cells under nutrient-rich conditions to wrinkled (rugose) forms under nutrient limitation. This morphological plasticity enhances surface area, improves nutrient uptake efficiency, and supports survival in oligotrophic soil environments. The organism is strictly aerobic, oxidase and catalase positive, and shows limited carbon utilization, reflecting adaptation to nutrient poor conditions. Its genome and phenotypic characteristics confirm its taxonomic novelty and ecological specialization. Overall, *Rugositalea oryzae* provides important insights into bacterial adaptation mechanisms in rice rhizosphere ecosystems.

Introduction

Rice is one of the world's most important cereal crops, and its rhizosphere supports a diverse microbial community that contributes to nutrient cycling, plant growth promotion, and soil health. Rhizosphere bacteria continuously adapt to changing environmental conditions, particularly nutrient limitation, through physiological and morphological modifications that improve their survival (Philippot *et al.*, 2013). Nutrient stress is one of the major environmental factors influencing bacterial growth and adaptation. According to Chung *et al.*, (2025), some rhizosphere bacteria alter their cell morphology to increase nutrient uptake efficiency and survive under nutrient deficient conditions. Such morphological plasticity represents an important ecological adaptation in soil bacteria. Among the recently discovered rice rhizosphere bacteria, *Rugositalea oryzae* is unique because it undergoes a reversible transition from smooth rod-shaped cells to regularly wrinkled cells during nutrient limitation. Chung *et al.*, (2025) first isolated strain YC6860^T from the rice rhizosphere and identified it as a novel member of the order Rhizobiales. Later on, Chung *et al.*, (2025) confirmed that wrinkle formation increases the bacterial surface area to volume ratio, thereby improving nutrient acquisition under nutrient poor conditions. Therefore, *Rugositalea oryzae* has emerged as an important model for understanding bacterial adaptation in the rice rhizosphere.

Isolation and Discovery of *Rugositalea oryzae*

Rugositalea oryzae was first isolated as strain YC6860^T from the rhizosphere soil of rice plants cultivated in a long term no tillage paddy field in Jinju, Republic of Korea. The researchers used low nutrient culture media to recover oligotrophic bacteria adapted to nutrient limited environments. During the isolation process, one bacterial colony exhibited unusual morphological characteristics and was selected for further characterization because of its distinct appearance compared with other rice rhizosphere bacteria Chung *et al.*, (2025). Following isolation, the strain was identified using a comprehensive polyphasic taxonomic approach. Colony morphology, Gram staining, physiological and biochemical characteristics, fatty acid methyl ester (FAME) analysis, respiratory quinone composition, polar lipid profiling, 16S rRNA gene sequencing, phylogenetic analysis, whole-genome sequencing, Average Nucleotide Identity (ANI), and digital DNA-DNA hybridization (dDDH) were performed. The combined phenotypic and genomic evidence demonstrated that strain YC6860^T was genetically distinct from previously described members of the order Rhizobiales, supporting its recognition as a novel genus and species (Chung *et al.*, 2025). During the characterization of strain YC6860^T, researchers observed that the bacterium altered its cell morphology in response to nutrient availability. Under nutrient rich conditions, the cells remained smooth and rod shaped, whereas nutrient deficient conditions induced the development of a characteristic wrinkled cell surface. This unique adaptive feature distinguished the isolate from related bacteria and led to the establishment of the new genus Rugositalea, while the species name oryzae reflects its origin from the rice rhizosphere. The discovery of *Rugositalea oryzae* has expanded our understanding of bacterial diversity and adaptive mechanisms in the rice rhizosphere (Chung *et al.*, 2025).

Taxonomy

Domain: Bacteria

Phylum: Pseudomonadota

Class: Alphaproteobacteria

Order: Rhizobiales

Family: Bradyrhizobiaceae

Genus: *Rugositalea*

Species: *Rugositalea oryzae*

Phylogenetic analysis confirmed that strain YC6860^T is distinct from all known related genera, justifying its classification as a new genus (Chung *et al.*, 2025).

Morphological Characteristics

Cells of *Rugositalea oryzae* are Gram negative, rod shaped, and motile with a polar flagellum. Their size typically ranges from 0.4-0.6 × 1.1-1.9 µm. Under normal conditions, colonies appear smooth and circular. However, under nutrient stress, the bacterium forms wrinkled (rugose) colonies and may show pleomorphic transitions from rod to coccoid forms. According to Chung *et al.*, (2025), this morphological switching is a rare adaptive response that enhances survival under environmental stress as shown in fig 1.

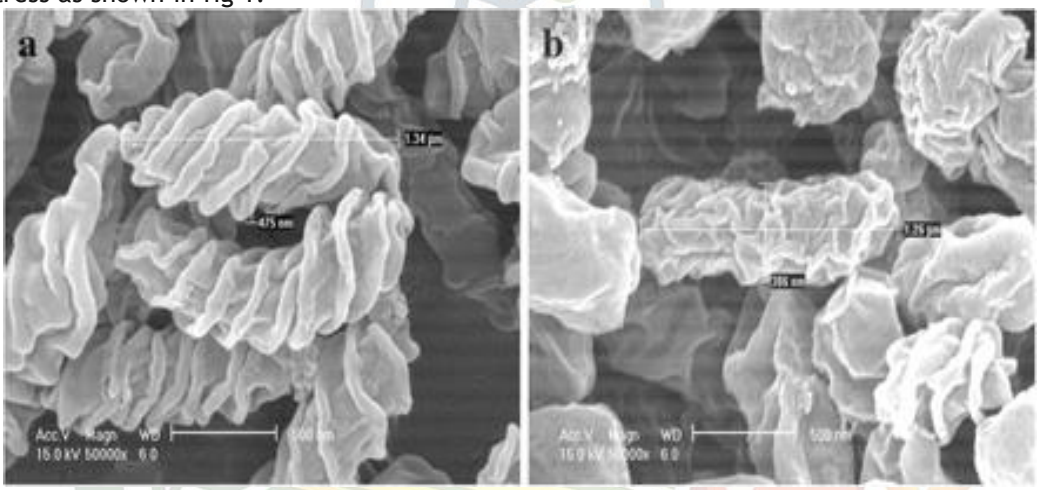


Fig.1. The growth of *Rugositalea oryzae* YC6860^T cells grown on (a) 0.1 LB and (b)0.5 LB broth at 28°C in a rotary shaker (50 rpm) for 5 days
(Source: Chung *et al.*, 2025)

Physiological and Biochemical Properties

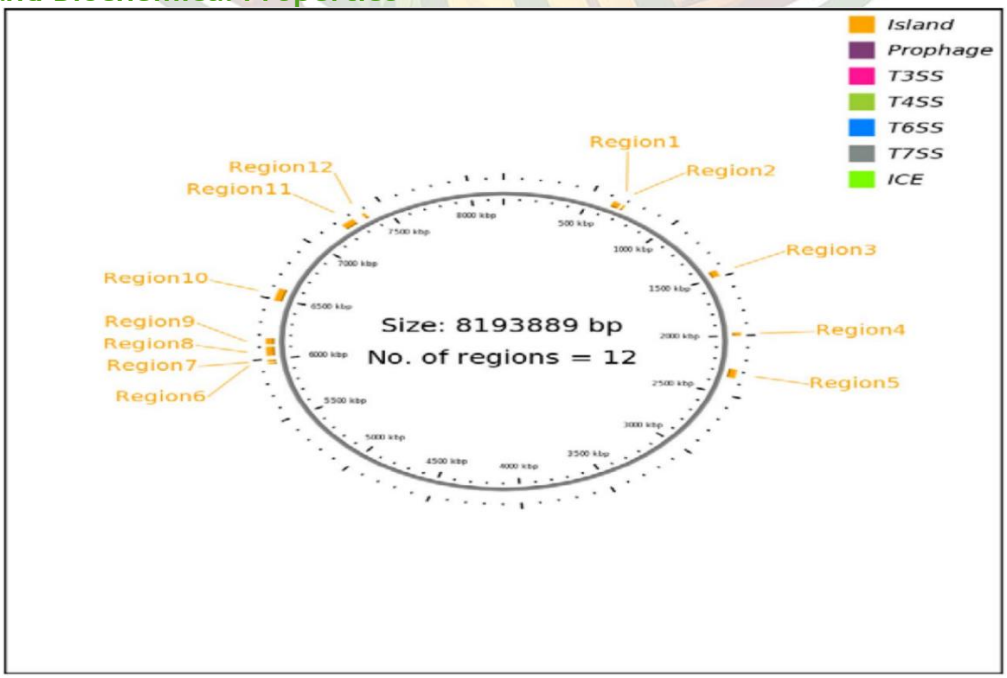


Fig.2.Map of the island like regions in the *Rugositalea oryzae* YC6860T 701 genome

The bacterium is strictly aerobic and shows positive reactions for oxidase and catalase tests. It grows optimally at 28°C, with a temperature range of 16-30°C and pH tolerance between 6 and 10. It does not require NaCl but is inhibited at higher salt concentrations above 0.5%. In biochemical tests, it utilizes limited carbon sources such as glucose and sucrose, while showing weak or no utilization of arabinose, mannitol, and fructose. These metabolic traits reflect its adaptation to nutrient poor soil conditions and slow-growing nature (Chung *et al.*, 2025).

Ecological Role in Rice Rhizosphere

The rice rhizosphere provides a nutrient rich but highly competitive microbial environment influenced by root exudates and soil conditions. Rugositalea oryzae survives in this environment by adapting to fluctuating nutrient availability. Chung *et al.* (2025) reported that the bacterium contributes to microbial diversity and shows strong stress adaptability. Its wrinkled colony formation is believed to enhance biofilm formation, surface attachment, and resistance to environmental stress.

Scientific Significance

The discovery of *Rugositalea oryzae* is important because it represents a completely new genus within Bradyrhizobiaceae. Its identification expands the understanding of microbial diversity in rice agricultural soils. Additionally, its unusual ability to switch morphology under stress conditions makes it a useful model for studying bacterial adaptation mechanisms. Studies by Chung *et al.*, (2025) highlight its importance in understanding survival strategies in oligotrophic environments.

Conclusion

Rugositalea oryzae represents a significant addition to the microbial diversity of rice rhizosphere ecosystems, as it establishes a new genus within Bradyrhizobiaceae. Its most notable biological feature is stress induced morphological switching, which plays a key role in adaptation to nutrient-limited environments. This ability not only enhances survival but also provides a model system for studying bacterial responses to environmental stress. The bacterium's physiological and biochemical traits further support its specialization for oligotrophic conditions typical of paddy soils. Future research on its genome functions, regulatory mechanisms of morphology, and plant microbe interactions may reveal its potential role in improving soil health and agricultural productivity. Overall, *Rugositalea oryzae* improves our understanding of microbial adaptation strategies in the rice rhizosphere and highlights the ecological complexity of soil bacterial communities.

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Impact of Fastidious Bacteria on Global Trade

Article ID: 74225

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Abstract
Fastidious bacteria are among the most destructive plant pathogens affecting global agriculture and international trade. Their fastidious growth requirements, broad host range and efficient transmission through insect vectors and infected planting materials make their detection and management particularly challenging. Increased globalization and the movement of plants and plant products have accelerated the spread of important pathogens such as *Xylella fastidiosa* and *Candidatus Liberibacter asiaticus* into previously disease free regions, resulting in significant crop losses, trade restrictions and economic impacts. This review summarizes the characteristics of major fastidious bacterial pathogens, their transmission pathways, the role of global trade in disease dissemination and the resulting agricultural and economic consequences. It also highlights key case studies, current biosecurity measures and future strategies for improving surveillance, early detection and sustainable disease management to reduce the global impact of these emerging plant pathogens.

Keywords: Fastidious bacteria, *Xylella fastidiosa*, *Candidatus Liberibacter* spp., Plant biosecurity, Plant quarantine, Disease dissemination.

Introduction
The rapid expansion of global trade, international travel and the movement of plant materials have significantly accelerated the transboundary spread of plant pathogens (Chapman *et al.*, 2017). The exchange of live plants and propagative materials has facilitated the introduction of several fastidious bacterial pathogens into new regions, threatening global agriculture, biodiversity and food security. Their establishment is further promoted by favourable climatic conditions, susceptible host plants and insect vectors (Frem *et al.*, 2020).

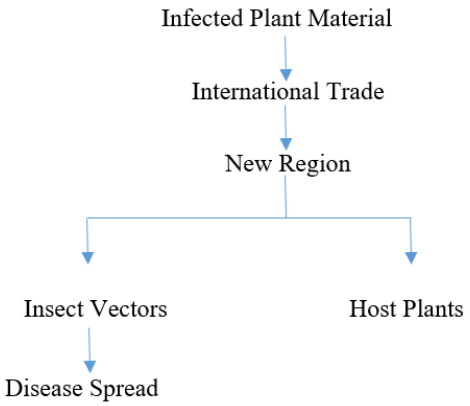
Among these pathogens, *Xylella fastidiosa* is one of the most important examples of trade mediated disease dissemination. This Gram negative, slow growing bacterium colonizes the xylem of host plants and is transmitted by xylem feeding insects. It disrupts water transport, causing leaf scorch, wilting, branch dieback, stunted growth and eventually plant death. Because of its broad host range, *X. fastidiosa* has become a major phytosanitary threat worldwide. The importance of *X. fastidiosa* became evident after its introduction into Europe, where it caused severe economic losses in olive production following its first detection in southern Italy in 2013 (EFSA, 2015 and Frem *et al.*, 2020). Likewise, Huanglongbing (HLB), caused by *Candidatus Liberibacter asiaticus*, has spread to more than 40 countries through infected planting materials and citrus psyllid vectors, posing a major threat to the global citrus industry. Therefore, understanding the impact of fastidious bacterial pathogens on global trade is essential for strengthening surveillance, quarantine, and sustainable disease management strategies (Da Graça and Korsten, 2004). To provide a conceptual overview, the major fastidious bacterial pathogens and their principal transmission pathways are illustrated in Fig. 1 and 2 before their impacts are discussed in detail.

Major Fastidious Bacterial Pathogens
Table 1. Major fastidious bacterial pathogens affecting agriculture and their principal transmission pathways (Chapman *et al.*, 2017; Da Graça and Korsten, 2004 and Frem *et al.*, 2020):

Pathogen	Major Crop	Disease	Transmission
Xylella fastidiosa	Olive, Grapevine, Citrus	OQDS, Pierce's disease	Xylem feeding insects + infected planting material
Candidatus Liberibacter asiaticus	Citrus	Huanglongbing (HLB)	Asian citrus psyllid + Infected Nursery Plants
Spiroplasma citri	Citrus	Citrus stubborn	Leafhopper
Phytoplasma spp.	Multiple Crops	Little leaf, Witches' broom	Leafhopper/Planthopper

Transmission Pathways of Fastidious Bacterial Pathogens
Fastidious bacterial pathogens are primarily transmitted through infected planting materials and insect vectors (Purcell and Hopkins, 1996). International trade facilitates the movement of infected nursery stock and propagative materials to new geographical regions, where pathogens become established in suitable host plants. Local spread then occurs through

sap-feeding insect vectors such as leafhoppers, spittlebugs and psyllids. This interaction between infected plant material, global trade and insect vectors plays a major role in the worldwide dissemination of fastidious bacterial diseases (EFSA, 2015).



Characteristics of Fastidious Bacteria

Fastidious bacteria are a specialized group of plant pathogenic microorganisms that require specific nutritional and environmental conditions for growth, making their isolation and cultivation under laboratory conditions particularly challenging. Most agriculturally important fastidious bacteria inhabit the vascular tissues of plants, primarily the xylem or phloem, where they establish systemic infections and interfere with the transport of water, minerals and photosynthates (Purcell and Hopkins, 1996). These pathogens are commonly transmitted by sap feeding insect vectors, including leafhoppers, spittlebugs and psyllids, as well as through infected propagative plant materials such as nursery stock and grafting material (Chapman *et al.*, 2017). Their restricted localization within vascular tissues enables efficient colonization while often allowing infected plants to remain symptomless during the early stages of infection, thereby facilitating undetected dissemination. Once established, fastidious bacteria induce progressive physiological disorders that reduce plant vigor, impair productivity and may ultimately result in plant death (Da Graça and Korsten, 2004). Because of their broad host range, dependence on insect vectors and difficulty of early detection, fastidious bacterial pathogens represent a major challenge for disease diagnosis, surveillance, quarantine and international biosecurity, particularly in an era of expanding global trade and movement of plant materials.

Impact of Global Trade on the Spread of Fastidious Bacteria

The rapid expansion of global trade has substantially increased the transboundary movement of fastidious bacterial plant pathogens by facilitating the international exchange of live plants, nursery stock, grafting materials, ornamental plants and other propagative commodities. Because many infected plants remain asymptomatic during the early stages of infection, they may pass routine inspections and serve as hidden sources of pathogen introduction into previously disease-free regions (Frem *et al.*, 2020). Following introduction, local establishment and dissemination are further promoted by indigenous insect vectors, favorable environmental conditions and suitable agricultural landscapes. The globalization of agricultural markets has therefore accelerated the emergence of several economically important fastidious bacterial diseases beyond their native geographical ranges. The spread of *Xylella fastidiosa* from the Americas to Europe and the worldwide expansion of Huanglongbing (HLB) through infected citrus propagative materials represent well-documented examples of trade-associated pathogen dissemination. These epidemics have resulted in substantial agricultural losses, disruption of international plant trade, increased quarantine restrictions and significant economic burdens on the horticultural sector. Consequently, strengthening phytosanitary regulations, implementing rigorous quarantine systems, promoting the use of certified disease free planting material and enhancing international surveillance have become essential strategies for minimizing the global spread of fastidious bacterial pathogens in an increasingly interconnected agricultural system (EFSA, 2015).

Xylella fastidious – A Global Example of Trade Driven Dissemination of Fastidious Bacteria

Xylella fastidiosa is one of the most important examples demonstrating how international trade has accelerated the global dissemination of fastidious bacterial plant pathogens (Rapicavoli *et al.*, 2018). Native to the Americas, the bacterium remained geographically restricted until its introduction into Europe, where it was first detected in olive orchards of Apulia, Italy, in 2013 (Trkulja *et al.*, 2022) The movement of infected but symptomless planting material through international trade is considered the principal pathway for its long-distance spread, while xylem feeding insect vectors facilitate local transmission after establishment (Sicard *et al.*, 2018). Since its introduction, *X. fastidiosa* has expanded into several European countries, posing a serious phytosanitary threat because of its exceptionally broad host range and its ability to infect numerous economically important crops. The epidemic has been particularly destructive in olive production, where Olive Quick Decline Syndrome has resulted in extensive tree mortality, substantial economic

losses and long term ecological and cultural impacts (Trkulja *et al*., 2022). The rapid emergence of *X. fastidiosa* in Europe highlights the close relationship between global trade, transboundary movement of plant material and the increasing risk of introducing invasive bacterial pathogens (Rapicavoli *et al*., 2018). This case emphasizes the importance of strengthened quarantine regulations, continuous surveillance, early detection and coordinated international biosecurity measures to reduce future disease incursions.

Huanglongbing (HLB) – A representative example of the Global Spread of Fastidious Bacterial Disease

Huanglongbing (HLB), commonly known as citrus greening disease, is considered one of the most destructive examples of how fastidious bacterial pathogens have become a global agricultural challenge through the movement of plant materials and international trade (Da Graça and Korsten, 2004). The disease is primarily associated with the phloem-limited bacterium *Candidatus Liberibacter asiaticus*, which is transmitted by citrus psyllids but can also be disseminated over long distances through the trade of infected nursery plants and propagation materials (Gottwald, 2010). Because infected plants often remain symptomless during the early stages of infection, they can unintentionally facilitate the introduction of the pathogen into previously disease-free regions (Ghosh *et al*., 2022). Since its initial reports in Asia, HLB has expanded across major citrus producing areas in Africa, the Americas and Oceania, becoming one of the most significant transboundary bacterial diseases of citrus (Gottwald, 2010). Infection disrupts phloem transport, leading to blotchy mottled leaves, shoot yellowing, malformed and poor quality fruits, premature fruit drop, progressive tree decline and eventual tree death (Da Graça and Korsten, 2004). The worldwide emergence of HLB demonstrates that the interaction between global trade, movement of infected propagative materials and efficient insect vectors can accelerate the spread of fastidious bacterial pathogens. Consequently, effective international quarantine systems, certified disease free planting materials, continuous surveillance, early diagnosis and integrated vector management have become essential components of global biosecurity strategies for protecting citrus production.

Economic and Agricultural Impact

Fastidious bacterial pathogens have emerged as a major threat to global agriculture because of their ability to infect economically important crops, reduce productivity and disrupt international trade. Diseases caused by these bacteria often result in severe yield losses, deterioration of fruit quality, increased production costs and premature decline or death of infected plants. Their wide host range and efficient spread through infected planting materials and insect vectors further increase the risk of outbreaks in new agricultural regions (Rapicavoli *et al*., 2018). The global spread of pathogens such as *Xylella fastidiosa* and *Candidatus Liberibacter* spp. has caused substantial economic losses in crops including olive, grapevine, citrus, coffee, almond and other horticultural species (Sicard *et al*., 2018). In addition to direct reductions in crop production, affected countries experience increased expenditure on surveillance, diagnostics, vector control, eradication programs and quarantine implementation. Furthermore, trade restrictions imposed to prevent pathogen dissemination can negatively affect the movement of agricultural commodities and planting materials, reducing market access and threatening farmers' livelihoods. Collectively, these impacts highlight the importance of effective disease prevention, early detection and international biosecurity measures for safeguarding agricultural productivity and global food security.

Challenges, Biosecurity and Future Perspectives

The management of fastidious bacterial diseases remains a major challenge because these pathogens are difficult to culture, frequently produce latent infections, possess broad host ranges and rely on insect vectors for natural transmission (Kruse *et al*., 2019). Increasing international trade and the continuous movement of planting materials further complicate disease prevention by creating opportunities for the introduction of pathogens into new geographical regions. Climate change, expansion of global transportation networks and the establishment of competent insect vectors are expected to increase the risk of future disease emergence and transboundary spread (Ghosh *et al*., 2022). Therefore, strengthening international phytosanitary regulations, improving quarantine inspection systems, adopting certified disease-free planting materials and implementing continuous surveillance and early molecular diagnostic techniques are essential for reducing pathogen dissemination (Paudyal, 2015). Future research should focus on rapid detection technologies, improved understanding of host pathogen vector interactions, climate-based disease risk prediction and the development of sustainable integrated disease management strategies. Enhanced international collaboration, data sharing and coordinated biosecurity policies will be critical for minimizing the agricultural and economic impacts of fastidious bacterial pathogens in an increasingly globalized world.

Conclusion

Fastidious bacterial pathogens continue to pose a serious threat to global agriculture because of their rapid dissemination through international trade, infected planting materials and insect vectors. Diseases caused by *Xylella fastidiosa* and *Candidatus Liberibacter asiaticus* demonstrate how global connectivity can accelerate pathogen spread and increase economic losses. Strengthening biosecurity measures, improving diagnostic technologies, enforcing effective quarantine

regulations and promoting international cooperation are essential to minimize future outbreaks. An integrated approach combining surveillance, early detection and sustainable disease management will be critical for protecting agricultural production and supporting safe global trade.

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Artificial Intelligence in Modern Plant Breeding: Accelerating Crop Improvement

Article ID: 74226

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Summary

Artificial intelligence (AI) is emerging as a powerful technology for transforming modern plant breeding, ramping up the speed, precision and effectiveness of efforts to improve crops. AI is integrating genomic, phenotypic, environmental and historical breeding data to help with decision making across the breeding pipeline. Through parent selection, intelligent phenotyping, disease detection, genomic prediction and yield prediction, AI allows breeders to create better crop varieties faster. The synergy between AI and traditional breeding provides promising prospects for tackling climate change, food security and sustainable agricultural production.

Introduction

Every improved crop variety begins long before a seed reaches the farmer's field. It all starts with the critical decisions of the plant breeders, the choice of suitable parent plants, the development of useful crosses and the evaluation of many breeding lines in different environmental conditions. Traditionally, these decisions relied on field observations and breeder experience. Recent advances in genomics, molecular breeding, high-throughput phenotyping and precision agriculture have generated large and complex datasets that AI can analyse rapidly to support accurate, data-driven breeding decisions.

AI is increasingly becoming an integral component of modern crop improvement programmes. By integrating advanced analytical tools with conventional breeding practices, AI enables breeders to make faster, more accurate and data-driven decisions throughout the breeding cycle. The following sections highlight the major applications of AI that are transforming contemporary plant breeding.

Major Applications for Artificial Intelligence in Modern Plant Breeding

The major applications of AI across different stages of modern plant breeding are summarized in Table 1.

Table 1. Applications for Artificial Intelligence in Modern Plant Breeding:

Breeding Stage	Challenge	AI Approach	Benefit
Parent Selection	Choosing superior parents	Machine learning models	Better parental combinations
Phenotyping	Manual trait evaluation	Computer vision & UAVs	Rapid objective assessment
Disease Detection	Late symptom identification	Deep learning	Early diagnosis
Genomic Selection	Predict breeding value	AI-assisted genomic prediction	Higher selection accuracy
Yield Prediction	Complex G×E interaction	Predictive analytics	Better variety selection

Smarter Parent Selection

Selecting suitable parents is the foundation of every breeding programme. AI integrates genomic, phenotypic and historical breeding records to predict superior parental combinations and prioritize promising crosses. This reduces unnecessary field evaluations, improves crossing efficiency and accelerates the development of improved crop varieties *(Farooq et al., 2024; Khan et al., 2022)*.

Intelligent Phenotyping

AI-powered computer vision, UAVs, hyperspectral imaging and image analysis enable rapid, objective and high-throughput phenotyping. These technologies accurately assess traits such as plant height, canopy architecture, biomass and stress responses, significantly reducing labour while improving selection efficiency and breeding accuracy *(Benos et al., 2021; Qiao et al., 2022; Fiorani & Schurr, 2013)*.

Early Disease Detection

AI-based image analysis and deep learning algorithms enable rapid and accurate detection of plant diseases, often before severe symptoms become visible. Early identification of resistant genotypes improves disease screening efficiency and supports the development of resilient crop varieties with greater precision *(Thomas et al., 2018)*.

Predicting Genetic Potential

AI-assisted genomic prediction combines molecular marker, phenotypic and environmental data to estimate breeding values more accurately than conventional approaches. Early identification of superior genotypes shortens breeding cycles, improves selection efficiency and accelerates genetic gain in crop improvement programmes *(Meuwissen et al., 2001; Crossa et al., 2017; Jurado-Ruiz et al., 2023)*.

Yield Prediction for Better Varieties

AI-driven predictive analytics integrates genomic, weather, soil and management data to forecast crop performance across diverse environments. These models help breeders identify stable, high-yielding genotypes with greater confidence, supporting the development of productive, climate-resilient and widely adapted crop varieties *(Farooq et al., 2024; Sampath et al., 2023)*.

Figure 1 illustrates the major applications of Artificial Intelligence across modern plant breeding and their contribution towards accelerated crop improvement.

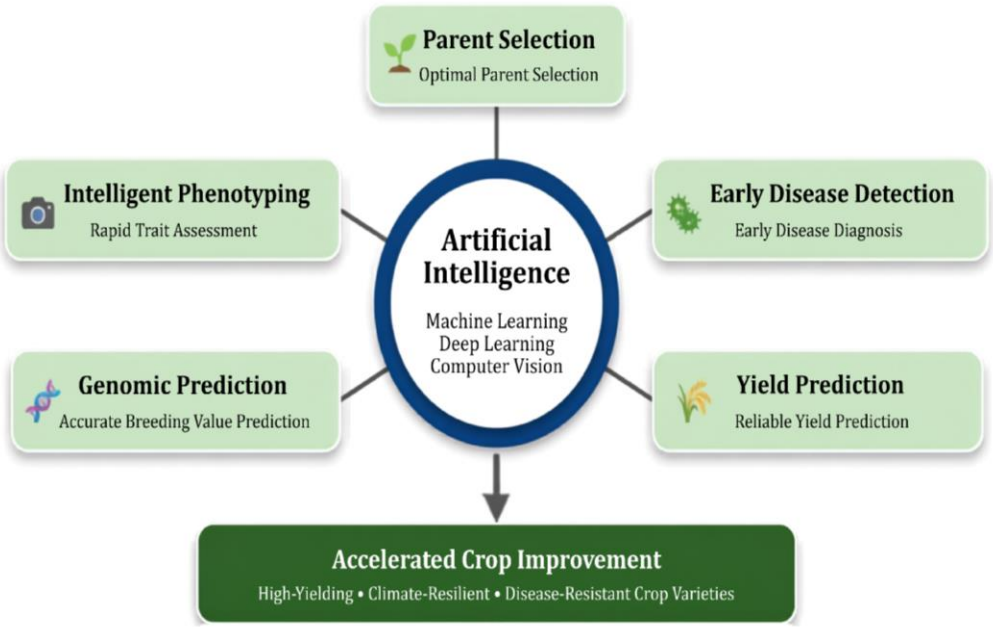


Figure 1. Applications for Artificial Intelligence in Modern Plant Breeding

AI technologies, including machine learning, deep learning, computer vision and predictive analytics, support key breeding activities such as parent selection, intelligent phenotyping, early disease detection, genomic selection and yield prediction, ultimately accelerating the development of high-yielding, climate-resilient and disease-resistant crop varieties.

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Opportunities and Challenges

AI improves breeding efficiency through automation, predictive modelling and data integration. However, wider adoption requires high-quality datasets, computational infrastructure and interdisciplinary expertise. AI should complement, not replace, the skill of plant breeders.

Conclusion

Artificial Intelligence is becoming an indispensable tool in modern plant breeding. By supporting evidence-based decisions across the breeding pipeline, AI accelerates crop improvement and contributes to the development of resilient, productive and sustainable crop varieties. By combining human expertise with AI, the next generation of plant breeding will be faster, smarter and better equipped to address global food security and climate challenges.

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Vermiwash Based Potassium Nanofertilizer: The Future of Potassium Nutrition in Plants

Article ID: 74227

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Abstract
Potassium (K) is a primary macronutrient vital for crop yield, stress tolerance and disease resistance quality. Application of potassium fertilizer in soil is very prudent for balanced nutrition in crops. But excessive use of chemical fertilizers causes soil degradation and environmental pollution. Vermiwash, a liquid extract from vermicompost units, is rich in soluble K, enzymes, hormones and plant growth-promoting substances but is underutilized. This article outlines a low-cost, eco-friendly protocol to convert vermiwash into potassium-based nanofertilizer, offering slow-release properties, higher uptake, and reduced environmental losses.

Introduction
Potassium (K) is one of the three primary macronutrients required for healthy plant growth. It plays a vital role in enzyme activation, photosynthesis, water regulation, disease resistance, stress tolerance, and the development of high-quality produce. Adequate potassium nutrition enables crops to withstand drought, pests, and diseases while improving yield and quality. Despite its importance, Potassium deficiency has become a major nutritional constraint in many Indian soils, with 49% of districts reporting low to medium available K (Balo, S *et al.,* 2024). Soil testing reports from Krishi Vigyan Kendra, Barpeta also indicate K deficiency in many farmer's fields. The low K content of these soils can be attributed to several factors, including: nutrient losses due to leaching and fixation, continuous uptake of K by plants from the soil and inadequate application of potassic fertilizer in their fields. India depends almost entirely on imported Muriate of Potash (MOP), making potassium fertilizers expensive and vulnerable to supply disruptions. Consequently, many farmers primarily apply urea and DAP while neglecting potassium, resulting in nutrient imbalance, declining soil fertility, and reduced crop productivity. Therefore, developing affordable, locally available, and environmentally sustainable potassium sources has become increasingly important.

Rationale for Nanofertilizers
Nanofertilizers contain nutrient particles measuring less than 100 nanometres. Their extremely small particle size provides a larger surface area, better adhesion to plant roots and leaves, improved nutrient absorption, and controlled nutrient release. These characteristics increase nutrient-use efficiency while reducing nutrient losses through leaching and fixation. Research has demonstrated that potassium nanofertilizers synthesized from vermiwash significantly improve seed germination and early crop growth, indicating their potential as an eco-friendly alternative to conventional potassium fertilizers.

Basis for Selecting Vermiwash as a Nanofertilizer Matrix
Vermiwash is a brownish leachate collected during vermicomposting. It contains essential nutrients like nitrogen, phosphorus, potassium, zinc, copper, manganese, iron along with Vitamin B12 and growth hormone like gibberellin. It also has antifungal and antibacterial properties. Converting this K into nano-sized particles (<100 nm) increases surface area, improves root adhesion, and enables controlled release. Nano-K fertilizers have shown 70% higher rate of germination in Toria crop (Ahmed *et al.,* 2025).

Preparation of Vermiwash
A 200 litre capacity bucket with disposal tap fitting in the bottom should be allowed to stand at height of about 2 ft (Fig 1). The drum should be filled with sand and gravels upto 5cm, followed by filling with a mixture of half decomposed organic or green waste and farmyard manure. Approximately, 200 to 300 earthworm species, preferably *Eisenia foetida* should be released at the top layer of the bucket. After two weeks of earthworm incorporation, drop wise water should be permitted to enter into the bucket. For this, a small bucket with a hole at bottom should be placed at the top of the big bucket, so that continuos flow of water is maintained (Ahmed, S., 2021). As the water percolates through the vermicompost, it collects dissolved nutrients, enzymes, and beneficial metabolites before draining through the outlet as vermiwash.



Fig 1: Vermiwash preparation

Procedure of Nanofertilizer Preparation

400 ml of 0.1 M potassium chloride should be added to100 ml of vermiwash in a 1000 ml conical flask. Then it should be heated at 70°C upto 24 hours, followed by incubation at 6000 rpm for 5 minutes. The resultant solution should be filtered and washed with ethanol for three times (Arslan, *et al.*, 2022).

Characterization of Potassium Nanofertilizer

The potassium nanofertilizer derived from vermiwash consist of total N 1.45%, P 0.79%, K 2.41%, Ca 0.11%, Mg 0.08% and Na 0.03%. Among the micro nutrients it contains Fe 15.2ppm, Cu 0.05ppm, Zn 0.08ppm, B 0.07ppm and Mn 0.04 ppm. It is also comprised of organic compound contents like carbohydrate 1.2%, crude fat 0.07%, crude protein 15.31% and tryptophan 0.09%. Cabilovski, *et al.*, (2023) reported that vermicompost leachate i.e Vermiwash comprises of many beneficial and essential nutrients that are important for plant growth and developement.

The average size of K nanoparticles in Vermiwash estimated through Dynamic Light Scattering (DLS) was reported to be 34.6 nm with 100 % intensity and Poly dispersity index (PDI) value 0.381 indicating a high degree of particle monodispersity (Sheoran *et al.*, 2021). The zeta potential of the extracted fertilizer was observed to be high (-31.9 mV) because of its smaller size. The high zeta potential of the particles prevents aggregation, resulting in a stable solution (Sheoran *et al.*, 2021).

The Transmission Electron Microscopy (TEM) analysis of the obtained vermiwash extract by using KCl as extracting agent shows spherical nano particles with size range from 20 to 28 nm (Fig 2).

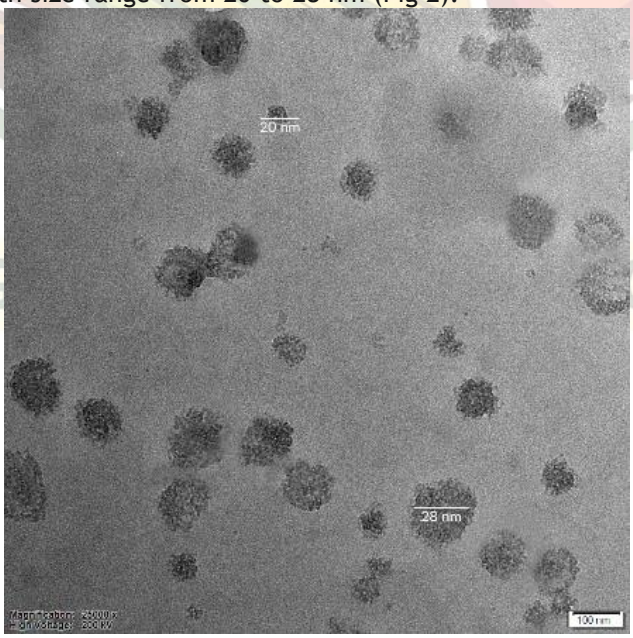


Fig 2: TEM image of potassium nanoparticles

Practical Implication of Potassium Nanofertilizer

Application of synthesized nanofertilizer from vermiwash had a significant positive correlation with germination percentage of Toria crop. The statistical analysis for Pearson correlation coefficient (r) was 0.97. This significant and positive result of the germination test might be due to the characteristics of nanofertilizers which have the ability to

enter plant tissues through the minute pores because of its smaller size. The germination percentage of Toria increased with increasing dose of K nanofertilizer applied and the highest was obtained with 20 ml/l of K nanofertilizer. Presence of other organic compounds like tryptophan, amino acids and other essential nutrients present in the nanofertilizer might also have boost the germination process. Tryptophan plays an important role during plants growth (J Lv *et al.,* 2019). In addition metal ions present in the nanofertilizer mix with organic components to create chelates which makes the plant resistence to precipitation loss (Aboul-Enein *et al.*, 2016).

Case Study

A farmer named Hardweep Talukdar, from Bhawanipur was satisfied with the application of potassium nanofertilizer synthesized from vermiwash in cauliflower and cabbage plants, where nearly 30 per cent of the crop was infected with pest. He irrigated the plants with the nanofertilizer at the rate of 20 ml/lit at weekly interval. Outcome brought smile to his face, because the visual observation of pest infestation was substantially reduced within two weeks of its application, thereby increasing crop yield (Fig.3).



Fig 3: Farmer spraying vermiwash in his crop field

Conclusion

Application of vermiwash based potassium nanofertilizer has the potential to improve crop productivity, enhance nutrient use efficiency, promote soil health and contribute to sustainable agricultural production, thereby uplifting the economy of the farming community.

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Biostimulants for Climate-Smart Vegetable Farming

Article ID: 74228

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Introduction

In recent years vegetable production has evolved beyond the goal of maximizing yield to achieving higher productivity, superior quality and environmental sustainability. The increasing demand for safe and nutritious vegetables, coupled with challenges such as climate change, declining soil fertility and excessive dependence on chemical fertilizers which has accelerated the search for sustainable crop management strategies (du Jardin, 2015).

Among the emerging innovations, plant biostimulants have gained considerable attention for their ability to improve crop performance through the stimulation of natural plant processes. Unlike conventional fertilizers, biostimulants do not primarily supply nutrients, instead they enhance nutrient use efficiency, promote plant growth and development, improve tolerance to abiotic stresses and enhance crop quality (Raza *et al*., 2024). By strengthening the plant's natural physiological and biochemical functions, biostimulants enable vegetable crops to perform efficiently under both favourable and stressful environmental conditions (Rouphael and Colla, 2020). As sustainable horticulture continues to gain momentum, biostimulants are increasingly recognized as an effective tool for improving vegetable productivity while reducing the environmental footprint of modern agriculture.

The Growing Importance of Biostimulants

Vegetable crops require efficient nutrient management and greater resilience to environmental stresses to sustain productivity and quality. Biostimulants have emerged as an effective approach to meet these requirements by enhancing the plant's natural metabolic activities and improving overall crop performance. Their application promotes vigorous root development, efficient nutrient absorption, enhanced photosynthetic activity and better utilization of water and mineral nutrients, leading to healthier plant growth (Bulgari *et al*., 2015).

In addition to improving vegetative growth and yield, biostimulants contribute to better fruit quality by enhancing colour, flavour, nutritional composition and shelf life. They also support beneficial soil microbial activity and improve soil health, making vegetable production systems more sustainable. Owing to these multiple benefits, biostimulants are increasingly becoming an integral component of modern horticulture and climate-smart vegetable production systems (Bayram and Murmu, 2025).

Types of Biostimulants

Plant biostimulants are broadly classified into different categories based on their origin and composition. Each type enhances plant growth and productivity through unique mechanisms (du Jardin, 2015; Pokluda *et al*., 2016).

Humic substances: Humic substances, including humic acid, fulvic acid and humin improve soil fertility, stimulate root growth and enhance nutrient uptake.

Protein hydrolysates: Protein hydrolysates contain amino acids and peptides that promote plant metabolism, improve nutrient assimilation and help plants cope with environmental stresses.

Seaweed extracts: Derived mainly from brown and red seaweeds. These extracts are rich in natural bioactive compounds that enhance plant growth, flowering, fruit set and yield.

Inorganic compounds: Beneficial elements such as silicon (Si) and selenium (Se) strengthen plant tissues and improve tolerance to drought, salinity and other abiotic stresses.

Plant extracts: Plant extracts contain naturally occurring bioactive compounds that stimulate plant growth, improve physiological functions and enhance stress tolerance.

Beneficial microorganisms: Microbial biostimulants including PGPR, PGPF and AMF improve nutrient availability, promote root development and support healthy soil microbial activity.

Chitosan and biopolymers: Chitosan and other natural biopolymers activate plant defense mechanisms, enhance stress tolerance and improve crop quality and shelf life.

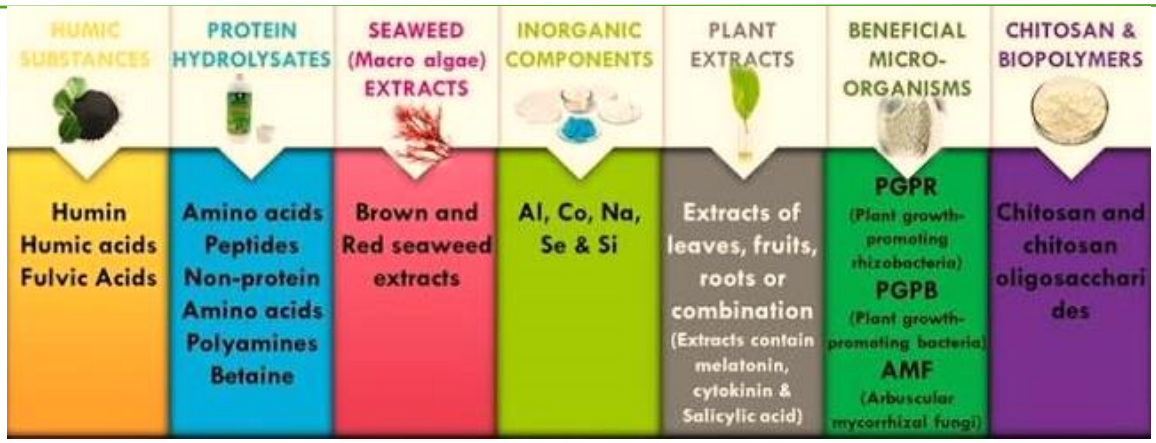


Figure 1. Major categories of plant biostimulants used in vegetable production

Mode of Action of Biostimulants

Unlike fertilizers, biostimulants do not directly supply nutrients to plants. Instead, they stimulate natural physiological and biochemical processes that enhance plant growth, productivity and resilience. Their primary mode of action involves promoting root development, improving nutrient uptake and increasing photosynthetic efficiency, enabling plants to utilize available resources more effectively.

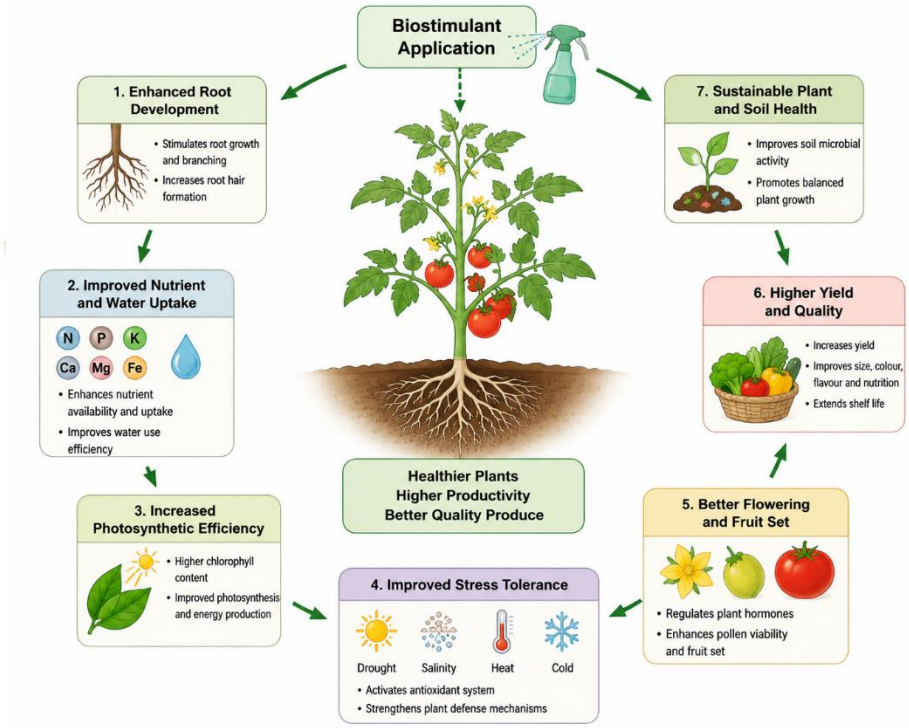


Figure 2. Mode of action of biostimulants in vegetable crops

Biostimulants also activate antioxidant defense systems and regulate plant hormones, helping crops withstand abiotic stresses such as drought, salinity and heat. These physiological responses result in improved flowering, fruit set, yield and produce quality, making biostimulants valuable tools for sustainable vegetable production (Canellas *et al.*, 2015).

Table 1. Examples of biostimulants and their effects in vegetable crops:

Crop	Biostimulant	Major benefits
Tomato	Seaweed extracts, humic substances	Increased plant growth, fruit yield and lycopene content
Cucumber	Protein hydrolysates, microbial biostimulants	Improved nutrient uptake, flowering and disease tolerance
Capsicum	Chitosan, seaweed extracts	Better fruit quality, firmness and stress tolerance
Onion	Protein hydrolysates	Increased bulb size, quality and shelf life

Lettuce & Spinach	Amino acids, humic substances	Higher chlorophyll content, leaf area and nutritional quality
Broccoli & Cabbage	Microbial biostimulants	Enhanced biomass production and nutrient uptake
Cucurbits	Seaweed extracts, amino acids	Improved flowering, fruit set and yield

Biostimulants for Climate-Resilient Vegetable Production

Climate change has emerged as a major challenge to vegetable production, exposing crops to frequent drought, salinity, extreme temperatures and nutrient deficiencies. These stresses adversely affect plant growth, flowering, fruit development and ultimately reduce yield and quality. Biostimulants have shown significant potential in enhancing the resilience of vegetable crops by activating natural defense mechanisms and improving their ability to withstand adverse environmental conditions.

Biostimulants stimulate antioxidant activity, improve water and nutrient use efficiency and regulate physiological processes that help plants tolerate abiotic stresses. They also maintain photosynthetic activity, protect cellular structures and promote faster recovery following stress exposure. Consequently, the integration of biostimulants into crop management practices offers a sustainable strategy for maintaining vegetable productivity under changing climatic conditions (Bulgari *et al.*, 2019).

Future Perspectives

With the increasing emphasis on sustainable and climate-smart agriculture, the role of biostimulants in vegetable production is expected to expand significantly. Future research should focus on developing crop-specific biostimulant formulations, understanding their mechanisms of action and optimizing application methods under diverse agro-climatic conditions. The integration of biostimulants with precision farming, organic production systems and integrated nutrient management will further enhance their effectiveness. Continued innovations and farmer awareness will be crucial for realizing the full potential of biostimulants in improving vegetable productivity while ensuring environmental sustainability.

Conclusion

Plant biostimulants have emerged as promising tools for sustainable vegetable production by improving nutrient use efficiency, stimulating plant growth, enhancing stress tolerance and producing high-quality vegetables. Their ability to reduce dependence on chemical inputs while maintaining productivity makes them an important component of modern horticulture. As research continues to advance and their adoption increases, biostimulants are expected to play a vital role in developing resilient, productive and environmentally sustainable vegetable production systems.

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Diseases in Horticultural Nurseries: Causes, Identification and Management

Article ID: 74229

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Abstract

A disease is defined as any abnormal condition that disrupts the normal physiological functions, structure or development of an organism, typically caused by continuous irritation from a causal agent. In plant science, diseases are broadly classified into biotic (infectious), caused by pathogens such as fungi, bacteria, viruses and nematodes and abiotic (non-infectious), resulting from environmental stresses like nutrient imbalance, temperature extremes, or improper cultural practices. Horticultural nurseries are particularly vulnerable to disease outbreaks due to high plant density, frequent irrigation and humid microclimatic conditions. Among the most common problems are fungal and oomycete diseases such as damping-off, root rot and powdery mildew; bacterial diseases like leaf spots and crown gall; and viral diseases including mosaic infections caused by Tobacco mosaic virus and Cucumber mosaic virus. Effective management of these diseases relies on integrated practices such as maintaining proper drainage, spacing, light and ventilation; using disease-free seeds and sterile growing media; applying bio-control agents like Trichoderma and recommended bactericides and ensuring strict nursery hygiene. Prompt removal and destruction of infected seedlings are also essential to prevent disease spread and ensure healthy plant production.

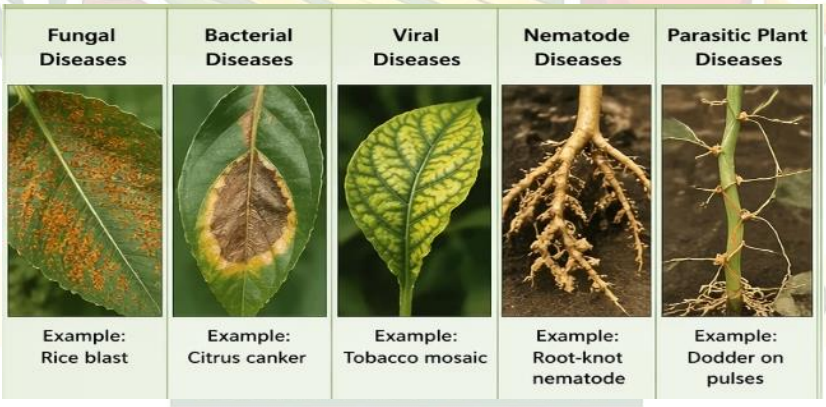
Keywords: disease, vegetable nursery, horticulture and nurser.

What is a Disease?

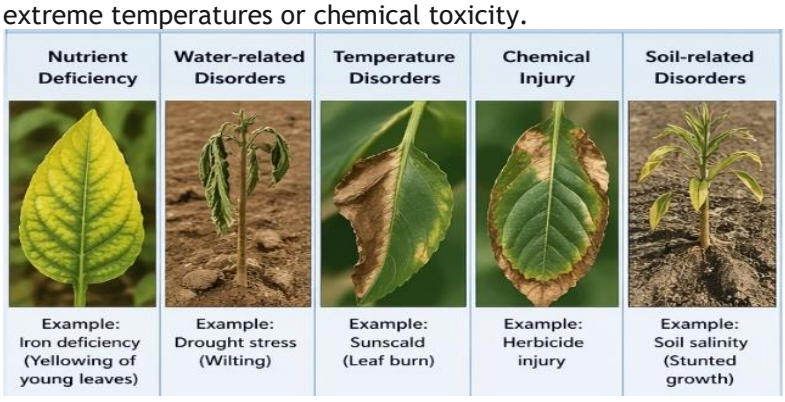
In biological terms, a **disease** is defined as any abnormal condition that negatively alters the physiological function, structural integrity or normal development of an organism. Unlike physical injuries (such as a broken branch or insect chewing), which happen instantaneously, a disease is typically the result of continuous irritation by a causal agent.

In the realm of botany and horticulture, plant diseases are broadly categorized into two main groups:

1. Biotic (Infectious) Diseases: Caused by living organisms known as pathogens. These include fungi, bacteria, viruses, viroids and nematodes.



2. Abiotic (Non-Infectious) Diseases: Caused by environmental extremes or poor cultural practices, such as nutrient deficiencies, improper pH, extreme temperatures or chemical toxicity.



Common Diseases Affecting Plants in a Horticulture Nursery

Horticulture nurseries are high-risk environments for disease outbreaks due to the high density of plants, frequent watering and warm, humid microclimates (especially in greenhouses). The most common nursery diseases include:

1. Fungal and Oomycete Diseases: Fungi are the most common cause of plant diseases in nurseries.



Damping off



Collar rot



Powdery mildew



Leaf spot

Fungal disease



Damping off



Root rot



Seedling blight



Downy blight

Oomycete disease

Fungal Disease			
Sr. No.	**Name**	**Symptoms**	**Favorable conditions**
1	Damping off	Pre & post emergence seedling death, water soaking lesion at stem base, seedling fall and die	High moisture, poor drainage, high seedling, seedling density
2	Collar rot	White mycelial growth at collar region, followed by brown rotting, seedlings wilt and collapse	Warm temperature (25-30°C), high humidity
3	Powdery mildew	White powdery growth on leaves, stunted growth, leaf curling	Moderate temperature (20-28°C), high humidity, poor air circulation
4	Leaf spot	Small brown to black spots on leaves, which enlarge and may coalesce, causing premature defoliation	High moisture, moderate temperature, overhead irrigation
Oomycete disease			
Sr. No.	**Name**	**Symptoms**	**Favorable conditions**
1	Damping off	Root turn brown/black, soft and decayed, seedling show wilting	Excess moisture, waterlogging, poor drainage, low temperature
2	Root rot	Root turn brown/black, soft and decayed; seedling show wilting, stunting and yellowing	Waterlogged soil, high humidity, poor aeration
3	Seed and seedling blight	Seeds rot before germination or young seedlings show brown, water-soaked lesions and die	High moisture, poor drainage, cool temperature
4	Downy mildew	Yellowing on leaves, downy growth on underside, restricted growth, eventual drying on leaves	High humidity, moderate temperature

Management: Effective nursery management requires a combination of proper cultural and preventive practices. Ensuring good drainage and appropriate watering is essential to avoid waterlogging and disease development. Overcrowding should be avoided by maintaining proper spacing between seedlings, which helps reduce humidity and limits the spread of pathogens. Adequate light and proper ventilation must also be ensured to promote healthy growth and minimize disease incidence. It is important to use disease-free seeds along with sterile growing media to prevent initial contamination. The preventive application of bio-fungicides such as Trichoderma can further protect seedlings from soil-borne pathogens. Additionally, any infected seedlings should be promptly removed and destroyed to prevent the spread of diseases within the nursery.

2. Bacterial Diseases: Bacteria typically enter plants through natural openings (like stomata) or wounds.



Bacterial Damping-off/ Seedling Rot



Bacterial Leaf Spot



Bacterial Wilt



Bacterial Soft Rot

Name	Symptoms	Stage	Management
Bacterial Damping-off/ Seedling Rot	Water soaked. soft and slimy lesions at the collar region. Seedlings collapse and rot. Foul smell in advanced stages.	Pre-emergence and post-emergence seedlings	Use disease-free seed and sterile nursery media. Avoid overwatering and ensure good drainage. Drench nursery beds with Copper oxychloride (0.3%) or Streptocycline (100 ppm). Maintain nursery hygiene and proper spacing.
Bacterial Leaf Spot	Small, water-soaked spots on leaves. Spots enlarge, become brown with yellow margins. Severe infection causes leaf drying and drop.	Post-emergence seedlings	Use certified, healthy seed. Spray Streptocycline (100 ppm) or Copper oxychloride (0.3%). Remove and destroy infected seedlings.
Bacterial Wilt	Sudden wilting of seedlings. Yellowing of leaves. Brown discoloration in vascular tissues (internal browning of stem).	Post-emergence seedlings	Use wilt free soil/media and resistant varieties. Drench soil with Pseudomonas fluorescens or Trichoderma spp. Remove and destroy infected seedlings.
Bacterial Soft Rot	Water-soaked lesions on leaves or stems. Soft. mushy and decayed tissues. Seedlings rot and collapse.	Pre and post emergence seedlings	Avoid excess moisture and injury to seedlings. Drench with Copper oxychloride (0.3%) or validamycin (0.1%). Ensure proper sanitation and drainage.

Management: Proper nursery management for disease prevention relies on several essential practices. The use of disease-free seeds along with sterile growing media helps minimize the risk of initial infection. Overwatering and water stagnation should be avoided, as excess moisture creates favourable conditions for pathogen development. Ensuring adequate light and proper ventilation is also important to maintain healthy seedling growth and reduce humidity levels. Preventive application of recommended bactericides can help control bacterial infections at an early stage. Additionally, maintaining strict hygiene in nursery tools, beds and surrounding areas is crucial to prevent the spread of pathogens and ensure overall nursery health.

3. Viral Diseases: Viruses are submicroscopic and cannot be chemically cured once inside the plant.



Cucumber mosaic virus



Tomato leaf curl virus



Yellow mosaic virus



Yellow mosaic virus

Management:

Causal virus	Symptoms	Affected Stage	Host plants
Cucumber mosaic virus (CMV)	- Light and dark green patches on leaves - Leaf distortion and crinkling	All stages (Especially early seedling stages)	Tomato, Brinjal, Chilli, Capsicum, Cucurbits, okra, Lettuce
Tomato leaf curl virus	- Leaves curl upward - Yellow mosaic and vein thickening - Stunted and bushy growth - Leaves become narrow	Seedling to pre-transplanting stage	Tomato, Chilli, Brinjal, Capsicum,
	- Vein clearing or banding on loaves. - Mild mosaic. - Stunted growth. - Leaves become narrow and malformed.	Seedling to young plant stage	Tomato, Tobacco, Capsicum, Brinjal, Okra and other Vegetables.
Yellow mosaic virus	- Yellow mosaic on older leaves - Leaf deformation - Stunting and yield reduction	All stages	Moong, Cow pea, Tomato, okra

Conclusion

Diseases in horticultural nurseries significantly affect seedling health, growthandsurvival, leading to reduced crop productivity and economic losses. Fungal, bacterial, oomyceteandviral diseases commonly develop under conditions of high moisture, poor drainage, overcrowding and inadequate sanitation. Effective disease management depends on integrated nursery practices such as using disease-free seeds, sterile growing media, proper irrigation, spacing, ventilation and maintaining nursery hygiene. The application of bio-control agents and recommended plant protection measures further helps in minimizing disease incidence. Timely identification and removal of infected seedlings are essential to prevent disease spread and ensure healthy, vigorous nursery production.

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Variable Rate Irrigation: A Way Forward

Article ID: 74230

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Summary of Article

With water constraint and increasing input prices, Indian agriculture is moving towards the use of precision irrigation systems. One such technique is varied Rate Irrigation (VRI) that delivers water at spatially varied rates over a field based on real-time needs of the crop, soil and topography, instead of the typical uniform application. VRI uses sensor, GPS, GIS and variable-speed sprinkler control to help optimize water use efficiency, save input costs, reduce nutrient leaching and increase produce uniformity. The essay addresses the concept, components, benefits, limitations and future scope of VRI as a possible way forward for sustainable and climate-resilient irrigation management.

Introduction

Irrigation is the largest user of fresh water in India and is a major contributor in the total water withdrawal. Traditional irrigation systems such as flood and sprinkler are typical centre-pivot systems that distribute water uniformly over a field based on the assumption of uniform soil type, topography, crop stage and water-holding capacity throughout. In reality most agricultural fields show significant spatial variation in soil texture, slope, drainage and crop vigour. Under such conditions uniform irrigation results in over-irrigation in some zones and under-irrigation in others leading to waterlogging, nutrient leaching, salinization, uneven crop growth and wastage of a precious resource. Variable Rate Irrigation (VRI) is a technology that allows a field to be divided into smaller management zones to apply water at rates based on the requirement of that zone. (Singh et al., 2015). The technology employs prescription maps derived from soil electrical conductivity surveys, remote sensing imagery, yield monitor data and topographic surveys, which are then connected to variable-speed drive systems and individually controlled sprinkler nozzles on centre-pivot or lateral-move irrigation systems.

Key Components of VRI Systems

1. Sensing and Mapping Tools: Soil moisture sensors, electromagnetic induction sensors, remote sensing and GPS-based yield monitors are used to characterise spatial variability and delineate management zones.

2. Prescription Map: A digital map that specifies the desired application rate for each zone or grid cell of the field.

3. Variable-Rate Control System: Software and controllers on centre-pivot or lateral-move systems that adjust nozzle flow, sprinkler cycling or travel speed according to the prescription map.

4. Telemetry and Automation: Wireless communication and cloud-based platforms that allow real-time monitoring and remote adjustment of irrigation schedules.

Benefits of Variable Rate Irrigation

Singh and Mishra (2015) have reported that water management at the site-specific level was more effective than uniform application of water. VRI has many agronomic and economic benefits. The matching of the supply with the actual crop demand improves the water use efficiency by reducing the runoff and deep percolation losses. It reduces energy and pumping costs of over-irrigation, and reduces leaching of nitrogen and other soluble nutrients protecting the ground water quality. VRI avoids waterlogging in low lying areas and moisture stress in coarse textured areas, resulting in uniform crop stand, better root development and more consistent yields across the field. It also helps the soil in the long run by preventing salt accumulation and erosion in over-irrigated areas.

Challenges and Limitations

VRI has not been very successful in India despite its promise, due to the high initial investment in sensors, controllers and retrofitting of the existing sprinkler systems. The small and fragmented land holdings, poor technical know-how among farmers, lack of reliable internet connectivity in rural areas and no trained service providers further restrict the widespread uptake. Accurate prescription maps also need reliable soil and crop data, which is often not readily available at the field level in smallholder systems.

Personal Opinion

In my view, VRI represents a logical next step in India's precision agriculture journey, but its success will depend on making the technology affordable and accessible to small farmers, possibly through custom-hiring centres, cooperative

models or subsidy-linked schemes. Integration of VRI with low-cost IoT sensors and mobile-based advisory platforms could substantially bring down costs and improve farmer confidence in adopting this technology.

Summary/ Conclusion

Variable Rate Irrigation provides a scientifically sound and economically viable pathway forward to address spatial variability in agricultural fields and achieve sustainable water management. With continued research, indigenous sensor and controller development for cost reduction, capacity building of farmers and supportive government policy, VRI can play a significant role in enhancing water use efficiency and climate resilience of Indian agriculture in the coming years.

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Rhodococcus fascians: An Emerging Threat to Global Plant Agriculture and Horticulture

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Abstract

The actinomycete *Rhodococcus fascians*, which has previously been linked to the leafy gall disease of herbaceous ornamentals, has gained fresh interest due to new outbreaks, new hosts and an uncommon occurrence of opportunistic human infection. Once a controllable annoyance for the nursery industry, it is now linked to an increasing number of new host and geographic records in Asia, Europe and North America, as well as pistachio bushy top syndrome, a disease that caused catastrophic losses in the western United States. Its virulence approach depends on a linear plasmid carrying cytokinin biosynthesis genes that hijack plant growth; genomic research has identified a varied species complex and a 2023-2024 taxonomic revision has transferred it to a newly suggested genus. In addition to outlining research priorities for a pathogen that is no longer readily written off as minor or settled, this review summarizes current understanding of its biology, pathophysiology, host range, diagnosis and management.

Keywords: *Rhodococcus fascians,* leafy gall disease, pistachio bushy top syndrome, cytokinin biosynthesis, virulence plasmid, host range expansion, taxonomic revision.

Introduction

For about a century, ornamentals have been known to suffer from fasciation and leafy gall disease. The causative bacteria was first identified by Tilford in 1936 from sick sweet peas. It was then termed Bacterium *fascians*, then *Corynebacterium fascians* and finally *Rhodococcus* in 1984 due to chemotaxonomic data. It was considered a persistent but low-stakes nursery issue for the majority of the 20th century, deforming chrysanthemums, sweet peas, geraniums and dahlias without endangering food security or going far beyond bedding plants.

Growers in California, Arizona and New Mexico were compelled to destroy and replant thousands of hectares of new orchards due to pistachio bushy top syndrome, which is now associated with *R. fascians*. Genomic sequencing has shown a diversified species complex, molecular monitoring continues to unearth new host and country records and a 2023-2024 phylogenomic re-analysis suggests transferring the organism into a new genus. Most surprisingly, the bacterium was found in tissue from an immunosuppressed transplant patient in a 2016 case report. This was the first indication that this traditional phytopathogen might operate opportunistically in humans under atypical conditions. The organism's taxonomy, its plasmid-encoded virulence approach, its growing host range and disease portfolio, the evidence supporting its more recent connections and the available diagnostic and management techniques are all included in this study.

Taxonomic History and Classification

Following Tilford's 1936 description as *Phytomonas fascians*, the species was reclassified as *Bacterium fascians* (Lacey, 1939) and *Corynebacterium fascians* (Dowson, 1942). The majority of contemporary literature refers to *Rhodococcus fascians*, which Goodfellow proposed in 1984 after demonstrating a close affinity to *Rhodococcus* by cell-wall chemistry and phenotypic data.

The organism is not taxonomically uniform, according to genomic research; surveys have shown at least thirteen different genetic groupings and multiple reviews characterise *R. fascians* as a species complex rather than a single homogeneous species, with practical implications for host selection and diagnostic behaviour.

The most recent phylogenomic re-analysis of the order *Mycobacteriales*, which was confirmed in 2024, discovered that *R. fascians* and a number of its relatives form a unique, more primitive lineage and suggested moving this clade to a new genus called *Rhodococcoides*.

The organism continues to appear under both designations because applied plant-pathology and regulatory literature has not yet reached a consensus on a single nomenclature. This serves as a warning that even the fundamental categorisation of an economically significant disease is still subject to change.

Biology and Molecular Pathogenesis

General Bacteriology and Life Cycle: Like its sibling *Rhodococcus equi*, *R. fascians* is a gram positive, pleomorphic, high GC actinomycete that produces branching hyphae that split into rod or coccus shaped cells. It is a harmless epiphyte for the most of its life cycle, only changing to an endophytic, harmful lifestyle when it finds a suitable host. Unlike Agrobacterium, which invades live cells, it usually stays in intercellular spaces. Because it lacks independent motility, it spreads mostly by water, tools and vegetative propagation material. It can survive in soil for one to two years when connected to plant waste and can survive in irrigation water for up to ninety days.

The Virulence Plasmid and the att-fas-hyp Cassette: In the model strain D188, virulence is dependent on a large (~200 kb), linear, conjugative plasmid called pFiD188 that carries three important loci: att, fas and hyp. The chromosome has one known virulence gene, vicA (malate synthase). The LysR-type gene attR controls the att locus, which is triggered by extracts from well-established galls and generates diffusible "inducing factors" that activate the fas operon, acting as a quorum-sensing-like checkpoint to certify successful infection. A cytokinin biosynthesis pathway is encoded by the fas operon, which consists of six open reading frames and the AraC-type regulator fasR. Its fasD gene (isopentenyl transferase) is the most commonly used molecular diagnostic marker. According to expression studies, the hyp locus contributes additional, less well-defined symptom aspects, while att acts early at the plant surface and fas persists during and after penetration, at locations of new meristem development (Crespi *et al.*, 1994).

Cytokinin-Mediated Reprogramming and Population Heterogeneity: In order to explain loss of apical dominance, activation of latent axillary meristems, delayed senescence and multiple-shoot proliferation, the fas operon facilitates the synthesis of a unique combination of five cytokinins whose combined activity varies from any single natural plant cytokinin. The "sidetracking gall hypothesis" states that a strong, localised auxin response causes extensive but disorganised vascular formation within the gall, while host strigolactone signalling acts as a counteracting defence that limits severity, resulting in a sustained biotrophic standoff rather than rapid kill. Bacterial cytokinins also stimulate host auxin and polyamine production, accessory signals that reinforce symptoms.

Because the virulence cassette is plasmid borne, individual cells may lose it during growth, and isolates are often combinations of plasmid-bearing and plasmid cured cells; in inoculation tests, the percentage of cells that are positive for the virulence gene substantially correlates with the severity of symptoms. This explains why pathogenic and nonpathogenic isolates are frequently found in the same tissue and it has led to sincere debate on *Rhodococcus's* causative role in recently reported outbreaks, most notably pistachio bushy top disease (Stes *et al.*,2011).

Disease Symptomatology and Host Range

The leafy gall syndrome is caused by infection and manifests as crowded, stunted shoots at nodes, flattened, ribbon-like fasciated stems, witches' broom-like axillary proliferation, inflated buds, reduced internodes and occasionally deformed roots. Laboratory validation is usually necessary since these symptoms are similar to abiotic stress or Agrobacterium galls. Although herbaceous perennials continue to be most commonly impacted, the host range is remarkably wide for a bacterial phytopathogen, recorded across at least forty to forty-four plant families and well over one hundred genera spanning dicots and monocots. Representative associations from the historical decorative range through the more recently verified tree crop case are summarised in the table below (Savory *et al.*, 2017).

Common disease name	Representative hosts	Typical symptom
Leafy gall of chrysanthemum	*Chrysanthemum* spp.	Clustered, stunted shoot proliferation
Fasciation of sweet pea	*Lathyrus odoratus*	Flattened, ribbon-like stems
Fasciation of geranium / petunia	*Pelargonium*, *Petunia* spp.	Shoot proliferation, lost apical dominance
Leafy gall of dahlia	*Dahlia* spp.	Reduced tuber yield; gall on cuttings
Lily fasciation	*Lilium* spp. (Asian, Oriental)	Flattened stems, multiple shoots
Pistachio bushy top syndrome	Pistacia vera, UCB-1 rootstock	Stunting, swollen buds, bark cracking

Why *Rhodococcus fascians* is Emerging as a Threat?

Pistachio Bushy Top Syndrome: Pistachio bushy top syndrome (PBTS) is characterised by stunted growth, shortened internodes, swollen lateral buds, sylleptic branching and bark cracking at the bud union; affected orchards showed 10-90% abnormal rootstocks and budding success as low as ~30%. It was first reported in 2015 on clonal UCB-1 pistachio rootstock in California and Arizona, with New Mexico following shortly after. PBTS1 (related to *R. corynebacterioides*) and PBTS2 (related to *R. fascians*) are the two co-occurring bacteria that are in charge. They work in concert, with PBTS2 seemingly strengthening PBTS1's resistance to copper and some antibiotics. Due to the lack of an antibiotic registered for pistachios and the poor history of antibiotic control of plant bacterial disease, growers have had little choice but to deal with the approximately one million nonbearing trees that were impacted across approximately 14,000 hectares, a catastrophic loss for the regional industry. *Rhodococcus's* causal role has been contested. A 2017 genomic comparison claimed that some PBTS isolates lacked the complete expected virulence-gene complement. Ten years later, may be this disagreement still serves as a real-life illustration of how unresolved the research behind a significant new epidemic.

Geographic Spread, New Hosts and Human Infection: In February 2020, South Korean quarantine authorities used a fasD-targeted PCR assay to detect contamination in approximately 492,000 lily bulbs, resulting in the destruction of approximately 1.3 million imported bulbs; subsequent isolation and inoculation confirmed pathogenic *R. fascians*, differentiated into at least four strains, as the cause of lily fasciation outbreaks on Jeju Island and in Gangwon Province. In other places, real-time PCR surveys in Pennsylvania revealed previously unreported host associations (Lee *et al.*,2022).

When several hundred sclerotic liver lesions were unintentionally found during an autopsy in an immunosuppressed bone marrow transplant recipient who had passed away from an unrelated infection in 2016, medical professionals announced the first known discovery of *R. fascians* in human tissue. The absence of other bacterial or fungal DNA suggested against contamination and the organism was recognised histologically. However, the authors presented the results cautiously rather than as evidence of a clinical illness. The case is noteworthy primarily because *R. fascians* is known to aerosolise and form biofilms, similar to the well-known opportunist *R. equi*. These characteristics could potentially promote incidental infection in a sufficiently weakened host as such medical practice becomes more widespread. (Majumder *et al.*, 2024).

Disease Management and Control

Antibiotic control of bacterial plant disease has historically performed badly, there is no licensed antibiotic for the pathogen on any crop, and there is no curative chemical treatment available. Thus, management depends on sanitation and prevention:

1. Don't take cuttings, divisions or bulbs from any sick or exposed source plant; instead, use propagation stock that has been verified pathogen-free.

2. Avoid reusing media or containers from contaminated stock without sterilisation; instead, disinfect equipment and propagation surfaces in between plants.

3. Because the bacteria can survive in water for around 90 days, limit overhead irrigation and untreated recycled irrigation water

4. Steer clear of replanting sensitive species (sweet pea, geranium, petunia and chrysanthemum) in beds that have been known to harbour sick plants within a year or two.

5. Rather than composting on-site, remove and destroy sick plants as soon as possible.

6. Since there is currently no resistant rootstock substitute for UCB-1, tree crops like pistachios should rely on verified clean stock and remove any suspicious young trees as soon as possible.

Beyond sanitation, research continues into biological control agents, the dynamics of virulence-gene loss and host defense pathways such as strigolactone signaling as a possible basis for breeding or treatments that enhance natural resistance rather than targeting the pathogen directly.

Future Outlook and Research Priorities

1. Reconcile the proposed *Rhodococcoides* reclassification with diagnostic, regulatory and applied plant pathology usage to avoid nomenclatural confusion.

2. Resolve the PBTS etiology debate with standardized, peer validated genomic and pathogenicity criteria to guide rootstock breeding and regulation.

3. Develop validated, low cost, field deployable diagnostics combining plasmid and chromosome-based markers to handle virulence gene instability.

4. Invest in resistant or tolerant rootstocks and cultivars, especially for pistachio, where no alternative to susceptible UCB-1 currently exists.

5. Pursue biocontrol and hormone-pathway-targeted strategies, including strigolactone based induced resistance, as antibiotic free alternatives.

6. Maintain surveillance for further geographic and host-range expansion and for any further evidence of opportunistic human infection, ideally through coordinated plant-pathology and clinical-microbiology monitoring.

Conclusion

Rhodococcus fascians demonstrates how a pathogen that has been around for a century can still cause real surprises, such as a catastrophic outbreak in a significant tree nut crop, the accumulation of new host and country records connected to international plant trade, a significant taxonomic reorganisation and a cautious presence in clinical case reports. Its wide host range and the practical challenge of detecting and controlling it are explained by its plasmid-encoded, quorum-sensing-like virulence switch, which hijacks cytokinin signaling instead of transferring DNA into the host. To keep up with an organism that constantly redefining the parameters of what was formerly thought to be a

minor, established plant disease, ongoing investments in genomic surveillance, validated diagnostics, resistant germplasm and harmonized nursery and quarantine standards will be required.

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Role of Trees Outside Forests in Mitigating Global Climate Change

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Introduction

Climate change is one of the most pressing environmental challenges of the twenty-first century. Rising atmospheric concentrations of greenhouse gases (GHGs), particularly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), have accelerated global warming, resulting in increasing temperatures, altered precipitation patterns, frequent extreme weather events, biodiversity loss, and declining ecosystem resilience. According to the Intergovernmental Panel on Climate Change (IPCC), limiting global warming requires rapid reductions in greenhouse gas emissions coupled with enhanced carbon sequestration through natural and managed ecosystems.

Forests are widely recognized as the largest terrestrial carbon sinks; however, trees growing outside designated forest areas also play an indispensable role in climate change mitigation. Trees Outside Forests (TOF) encompass all trees occurring on agricultural lands, urban landscapes, roadsides, homesteads, institutional campuses, canals, and community lands. Although these trees are often overlooked in national carbon accounting, their cumulative contribution to biomass production, carbon storage, biodiversity conservation, and ecosystem services is substantial.

With increasing urbanization, shrinking forest areas, and expanding agricultural landscapes, TOF offers a practical and scalable solution for enhancing carbon sequestration while simultaneously supporting food production, livelihood security, and environmental sustainability. Integrating trees into non-forest landscapes represents one of the most effective nature-based solutions for mitigating climate change and improving ecosystem resilience.

What are Trees Outside Forests?

Trees Outside Forests (TOF) refer to all trees growing on land that is not officially classified as forest. According to the Food and Agriculture Organization (FAO), TOF includes trees occurring singly, in rows, scattered on agricultural fields, or grouped in areas too small to meet the minimum criteria for forest classification. Similarly, the Forest Survey of India (FSI) recognizes TOF as trees located outside recorded forest areas that contribute significantly to national tree cover and environmental sustainability.

TOF occur in diverse land-use systems and contribute to ecological stability while providing multiple goods and services.

Major types of Trees Outside Forests include:

a. Agroforestry systems
b. Home gardens
c. Farm boundary plantations
d. Block plantations on private lands
e. Roadside plantations
f. Railway-side plantations
g. Canal-side plantations
h. Urban and peri-urban trees
i. Institutional plantations
j. Community woodlots
k. Trees in parks and recreational areas
l. Trees on degraded lands and wastelands
m. Shelterbelts and windbreaks
n. Riparian vegetation along rivers and streams

These tree resources bridge fragmented forest landscapes and enhance ecosystem connectivity while supporting rural and urban livelihoods.

Role of TOF in Climate Change Mitigation

1. Carbon sequestration in biomass and soil: Trees absorb atmospheric carbon dioxide through photosynthesis and store carbon in their stems, branches, leaves, roots, and surrounding soils. TOF significantly contributes to carbon sequestration across agricultural and urban landscapes, thereby reducing greenhouse gas concentrations.

2. Long-term carbon storage: Woody biomass stores carbon for decades or even centuries. Timber harvested from TOF continues to retain carbon in furniture, buildings, and other wood products, extending the duration of carbon storage beyond the life of the tree.

3. Reduction of atmospheric CO_2 concentration: Expanding tree cover outside forests increases the global capacity to remove atmospheric CO_2. Large-scale adoption of agroforestry and urban tree planting can substantially offset emissions from agriculture, transportation, and industrial activities.

4. Replacement of fossil fuel-intensive materials: Wood products obtained from TOF can substitute carbon-intensive materials such as steel, cement, concrete, plastics, and aluminum. The use of sustainably harvested timber lowers embodied carbon in construction and manufacturing sectors.

5. Bioenergy production: Pruned branches, fuelwood, and biomass residues generated from TOF serve as renewable energy sources. Sustainable bioenergy reduces dependence on fossil fuels and contributes to lowering net greenhouse gas emissions.

6. Improvement of soil organic carbon: Leaf litter, root turnover, and organic residues from trees enhance soil organic matter, improve soil carbon stocks, increase microbial activity, and promote long-term soil fertility.

7. Climate change adaptation benefits: While mitigating climate change, TOF also helps communities adapt to changing climatic conditions.

8. Temperature regulation: Tree canopies reduce surface temperatures through shading and evapotranspiration, thereby minimizing urban heat island effects and protecting crops from heat stress.

9. Microclimate improvement: Trees moderate local climatic conditions by reducing temperature fluctuations, maintaining humidity, and lowering wind velocity, creating favorable environments for agricultural production.

10. Windbreak and shelterbelt effects: Trees planted along farm boundaries and roads act as windbreaks that reduce wind speed, protect crops from lodging, and minimize soil moisture loss.

11. Soil Erosion control: Tree roots stabilize soil, while canopy cover reduces the impact of raindrops, thereby minimizing soil erosion and conserving fertile topsoil.

12. Flood mitigation: Trees enhance rainfall interception, increase infiltration, and reduce surface runoff, helping to lower flood risks in both rural and urban areas.

13. Drought resilience: Deep-rooted trees improve groundwater recharge and maintain soil moisture, enabling agricultural systems to withstand prolonged dry periods.

14. Water conservation: Tree cover improves watershed health by regulating hydrological cycles, enhancing groundwater recharge, and protecting water quality.

15. Environmental benefits: Trees Outside Forests provide numerous ecosystem services that extend beyond carbon sequestration.

16. Biodiversity conservation: TOF offers habitats, nesting sites, and food resources for birds, insects, mammals, reptiles, and beneficial pollinators, thereby conserving biodiversity in agricultural and urban landscapes.

17. Habitat connectivity: Scattered trees and tree corridors connect fragmented forests, facilitating wildlife movement and maintaining ecological connectivity.

18. Air pollution reduction: Trees absorb gaseous pollutants, capture particulate matter, and release oxygen, thereby improving air quality and public health.

19. Improvement of water quality: Tree roots filter sediments, nutrients, and pollutants before they enter water bodies, improving freshwater quality.

20. Nutrient cycling: Leaf litter decomposition returns essential nutrients to the soil, enhancing nutrient availability and reducing dependence on chemical fertilizers.

21. Enhancement of ecosystem services: TOF contributes to pollination, pest regulation, climate regulation, soil fertility, carbon storage, and cultural services, thereby strengthening ecosystem resilience.

22. Socio-economic benefits: Trees Outside Forests contribute significantly to rural livelihoods and sustainable development.

23. Timber and fuelwood production: TOF provides timber, poles, firewood, and construction materials, reducing harvesting pressure on natural forests.

24. Fruits, fodder, and medicinal products: Fruit trees, fodder species, medicinal plants, gums, resins, oils, and other non-timber forest products diversify farm outputs and improve nutritional security.

25. Livelihood diversification: Multiple tree products generate year-round income opportunities for farming households and reduce dependence on a single agricultural enterprise.

26. Employment generation: Nursery development, plantation establishment, harvesting, processing, transportation, and value addition create substantial employment opportunities.

27. Income security for farmers: Trees act as long-term financial assets by providing periodic returns through timber harvesting, fruit production, and ecosystem service payments.

28. Sustainable rural development: TOF strengthens rural economies by enhancing farm productivity, reducing climate risks, and promoting sustainable resource management.

29. Role of agroforestry as TOF: Agroforestry represents one of the most efficient forms of Trees Outside Forests and is recognized as a climate-smart land-use system.

30. Agroforestry as a climate-smart land-use system: Integration of trees with crops and livestock increases productivity while enhancing ecological sustainability and resilience to climate variability.

31. Carbon sequestration potential: Agroforestry systems store significant amounts of carbon in aboveground biomass, belowground biomass, litter, and soils, making them effective long-term carbon sinks.

32. Enhanced farm resilience: Tree-based farming systems improve soil fertility, reduce erosion, regulate microclimates, diversify production, and buffer farmers against climatic uncertainties.

33. Food, nutritional, and economic security: Agroforestry simultaneously produces food, fodder, timber, fruits, fuelwood, medicines, and other marketable products, ensuring sustainable livelihoods and improved nutritional outcomes.

Global and Indian Initiatives

Several international and national initiatives recognize the importance of Trees Outside Forests in combating climate change.

1. Paris Agreement: Encourages countries to enhance carbon sinks through afforestation, reforestation, and sustainable land management.

2. UN Decade on Ecosystem Restoration (2021–2030): Promotes restoration of degraded ecosystems, including tree-based restoration in agricultural and urban landscapes.

3. Bonn Challenge: Supports global restoration of degraded and deforested lands to improve carbon sequestration and ecosystem services.

4. REDD+: Recognizes sustainable forest management and enhancement of forest carbon stocks as important climate mitigation strategies.

5. Sustainable Development Goals (SDGs): TOF contributes directly to SDGs related to climate action (SDG 13), life on land (SDG 15), zero hunger (SDG 2), clean water (SDG 6), and sustainable cities (SDG 11).

6. National Agroforestry Policy (India): India became the first country to adopt a dedicated National Agroforestry Policy in 2014, promoting integration of trees into agricultural landscapes.

7. Green India Mission: Focuses on increasing forest and tree cover while enhancing ecosystem services and climate resilience.

8. Sub-Mission on Agroforestry (SMAF): Provides financial assistance for tree planting on farmlands and encourages climate-resilient agriculture.

9. National Afforestation Programme: Promotes restoration of degraded lands through community participation and large-scale tree planting.

Challenges

Despite their enormous potential, several challenges hinder wider adoption of Trees Outside Forests.

1. Fragmented landholdings limit tree planting opportunities.
2. Limited awareness regarding ecological and economic benefits.
3. Inadequate policy support and institutional coordination.
4. Poor market access for tree products.
5. Lack of quality planting material and certified nurseries.
6. Long gestation periods discourage investment.
7. Climate extremes, pests, and diseases affect tree survival.
8. Regulatory restrictions on harvesting and transportation of certain tree species.

Addressing these constraints requires integrated policies, scientific management, and stakeholder participation.

Future Perspectives

The future of climate change mitigation increasingly depends on expanding tree cover beyond conventional forests.

Priority actions include:

1. Large-scale expansion of agroforestry systems.

2. Promotion of urban and peri-urban greening.
3. Development of carbon credit and payment for ecosystem service mechanisms.
4. Application of GIS, remote sensing, drones, and artificial intelligence for TOF inventory and monitoring.
5. Community participation through farmer producer organizations, self-help groups, and local institutions.
6. Stronger policy integration among agriculture, forestry, climate, and rural development sectors.
7. Promotion of native and climate-resilient tree species.
8. Strengthening research on carbon sequestration potential and ecosystem services.

Conclusion

Trees Outside Forests have emerged as one of the most effective nature-based solutions for mitigating global climate change while simultaneously enhancing climate resilience, biodiversity conservation, and sustainable livelihoods. Although individually small and geographically dispersed, their cumulative contribution to carbon sequestration, ecosystem restoration, and environmental sustainability is immense. Integrating trees into agricultural landscapes, urban environments, institutional campuses, and community lands can substantially increase national tree cover without competing with existing forests. Strengthening policy support, scientific management, technological innovations, and community participation will be essential for realizing the full potential of TOF. Expanding Trees Outside Forests is therefore not only an environmental necessity but also a strategic investment towards achieving global climate goals, sustainable development, and a resilient future.

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Advancements in Modern Harvesting Tools for Efficient Forestry Logging Operations

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Abstract
Advancements in modern harvesting tools have revolutionized forestry logging operations, significantly improving efficiency, safety, and sustainability. Mechanized equipment such as feller-bunchers, harvesters, and forwarders are now integral to large-scale logging, replacing manual labor and reducing operational costs. These tools use state-of-the-art technologies, including GPS, remote sensing, and real-time data analysis, to enhance precision in tree cutting, sorting, and transportation. Automated systems allow for more accurate felling, leading to reduced waste and better utilization of timber resources. Modern harvesting machines are designed to minimize environmental impact by reducing soil compaction, preventing damage to surrounding vegetation, and ensuring minimal disruption to the forest ecosystem. Additionally, advanced saws and chain systems increase cutting speed and efficiency, while multi-functional equipment enhances versatility by performing multiple tasks in a single operation, further boosting productivity. These technological improvements not only contribute to higher operational efficiency but also promote sustainable forest management by enabling better planning and execution of logging activities. As a result, these advancements support responsible harvesting practices, ensuring that forests are managed for long-term ecological health while meeting commercial demands. In summary, the integration of modern harvesting tools is transforming the forestry industry, enhancing both economic and environmental outcomes in logging operations.

Keywords: Machine, Logging, Tools and Sustainable.

Introduction
Forestry logging operations have evolved significantly with advancements in modern harvesting tools, enhancing efficiency, safety, and sustainability. Traditional logging methods relied heavily on manual labor and basic tools such as axes and saws, which were time-consuming and physically demanding. However, with the introduction of mechanized equipment, such as chainsaws, skidders, harvesters, and forwarders, the industry has transformed. These modern tools not only increase productivity but also minimize environmental impact by reducing soil disturbance and optimizing timber extraction.

The adoption of modern harvesting technology is crucial for meeting the growing global demand for timber while ensuring sustainable forest management. Equipment such as feller bunchers and processors allow for precise cutting and sorting of logs, reducing waste and improving wood utilization. Additionally, innovations like GPS technology, remote sensing, and automated systems enhance operational efficiency and worker safety. As forestry continues to integrate advanced technologies, modern harvesting tools will play a key role in balancing economic viability with environmental conservation.

Evolution of Forestry Harvesting Tools
The evolution of forestry harvesting tools has been shaped by technological advancements, changing labor needs, and environmental considerations. Over time, tools have progressed from simple hand implements to highly efficient, automated machines designed for sustainable logging.

1. Primitive and early tools (prehistoric - 18th century): In the earliest periods, humans relied on stone axes and adzes to cut down small trees. As metallurgy advanced, bronze and iron axes replaced stone tools, making tree felling more efficient. By the 15th century, the two-person crosscut saw became an important tool, allowing workers to cut logs more easily and reducing the reliance on single-person axes. These tools laid the foundation for more advanced forestry practices.

2. Industrial revolution innovations (18th - 19th century): The Industrial Revolution introduced machinery that significantly improved timber harvesting and processing. Steam-powered sawmills emerged in the late 18th century, reducing the need for manual saws and enabling faster wood processing. Tools like bucking saws and pit saws allowed logs to be cut more efficiently, while oxen- and horse-drawn sleds and wagons facilitated the transportation of felled logs from forests to mills. These innovations marked the beginning of mechanized forestry.

3. Mechanization era (early - mid 20th century): The early 20th century saw rapid mechanization in forestry. The invention of chainsaws in the 1920s and 1930s revolutionized tree felling, replacing traditional axes and saws with a

much faster and more efficient alternative. The introduction of steam and gasoline-powered tractors in the early 1900s further enhanced log transportation. By the mid-20th century, skidders were developed to drag logs from the forest to processing sites. Additionally, power saws and portable mills improved on-site timber processing, reducing transportation costs and increasing efficiency.

4. Modern mechanized harvesting (late 20th century - present): Forestry in the late 20th and early 21st centuries has been characterized by full mechanization. Harvesters, introduced in the 1970s, are capable of cutting, delimbing, and processing trees on-site, drastically increasing productivity. Feller bunchers, developed in the 1980s, allow workers to grasp multiple trees, cut them, and neatly stack them for easier transportation. Meanwhile, forwarders and modern skidders enable efficient log transportation while minimizing environmental impact. Chainsaws have also undergone significant advancements, becoming lighter, more fuel-efficient, and equipped with safety features. The introduction of remote-controlled and GPS-guided equipment has further refined precision logging, reducing waste and ensuring sustainable forestry practices.

5. Future trends in forestry harvesting: As technology continues to advance, the future of forestry harvesting is shifting toward automation and sustainability. AI-driven drones and robotic harvesters are being developed to enhance precision cutting while reducing labor costs. The adoption of electric and hybrid forestry equipment is expected to lower carbon emissions and decrease dependence on fossil fuels. Additionally, sustainable harvesting technologies, such as smart sensors that assess tree health before cutting, will help minimize environmental impact and promote responsible forestry management.

The evolution of forestry harvesting tools has transformed the industry from labor-intensive manual work to highly efficient mechanized operations. With continued advancements in automation and sustainability, the future of forestry will likely focus on balancing productivity with environmental responsibility, ensuring forests remain a vital resource for future generations.

Need for Modern Harvesting Tools in Forestry Logging

1. Increased efficiency & productivity: Modern harvesting tools significantly increase efficiency and productivity in logging operations. Machines like harvesters and forwarders can perform multiple tasks such as cutting, delimbing, and processing logs within minutes, which speeds up the entire process. A single harvester can replace several manual workers, enabling higher daily output and more streamlined operations. This automation ensures that logging activities are completed swiftly and with precision.

2. Safety of workers: Worker safety is a major concern in forestry, as traditional logging methods involve physically demanding and dangerous tasks such as tree felling using chainsaws. Modern mechanized equipment reduces the need for manual labor, allowing operators to work from the safety of enclosed cabins. This minimizes exposure to hazards like falling trees, rough terrain, and harsh weather conditions, significantly reducing the risk of injuries and fatalities.

3. Sustainable & eco-friendly logging: Sustainability is a key consideration in modern forestry, and advanced harvesting tools contribute to eco-friendly logging practices. Precision cutting, guided by GPS and laser technology, helps minimize unnecessary tree loss and optimizes harvesting. Additionally, modern skidders and forwarders reduce soil compaction, preserving forest ecosystems. Advanced saws and chippers ensure maximum wood utilization, reducing waste and promoting responsible resource management.

4. Cost savings in the long run: Investing in modern harvesting tools results in significant cost savings over time. The need for fewer workers lowers labor costs, while fuel-efficient machinery reduces operational expenses. Modern equipment also experiences fewer breakdowns, as hydraulic and automated systems minimize maintenance downtime. These factors contribute to increased profitability and sustainability in logging operations.

5. Precision & smart technology: The integration of automation and smart technology has transformed forestry logging. Modern machines come equipped with automated controls for accurate cutting, reducing human error. Remote sensing and GPS technology optimize logging routes, minimizing unnecessary movement and fuel consumption. Additionally, smart sensors collect valuable data on log volume, tree species, and location, enabling better planning and resource management.

6. Common modern harvesting tools & machines: Several modern machines have become essential in forestry logging. Harvesters perform multiple functions, including cutting, delimbing, and processing logs. Forwarders transport logs efficiently without damaging the soil, while skidders drag logs from the felling site to loading areas. Feller bunchers enhance productivity by cutting multiple trees at once and stacking them neatly. AI-assisted chainsaws, featuring automatic tensioning and vibration reduction, further improve safety and precision in manual operations.

Modern Harvesting Tools in Forestry Logging Operations

The evolution of modern harvesting tools in forestry logging operations has been driven by the need for increased efficiency, safety, sustainability, and reduced environmental impact. These advanced tools integrate cutting-edge technology and engineering to improve the effectiveness of logging while ensuring that forest health is maintained, and

damage to ecosystems is minimized. The following is a detailed exploration of the most common modern tools used in forestry logging operations.

1. Mechanical harvesters: Mechanical harvesters are highly specialized machines designed to carry out multiple logging tasks, such as felling trees, delimbing, and bucking (cutting trees into logs). These machines are widely used in commercial timber production and are capable of working in a variety of terrains and conditions, including both flat and steep forested areas.

Harvesters typically feature a large hydraulic arm equipped with various cutting heads. These heads can saw down trees, remove their limbs, and segment the trunks into logs of specific lengths. The process is automated, and the operator controls the machinery from a cabin, enhancing both safety and operational efficiency.

2. Feller-Bunchers: Feller-bunchers are specialized machines designed to fell trees and gather them into a bunch. These machines are ideal for clearing larger areas of forest and accumulating trees in one spot for easier transportation and processing.

Feller-bunchers are equipped with a large cutting head that can grasp and cut a tree, holding it in a bunch for easy transport. After cutting one tree, the machine moves to the next, continuing to gather trees into one location. A skidder or another machine is then used to transport the bunch of logs.

3. Skidders: Skidders are powerful machines used to drag felled trees or logs from the forest to a landing area where they can be processed or loaded onto trucks. These machines are essential for efficiently moving logs over rugged terrain.

Skidders use either a cable or a hydraulic grapple system to pull logs from the forest. There are two primary types:

4. Chainsaws: Despite the rise of mechanized equipment, chainsaws remain widely used in modern forestry operations, particularly for smaller-scale tasks or selective cutting in areas where larger machines cannot operate. Chainsaws are portable, versatile, and essential tools for operators in the field.

A chainsaw is a handheld device that features a rotating chain with sharp teeth that cut through wood. It can be powered by gasoline or electricity, depending on the model. Chainsaws are primarily used for felling trees, cutting logs to specific lengths, and other smaller logging tasks.

5. Tree harvesting heads: Tree harvesting heads are attachments that can be fitted to mechanical harvesters to turn them into multi-functional machines capable of felling, delimbing, and bucking trees. These heads are crucial for enhancing the efficiency and precision of logging operations.

The harvesting head is hydraulically operated, using saws, knives, and rollers to cut trees, remove limbs, and segment trunks into logs of predetermined lengths. The entire operation is controlled by the harvester's operator, offering precise control over the cutting process.

6. Log trucks and trailers: Once logs are felled and processed, they need to be transported to processing sites such as sawmills. Modern log trucks and trailers are designed to efficiently handle large volumes of wood, making transportation easier and more cost-effective.

Log trucks are equipped with hydraulic systems to load and unload logs. They often feature specialized trailers designed to carry multiple logs at once. Some trucks even have built-in cranes for self-loading, reducing the need for additional equipment.

The development of modern harvesting tools in forestry logging operations has significantly transformed the industry. The integration of technology has made logging more efficient, safer, and more sustainable. From mechanical harvesters and feller-bunchers to chainsaws and tree harvesting heads, these tools are designed to maximize productivity while minimizing environmental impacts. As forestry operations continue to evolve, innovations such as precision forestry and automation promise to further enhance the sustainability and efficiency of logging practices. These advances not only ensure a more effective harvest but also support the long-term health and vitality of forests.

Benefits of Using Modern Harvesting Tools

The use of modern harvesting tools has revolutionized the agricultural industry, providing numerous advantages that enhance productivity, reduce costs, and improve crop quality. Traditional manual harvesting methods are often labor-intensive, time-consuming, and prone to inefficiencies. In contrast, modern tools such as combine harvesters, reapers, and threshers streamline the process, making farming more profitable and sustainable (Batte, M. T., & Arends, R. J., 2018)

1. Increased efficiency and speed: One of the most significant benefits of modern harvesting tools is their ability to complete the harvesting process quickly and efficiently. Traditional methods require substantial manual labor and take a long time to cover large agricultural fields. In contrast, modern machinery can harvest vast areas in a much shorter time, ensuring that crops are collected at the right stage of maturity. This efficiency helps prevent losses caused by weather conditions, pest attacks, or delayed harvesting. By accelerating the harvesting process, farmers can maintain a steady supply of produce to meet market demands (Kassam *et al.*, 2018)

2. Reduced labor costs: Mechanized harvesting significantly reduces the dependence on manual labor, which is often expensive and scarce, especially during peak seasons. Many modern harvesting machines are capable of performing multiple tasks simultaneously, replacing the need for a large workforce. This reduction in labor requirements helps farmers save on wages and other associated costs. Additionally, in regions facing labor shortages, modern tools enable continuous harvesting without disruption, ensuring that the farming process remains smooth and efficient.

3. Improved precision and reduced crop losses: Modern harvesting tools are designed to ensure precise cutting and collection of crops, minimizing damage and waste. Traditional methods often lead to uneven cutting, resulting in grain loss or damage to delicate produce. Advanced machinery, such as precision harvesters, reduces such inefficiencies by maintaining uniformity in cutting height and collecting grains or produce with minimal spillage. As a result, farmers can maximize their yield, improving overall productivity and profitability (Siry and Cubbage, 2021).

4. Better quality produce: The quality of harvested crops plays a crucial role in determining their market value. Manual harvesting methods can sometimes cause contamination due to improper handling, exposure to dirt, or excessive delays in collection. Modern tools, on the other hand, ensure that harvested crops are handled with care, reducing contamination risks and post-harvest losses. Automated systems help maintain the freshness and nutritional value of produce, making it more attractive to buyers and increasing the chances of higher earnings.

5. Reduced physical strain on farmers: Traditional harvesting methods require farmers to spend long hours in the field, often in extreme weather conditions, performing physically demanding tasks such as cutting, bundling, and transporting crops. This repetitive labor can lead to fatigue, musculoskeletal disorders, and other health issues. By adopting modern harvesting tools, farmers can significantly reduce physical exertion and focus on other essential farm management activities. This improvement in working conditions enhances overall well-being and allows for more sustainable farming practices.

6. Suitability for large-scale farming: Mechanized harvesting is particularly beneficial for large-scale farming operations where vast areas of land need to be harvested efficiently. Commercial farms require timely and systematic harvesting to meet supply chain demands. Modern tools make large-scale harvesting feasible by ensuring speed, accuracy, and consistency. This mechanization allows commercial farmers to maintain high production levels, meet market deadlines, and minimize post-harvest losses.

7. Adaptability to different crops: Modern harvesting tools are designed to cater to various types of crops, making them versatile and adaptable. Equipment such as combine harvesters can be adjusted for use in harvesting grains like wheat, rice, and maize, while specialized tools like sugarcane harvesters and fruit-picking machines cater to specific agricultural needs. For instance, tree shakers are used for harvesting fruits like almonds and olives, ensuring minimal damage while improving collection efficiency. This adaptability allows farmers to choose machinery that best suits their crop type, leading to optimized harvesting processes.

8. Environmental benefits: Many modern harvesting machines are designed with eco-friendly features, helping to reduce environmental impact. Advanced fuel-efficient engines minimize carbon emissions, and some equipment even operates on renewable energy sources. Additionally, precision harvesting reduces unnecessary crop destruction and prevents soil degradation, ensuring sustainable land use. By adopting modern tools, farmers can contribute to environmental conservation while maintaining high productivity levels.

9. Integration with smart farming technologies: The advancement of agricultural technology has led to the development of harvesting machines equipped with smart farming features such as GPS navigation, sensors, and automation systems. These features enable farmers to monitor harvesting operations in real time, collect data on crop conditions, and make informed decisions to improve efficiency. Precision harvesting, guided by automation and data analysis, ensures optimal resource utilization, reduces input costs, and maximizes yield output. Such technological integration is transforming modern agriculture into a more data-driven and efficient industry.

Challenges and Future Prospects of Modern Tools in Forestry Logging Operations

1. High initial investment costs: The adoption of modern forestry logging tools such as harvesters, forwarders, and skidders requires a significant capital investment. These advanced machines, while increasing efficiency, are expensive to purchase and maintain. Small-scale logging operators, who form a substantial portion of the industry, often struggle to afford these technologies. The high upfront cost serves as a major barrier, limiting access to improved logging methods and preventing widespread modernization within the sector (Galloway, J. N., & Townsend, S. A. (2020)

2. Environmental concerns: One of the major challenges of mechanized logging is its impact on the environment. The use of heavy machinery in forest areas can lead to soil compaction, affecting water absorption and root growth. Additionally, mechanized operations may contribute to habitat destruction, thereby endangering local biodiversity. Increased carbon emissions from fuel-powered equipment further exacerbate climate change concerns. Achieving a balance between operational efficiency and sustainable forest management remains a critical issue that must be addressed.

3. Lack of skilled workforce: Operating modern forestry equipment requires specialized training and technical knowledge. Unfortunately, many logging regions, particularly in developing countries, lack adequate training facilities for machine operators. This gap in skills results in inefficient machinery usage, frequent breakdowns, and potential safety hazards. Without proper training programs, the full potential of advanced logging tools remains underutilized, and the risk of accidents in logging operations increases.

4. Infrastructure limitations: The effectiveness of modern logging tools is highly dependent on supporting infrastructure such as roads and power supply. In remote forested regions, poor road networks make it difficult to transport heavy machinery, thereby reducing operational efficiency. Additionally, many modern machines rely on electricity or advanced fuel systems, and the lack of reliable power sources in some areas further complicates their adoption. Improving infrastructure is essential to maximize the benefits of mechanized logging operations.

5. Maintenance and spare parts availability: Modern logging machinery requires frequent maintenance to function optimally. However, access to spare parts and servicing facilities is often limited, particularly in remote logging areas. Delays in obtaining necessary repairs can lead to extended downtime, affecting productivity and profitability. Furthermore, the high cost of spare parts and technical servicing adds another financial burden to loggers, making maintenance a significant challenge.

6. Regulatory and compliance issues: Forestry operations are subject to stringent environmental and safety regulations. Compliance with sustainable logging certifications, such as the Forest Stewardship Council (FSC) guidelines, requires significant adjustments in operational practices. Some modern machinery may not meet regulatory standards, necessitating costly modifications or replacements. Moreover, fluctuating government policies and international environmental agreements can create uncertainty in the adoption of advanced logging tools.

7. Impact on traditional logging communities: The mechanization of forestry operations has significant socio-economic implications, particularly for traditional logging communities. The introduction of automated machinery reduces the need for manual labor, potentially leading to job losses among workers who rely on logging for their livelihood. The transition to mechanized systems must be managed carefully to prevent economic displacement and ensure that affected workers are provided with alternative employment opportunities or retraining programs.

Future Prospects of Modern Tools in Forestry Logging

1. Adoption of automation & AI: The future of forestry logging is increasingly being shaped by automation and artificial intelligence (AI). Autonomous logging equipment and AI-driven decision-making tools are being developed to enhance efficiency and safety. Drones are being used for forest monitoring, helping in resource planning and environmental assessment. These advancements not only improve productivity but also reduce human involvement in high-risk operations, thereby enhancing worker safety.

2. Eco-friendly and precision logging: Sustainable logging practices are becoming a priority, with modern tools enabling precision logging techniques. Technologies such as GPS-guided machinery and LiDAR-based forest mapping allow for selective logging, reducing unnecessary tree removal and minimizing environmental impact. By integrating these technologies, forestry operations can optimize resource use while maintaining ecological balance, supporting long-term sustainability.

3. Electrification and sustainable machinery: As industries worldwide move toward greener alternatives, the development of electric and hybrid forestry machinery is gaining momentum. These machines reduce dependency on fossil fuels, lowering carbon emissions and promoting sustainability. The introduction of battery-powered equipment is expected to revolutionize logging operations, offering a cleaner and more efficient alternative to traditional fuel-powered machinery.

4. Integration of IoT and smart sensors: The incorporation of the Internet of Things (IoT) in forestry logging operations allows real-time monitoring of machinery performance. Smart sensors can provide predictive maintenance alerts, helping prevent unexpected breakdowns and optimizing machine lifespan. IoT-driven systems enhance operational efficiency, reduce downtime, and contribute to cost savings for logging companies.

5. Improved training and workforce development: To bridge the skill gap in forestry mechanization, investments in workforce training are essential. Governments and industry stakeholders are increasingly focusing on expanding training programs for modern logging equipment. By equipping workers with the necessary technical skills, the industry can ensure the effective use of advanced machinery while improving safety standards.

6. Better policy support & incentives: The successful integration of modern tools in forestry logging requires supportive policies and incentives. Governments and environmental organizations are promoting responsible mechanization through financial incentives, subsidies, and tax benefits for sustainable logging practices. Encouraging the adoption of eco-friendly technology through policy support will facilitate a smoother transition to modernized forestry operations.

7. Enhanced safety measures: Worker safety is a critical concern in forestry logging, and modern technology is playing a key role in mitigating risks. The development of robotic loggers and remote-controlled equipment reduces human

exposure to hazardous environments. Enhanced safety measures, such as real-time monitoring systems and automated emergency response mechanisms, are expected to further improve workplace safety in the logging industry.

Conclusion

While modern tools in forestry logging bring significant advantages in terms of efficiency, productivity, and safety, various challenges must be addressed to ensure their successful implementation. High costs, environmental concerns, regulatory complexities, and workforce limitations remain key hurdles in the widespread adoption of mechanized logging. However, with advancements in automation, AI, electrification, and precision logging techniques, the future of forestry operations looks promising. By fostering sustainable practices, investing in workforce development, and implementing supportive policies, the industry can achieve a more responsible and technologically advanced approach to logging. The continued evolution of modern tools will play a crucial role in shaping the future of sustainable forestry management.

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Need for a New National Forest Policy in India: A Roadmap for Sustainable Forest Management

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Introduction

Forests have always been the foundation of human civilization, providing food, water, shelter, medicines, fuel, and countless ecosystem services that sustain life on Earth. In India, forests are deeply intertwined with the country's ecological security, cultural heritage, and economic development. Stretching from the snow-clad Himalayas to the tropical rainforests of the Western Ghats and the mangrove ecosystems of the Sundarbans, India's forests support an extraordinary diversity of life while serving as natural infrastructure that regulates climate, conserves soil and water, and sustains millions of livelihoods. As the world grapples with the twin crises of climate change and biodiversity loss, forests have emerged as one of the most effective nature-based solutions for ensuring environmental sustainability and human well-being.

Globally, forests cover about 4.06 billion hectares, representing approximately 31% of the Earth's land surface, and they contain nearly 662 billion tonnes of carbon in living biomass, deadwood, litter, and forest soils. These forests absorb enormous quantities of atmospheric carbon dioxide through photosynthesis, thereby slowing the accumulation of greenhouse gases responsible for global warming. The Food and Agriculture Organization (FAO) estimates that forests remove several billion tonnes of carbon dioxide from the atmosphere every year, making them indispensable in global efforts to mitigate climate change. Beyond carbon sequestration, forests regulate rainfall patterns, maintain regional hydrological cycles, reduce soil erosion, recharge groundwater, moderate local temperatures, and provide habitat for nearly 80% of the world's terrestrial biodiversity. These ecosystem services, although often invisible in conventional economic assessments, contribute trillions of dollars annually to the global economy.

India occupies only 2.4% of the world's geographical area, yet it harbours nearly 8% of the world's recorded biodiversity, making it one of the world's 17 megadiverse countries. Its forests encompass a remarkable variety of ecosystems, including tropical evergreen forests, deciduous forests, thorn forests, alpine forests, mangroves, and island ecosystems. These habitats support thousands of species of flowering plants, mammals, birds, reptiles, amphibians, insects, fungi, and microorganisms. Many globally threatened species such as the Bengal tiger, Asian elephant, one-horned rhinoceros, lion-tailed macaque, Nilgiri tahr, red panda, snow leopard, and Great Indian Bustard depend directly or indirectly on healthy forest ecosystems for their survival. Conserving these forests is therefore essential not only for protecting biodiversity but also for maintaining ecological balance and ensuring long-term environmental resilience.

The significance of forests extends well beyond biodiversity conservation. Nearly 275 million people in India depend directly or indirectly on forests for their livelihoods, including a large proportion of tribal and other forest-dependent communities. Forests provide fuelwood, fodder, bamboo, medicinal plants, honey, resins, gums, fibres, fruits, edible leaves, mushrooms, and numerous Non-Timber Forest Products (NTFPs) that contribute significantly to household income and nutritional security. Traditional knowledge associated with forest ecosystems has been passed down through generations, enabling communities to sustainably utilize natural resources while conserving biodiversity. Forests also support agriculture by regulating local climate, protecting watersheds, conserving pollinators, and improving soil fertility. Thus, the relationship between forests and rural livelihoods is both ecological and socio-economic.

The importance of forests has become even more evident in the context of global climate change. According to the Intergovernmental Panel on Climate Change (IPCC), the Earth's average surface temperature has already increased by approximately 1.1°C above pre-industrial levels, resulting in more frequent and intense heatwaves, floods, droughts, cyclones, and wildfires. India has witnessed several of these climate-induced events in recent years, affecting agriculture, water resources, infrastructure, biodiversity, and public health. Forest ecosystems help reduce these impacts by storing carbon, regulating microclimates, stabilizing slopes, reducing flood intensity, and enhancing the resilience of both natural ecosystems and human communities. Consequently, conserving and expanding forest cover is increasingly recognized as one of the most cost-effective strategies for climate change mitigation and adaptation.

Recognizing the critical role of forests in addressing global environmental challenges, India has made several ambitious international commitments. Under the Paris Agreement, the country has pledged to create an additional carbon sink of 2.5–3.0 billion tonnes of CO_2 equivalent through increased forest and tree cover by 2030. India is also a signatory to the Convention on Biological Diversity (CBD) and supports the Kunming–Montreal Global Biodiversity Framework, which aims to halt biodiversity loss and restore degraded ecosystems. Furthermore, initiatives such as the Green India Mission, National Agroforestry Policy (2014), Mission LiFE (Lifestyle for Environment), and the Bonn Challenge demonstrate India's

commitment to restoring degraded landscapes, enhancing ecosystem services, and promoting sustainable natural resource management. Achieving these commitments, however, will require a robust and forward-looking forest policy that reflects current scientific knowledge and emerging environmental realities.

Recent assessments highlight both encouraging progress and continuing challenges. According to the India State of Forest Report (ISFR) 2023, India's forest cover stands at 715,343 km^2, accounting for 21.76% of the country's geographical area, while tree cover outside recorded forests contributes an additional 112,014 km^2 (3.41%), resulting in a combined forest and tree cover of 25.17%. The report also estimates that India's forests currently store approximately 30.43 billion tonnes of CO_2 equivalent carbon, reflecting the growing importance of forests in climate mitigation. At the same time, however, several forest ecosystems continue to experience degradation due to habitat fragmentation, invasive alien species, forest fires, unplanned infrastructure development, mining, encroachments, pollution, and the increasing impacts of climate change. In many regions, improvements in forest area have not always been accompanied by corresponding improvements in forest quality, biodiversity, or ecological integrity. This underscores the need to shift the focus from merely increasing forest area to enhancing ecosystem health and resilience.

India's forest governance has evolved considerably over the past century through successive National Forest Policies introduced in 1894, 1952, and 1988. Among these, the National Forest Policy of 1988 marked a historic transition by placing ecological stability, biodiversity conservation, and community participation above commercial timber production. The policy promoted social forestry, participatory forest management, and environmental conservation at a time when concerns over deforestation and environmental degradation were rapidly increasing. Its principles continue to guide forest management across the country and have significantly influenced programmes such as Joint Forest Management and community-based conservation.

However, nearly four decades have passed since the adoption of the 1988 policy, during which the environmental, social, economic, and technological landscape has changed dramatically. The policy was formulated before the emergence of global climate agreements, carbon markets, ecosystem restoration initiatives, advanced geospatial technologies, artificial intelligence, digital forest monitoring, large-scale agroforestry programmes, and contemporary concepts such as ecosystem services, nature-based solutions, and payment for ecosystem services. Today, forest management requires an integrated approach that addresses climate resilience, biodiversity conservation, sustainable livelihoods, green economic development, and technological innovation simultaneously.

A new National Forest Policy is therefore not merely desirable but essential for India's future. Such a policy must respond to contemporary environmental challenges while balancing ecological conservation with developmental aspirations. It should recognize forests as dynamic ecosystems that provide multiple ecological, economic, and social benefits, promote science-based decision-making, encourage community participation, strengthen the role of Trees Outside Forests and agroforestry, harness modern technologies for monitoring and governance, and support India's commitments toward climate action and sustainable development. By adopting a holistic and forward-looking policy framework, India can ensure that its forests continue to provide ecological security, support millions of livelihoods, conserve biodiversity, and contribute meaningfully to a resilient and sustainable future.

Forest Restoration, Livelihood Security and Building a Sustainable Forest-Based Economy

Forests are dynamic ecosystems that continuously undergo natural changes due to ecological succession, climatic variations, and disturbances. However, rapid human-induced pressures over the past several decades have accelerated forest degradation across many parts of India. Unsustainable extraction of forest resources, shifting cultivation in vulnerable landscapes, unplanned infrastructure development, mining, overgrazing, forest fires, invasive alien species, and climate change have reduced the ecological integrity of many forest ecosystems. Although satellite assessments indicate that India's forest and tree cover has remained relatively stable and has shown gradual improvement in some regions, the quality of forests has not improved uniformly. Dense natural forests in several landscapes have been fragmented or degraded, reducing their ability to provide critical ecosystem services such as carbon sequestration, biodiversity conservation, watershed protection, and climate regulation. These realities underscore the urgent need for a National Forest Policy that prioritizes ecological restoration alongside conservation.

Forest restoration today is no longer viewed simply as planting trees. Modern restoration emphasizes rebuilding ecosystem structure, restoring ecological processes, improving biodiversity, and enhancing the resilience of landscapes against climate change. The United Nations Decade on Ecosystem Restoration (2021–2030) has highlighted restoration as one of the most effective strategies for addressing climate change, biodiversity loss, and land degradation simultaneously. Scientific studies demonstrate that restoring degraded forests enhances soil fertility, improves groundwater recharge, stabilizes slopes, reduces flood risks, and creates habitats for wildlife. Restored forests also sequester substantial amounts of atmospheric carbon while improving the livelihoods of local communities through sustainable production of timber and non-timber forest products.

India has emerged as one of the leading countries supporting global restoration initiatives. Under the Bonn Challenge, the country has pledged to restore 26 million hectares of degraded and deforested land by 2030, making it one of the world's largest landscape restoration commitments. Programmes such as the Green India Mission, National Afforestation

Programme, Compensatory Afforestation Fund Management and Planning Authority (CAMPA), watershed development projects, and state-level afforestation programmes have contributed significantly to increasing vegetation cover. Nevertheless, restoration efforts often focus on the number of trees planted rather than on long-term ecological recovery. A future National Forest Policy should therefore promote scientifically planned ecological restoration that emphasizes native species, genetic diversity, site suitability, long-term monitoring, and community participation rather than short-term plantation targets alone.

An important debate in contemporary forestry concerns the choice between monoculture plantations and ecologically diverse native forests. Monoculture plantations of fast-growing species may provide timber, pulpwood, or fuelwood within a short period, but they generally support lower biodiversity, store less resilient carbon stocks, and offer fewer ecosystem services than natural mixed forests. In contrast, restoration using indigenous tree species improves habitat quality, enhances pollinator diversity, supports soil microorganisms, and increases resilience against pests, diseases, and climatic extremes. Native forests also sustain traditional livelihoods by providing diverse non-timber forest products and maintaining ecological interactions that have evolved over centuries. Therefore, a revised forest policy should clearly distinguish commercial plantations from ecological restoration and prioritize the recovery of degraded natural ecosystems wherever feasible.

The importance of forests extends far beyond ecological functions because they directly support the livelihoods of millions of Indians. According to estimates by the Ministry of Environment, Forest and Climate Change and several national studies, nearly 275 million people depend wholly or partially on forests for subsistence and income. This includes a large proportion of Scheduled Tribes and other forest-dependent communities living in and around forest landscapes. For these communities, forests are not merely sources of raw materials but also repositories of culture, traditional knowledge, spirituality, and identity. Seasonal collection of forest produce provides food security, nutrition, employment, and income, especially during agricultural lean periods. Consequently, sustainable forest management must balance biodiversity conservation with livelihood security, ensuring that conservation efforts enhance rather than restrict the well-being of local communities.

Among the various livelihood resources provided by forests, Non-Timber Forest Products (NTFPs) occupy a central position. NTFPs include bamboo, cane, medicinal plants, tendu leaves, honey, gums, resins, lac, mahua flowers, sal seeds, edible mushrooms, wild fruits, aromatic plants, fibres, dyes, and numerous other biological resources. These products contribute significantly to household income in rural and tribal areas while supplying raw materials to several cottage and forest-based industries. India possesses one of the richest diversities of medicinal and aromatic plants in the world, many of which are harvested from forest ecosystems and form the backbone of traditional healthcare systems such as Ayurveda, Siddha, and Unani. Sustainable harvesting and scientific management of these resources are therefore essential for both biodiversity conservation and rural development.

Despite their enormous economic importance, the value of many ecosystem services and NTFPs remains inadequately recognized in national planning. Forest-dependent communities often receive only a small share of the final market value because of weak market linkages, inadequate processing facilities, lack of storage infrastructure, fluctuating prices, and dependence on intermediaries. A modern National Forest Policy should strengthen value addition, local processing, producer cooperatives, digital marketing platforms, certification systems, and fair pricing mechanisms. Promoting small-scale forest enterprises based on sustainably harvested NTFPs can substantially improve rural incomes while encouraging conservation of natural forests.

Traditional ecological knowledge represents another invaluable asset that deserves greater recognition in future forest governance. Indigenous and tribal communities have developed sophisticated systems of forest management over generations, including sustainable harvesting practices, sacred groves, community protection mechanisms, seasonal resource use, and conservation of culturally significant species. Such knowledge often complements modern scientific approaches and contributes to ecosystem resilience. Integrating traditional knowledge with contemporary forest science can improve restoration programmes, biodiversity conservation, fire management, and climate adaptation strategies. A revised National Forest Policy should therefore promote collaborative management models that respect local knowledge while strengthening scientific research and adaptive management.

The relationship between forests and agriculture has also evolved considerably in recent decades. Agroforestry, farm forestry, and integrated farming systems demonstrate that productive landscapes can simultaneously support food production, biodiversity conservation, and carbon sequestration. Trees growing on farms improve soil fertility through nutrient cycling, reduce wind erosion, increase water infiltration, moderate microclimatic conditions, and provide diversified income through timber, fruits, fodder, and fuelwood. These multifunctional landscapes reduce pressure on natural forests while strengthening the resilience of agricultural systems to climate variability. Integrating agroforestry more explicitly into the National Forest Policy would help bridge the traditional divide between agriculture and forestry, creating a more holistic approach to sustainable land management.

Forests are also increasingly recognized as important contributors to India's emerging green economy. Beyond timber production, forests provide ecosystem services that support agriculture, hydropower generation, tourism, pharmaceutical industries, climate regulation, and water security. Nature-based tourism, ecotourism, wildlife tourism,

bamboo industries, medicinal plant cultivation, carbon markets, and ecosystem restoration projects have generated new employment opportunities while encouraging conservation. The global transition toward low-carbon development has further increased the economic value of forests as providers of carbon sequestration, renewable raw materials, and bio-based products. According to international estimates, investments in ecosystem restoration generate multiple times their initial economic value through improved ecosystem services, reduced disaster risks, enhanced agricultural productivity, and employment generation. Recognizing forests as natural capital rather than merely as sources of extractive products can significantly strengthen India's sustainable development pathway.

An emerging opportunity closely linked with the green economy is the development of carbon markets and Payment for Ecosystem Services (PES). Healthy forests provide services such as carbon storage, watershed protection, soil conservation, biodiversity conservation, and climate regulation that benefit society as a whole. However, these services are rarely reflected in conventional markets. Payment for Ecosystem Services creates mechanisms through which individuals, industries, or governments compensate landowners and communities for maintaining or enhancing ecosystem functions. Similarly, voluntary and compliance carbon markets provide financial incentives for activities that increase carbon sequestration through afforestation, reforestation, agroforestry, and improved forest management. A forward-looking National Forest Policy should establish clear institutional frameworks for carbon accounting, benefit sharing, monitoring, and equitable participation of local communities in carbon finance mechanisms. Such reforms would create new livelihood opportunities while supporting India's climate commitments.

The future of India's forests also depends on strengthening the role of youth, women, researchers, entrepreneurs, and local institutions in forest-based development. Women constitute a major workforce in fuelwood collection, fodder gathering, NTFP harvesting, nursery raising, and community forestry activities. Their participation in decision-making has consistently improved the effectiveness of conservation programmes. Similarly, educated rural youth are increasingly adopting agroforestry, bamboo cultivation, ecotourism, nursery enterprises, medicinal plant cultivation, and digital forest-based businesses. By providing technical training, entrepreneurship support, access to finance, and market connectivity, a new forest policy can transform forests into engines of sustainable rural development while reducing migration and improving livelihood security.

Ultimately, forest restoration and livelihood security should not be viewed as competing objectives but as complementary pillars of sustainable forest management. Healthy forests support prosperous communities, and empowered communities are often the most effective custodians of forests. A modern National Forest Policy must therefore move beyond the traditional focus on protection alone and embrace an integrated approach that combines ecological restoration, biodiversity conservation, sustainable livelihoods, green economic growth, and climate resilience. Such a policy would strengthen India's ability to meet national development priorities while safeguarding its invaluable natural heritage for future generations.

Why India Needs a New National Forest Policy?

1. Climate Change and Carbon Sequestration:

a. Increasing frequency of climate extremes.
b. India's commitments under the Paris Agreement.
c. Role of forests as carbon sinks.
d. Net Zero and carbon neutrality goals.

2. Biodiversity Conservation:

a. Habitat degradation and fragmentation.
b. Conservation of threatened flora and fauna.
c. Landscape-level ecosystem management.

3. Trees Outside Forests (TOF):

a. Expanding tree cover beyond recorded forests.
b. Agroforestry and urban forestry.
c. Role of farmers and private lands.

4. Forest Restoration:

a. Restoration of degraded forests.
b. Afforestation and ecological restoration.
c. Native species versus monoculture plantations.

5. Livelihood Security:

a. Forest-dependent communities.
b. Tribal livelihoods and traditional knowledge.
c. Sustainable harvesting of Non-Timber Forest Products (NTFPs).

Emerging Challenges

1. Forest fires
2. Invasive alien species
3. Human–wildlife conflict
4. Encroachments
5. Mining and infrastructure development
6. Urbanization
7. Illegal logging
8. Water scarcity
9. Forest degradation.

Integrating Forests with National Development Goals

1. Climate resilience
2. Green economy
3. Sustainable Development Goals (SDGs)
4. Green India Mission
5. Mission LiFE
6. Land Degradation Neutrality
7. Bioeconomy and ecosystem services.

Strengthening Community Participation

1. Joint Forest Management (JFM)
2. Community Forest Resource (CFR) management
3. Women and youth participation
4. Benefit-sharing mechanisms
5. Participatory forest governance.

Policy Priorities for the Future

1. Increase forest and tree cover.
2. Promote Trees Outside Forests.
3. Incentivize agroforestry.
4. Strengthen biodiversity conservation.
5. Enhance ecosystem restoration.
6. Develop payment for ecosystem services (PES).
7. Improve forest governance and transparency.
8. Encourage public–private partnerships.
9. Promote sustainable forest-based enterprises.
10. Strengthen research, education, and capacity building.

Emerging Challenges in Forest Governance

India's forests are facing a wide range of environmental and socio-economic challenges that threaten their ecological integrity and long-term sustainability. Climate change has intensified the frequency of droughts, floods, cyclones, heat waves, and forest fires, altering species composition and reducing the resilience of forest ecosystems. The increasing incidence of forest fires in many parts of the Himalayas, Central India, and the Western Ghats has resulted in loss of biodiversity, degradation of soil quality, and release of significant amounts of greenhouse gases into the atmosphere. Rising temperatures and changing rainfall patterns are also affecting natural regeneration, flowering, fruiting, and wildlife habitats.

Habitat fragmentation caused by roads, railways, mining, dams, transmission lines, and urban expansion has become another major concern. Continuous forests are increasingly being divided into smaller patches, restricting wildlife movement and reducing genetic diversity. This has contributed to a rise in human–wildlife conflicts involving elephants, tigers, leopards, bears, and other wild animals, leading to crop damage, livestock losses, and occasional human casualties. Conserving wildlife today therefore requires maintaining ecological corridors and adopting landscape-level planning rather than focusing only on protected areas.

Invasive alien species such as Lantana camara, Prosopis juliflora, Chromolaena odorata, and Parthenium hysterophorus have spread rapidly across many forest ecosystems. These species suppress native vegetation, reduce fodder availability, increase fire hazards, and negatively affect biodiversity. Simultaneously, illegal logging, encroachments, overgrazing, unsustainable extraction of forest resources, and developmental pressures continue to degrade forest ecosystems. The combined impact of these challenges highlights the need for a modern National Forest Policy that integrates biodiversity conservation, climate adaptation, ecological restoration, and sustainable resource management into a single framework.

Technological Innovations in Forest Governance

Modern technology has transformed the way forests are monitored, managed, and conserved. Remote Sensing and Geographic Information Systems (GIS) enable continuous assessment of forest cover, land-use changes, biomass, and forest health over large geographical areas. The India State of Forest Report (ISFR) is prepared using satellite imagery integrated with extensive field observations, providing reliable information for policy planning and decision-making.

Emerging technologies such as drones, LiDAR, Global Navigation Satellite Systems (GNSS), Artificial Intelligence (AI), and Machine Learning are making forest management more accurate and efficient. Drones are increasingly used for forest fire surveillance, wildlife monitoring, plantation assessment, and mapping inaccessible areas. AI-based models help predict forest fire risks, identify illegal encroachments, detect pest outbreaks, and analyse satellite data rapidly. Digital forest inventories and mobile applications allow frontline forest staff to collect real-time information on tree growth, biodiversity, forest offences, and restoration activities, improving transparency and decision-making.

Technology is also playing an important role in climate change mitigation. Advanced carbon accounting tools help estimate carbon stocks, monitor carbon sequestration, and support participation in carbon markets and REDD+ initiatives. Geographic information systems combined with climate models assist in identifying degraded landscapes suitable for restoration and planning climate-resilient plantations using appropriate native species. Digital platforms also facilitate citizen participation by enabling communities to report forest fires, illegal felling, wildlife sightings, and habitat degradation through mobile applications.

A future National Forest Policy should encourage greater investment in geospatial technologies, artificial intelligence, digital databases, and decision-support systems while strengthening the technical capacity of forest departments. Integrating scientific innovations with traditional ecological knowledge and community participation will improve forest governance, enhance transparency, and ensure sustainable management of India's forest resources in the face of rapidly changing environmental conditions.

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Hybrid Rice: Unlocking Nature's Yield Potential

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Abstract
Hybrid rice is one of the most important advancements in modern rice breeding, utilizing hybrid vigor (heterosis) to produce plants with superior yield, better adaptability and greater resilience than conventional rice varieties. As the demand for food continues to increase while cultivable land remains limited, hybrid rice has emerged as an effective strategy for enhancing rice production and supporting global food security. This article discusses the fundamental principles of hybrid rice, its objectives, the major systems used for hybrid seed production, current challenges and future opportunities. On-going progress in breeding techniques and seed production technologies is expected to facilitate the development of high-yielding, climate-resilient and resource-efficient hybrid rice varieties, thereby promoting sustainable agriculture and helping meet the food requirements of a growing population.

Keywords: Hybrid rice, heterosis, CGMS, EGMS, CHA, yield potential, inbred, food security.

Introduction
Rice is the primary food source for more than half of the world's population (Muthayya *et al*., 2014), making its sustainable production essential for global food security. As the demand for rice keeps growing because of population increase and less farmland, boosting crop productivity has become a significant challenge. Hybrid rice has appeared as a hopeful solution by using heterosis (hybrid vigor) to create plants with higher yields, improved adaptability, and better resilience compared to regular rice varieties.

Developed through plant breeding methods hybrid rice brings together good qualities from chosen parent plants. This results in grain production and better growth, in different environments. Hybrid rice combines traits from carefully selected lines giving it higher grain production. It also performs under various growing conditions. By increasing productivity without proportionally expanding cultivated land, hybrid rice plays a vital role in ensuring food security, improving farmers' incomes and promoting sustainable agriculture. Advancements in hybrid rice breeding continue to enhance the development of superior rice cultivars with increased productivity, greater resilience to environmental stresses and improved adaptability to diverse and changing climatic conditions.

What is Hybrid Rice?
Hybrid rice is the first-generation (F_1) offspring produced by crossing two genetically diverse rice parents with desirable traits. Hybrid rice generally exhibits higher grain yield, better adaptability and improved tolerance to biotic and abiotic stresses. Exploiting heterosis is the foundation of hybrid rice technology, enabling significant yield improvement over conventional varieties. It is developed to exploit heterosis (hybrid vigor), resulting in superior performance compared with conventional inbred rice varieties.

Difference Between Hybrid and Inbred Rice

Hybrid Rice	Inbred Rice
Produced by crossing two genetically distinct parents.	Developed through repeated self-pollination and selection.
Exhibits hybrid vigor (heterosis).	Does not exhibit hybrid vigor.
Produces 20–30% higher yield under suitable management (Virmani *et al*., 2003).	Generally has lower yield potential than hybrids.
Farmers need to purchase fresh hybrid seed each season to maintain performance.	Farmers can save seed from one season to the next with little loss of varietal purity.
Requires specialized hybrid seed production systems.	Seed production is simple through self-pollination.

Objectives of Hybrid Rice Cultivation
1. To enhance rice productivity by utilizing the benefits of hybrid vigor (heterosis).
2. To contribute to global food security by increasing rice production without expanding the cultivated area.

3. To improve the profitability and livelihoods of farmers through higher and more stable yields.

4. To develop rice varieties with improved adaptability to changing climatic conditions and greater tolerance to drought, heat, flooding, salinity and other environmental stresses.

5. To strengthen resistance against major pests and diseases, thereby minimizing yield losses and reducing dependence on crop protection measures.

6. To maximize the efficient use of essential resources such as land, water and plant nutrients for sustainable crop production.

7. To encourage environmentally sustainable rice cultivation by producing higher yields from existing agricultural land.

8. To address the rising demand for rice driven by population growth and increasing food requirements.

Hybrid Rice Production Systems

Feature	Three-line	Two-line	CHA-based	One-line
Sterility mechanism	CGMS	EGMS	Chemical induction	Apomixis
Parents required	A + B + R	EGMS + Pollinator	Female + Male	Single genotype
Maintainer line	✓ Required	✗ Not required	✗ Not required	✗ Not required
Restorer gene required	✓ Yes	Not always	✗ No	✗ No
Commercial status	Widely adopted	Limited commercial use	Mainly research	Experimental

Challenges and Limitations of Hybrid Rice

1. Hybrid seeds are more expensive than conventional inbred rice seeds due to the complexity of seed production.

2. Farmers must purchase new hybrid seed every cropping season, as saved seed does not maintain the same yield potential.

3. Hybrid seed production requires specialized techniques, skilled labour and strict isolation to ensure genetic purity.

4. Grain quality characteristics such as size, shape, aroma and cooking quality may differ among hybrids, influencing consumer acceptance.

5. Many hybrid rice varieties perform best under optimum crop management, including adequate irrigation, fertilizer application and pest management.

6. Some hybrids may perform well only in specific agro-climatic regions, requiring location-specific evaluation before large-scale cultivation.

7. Timely access to quality hybrid seed can be a challenge in some rice-growing areas.

Future Prospects of Hybrid Rice

1. Development of climate-resilient hybrids with improved tolerance to changing environmental conditions.

2. Enhancement of grain quality by improving cooking, eating, milling and nutritional characteristics.

3. Breeding for multiple stress tolerance, including resistance to drought, heat, salinity, submergence and other abiotic stresses.

4. Integration of advanced breeding technologies, such as molecular breeding, genomic selection and gene editing to accelerate hybrid development.

5. Improvement of hybrid seed production technologies to increase seed quality, reduce production costs and ensure timely seed availability.

6. Development of high-yielding and resource-efficient hybrids with better nutrient and water-use efficiency.

7. Greater adoption of hybrid rice through farmer awareness, improved seed distribution and supportive government policies.

8. Strengthening global food security by developing sustainable hybrid rice varieties capable of meeting the increasing demand for rice.

Potential Research Opportunities

1. Discovery of new CMS sources and fertility restorer genes.

2. Development of superior chemical hybridizing agents (CHAs).

3. Exploitation of apomixis for one-line hybrid systems.

4. Application of genomic selection, gene editing and artificial intelligence in hybrid breeding.

5. Improvement of hybrid seed production efficiency and reduction of seed production costs.
6. Bio-fortification and enhancement of grain quality through molecular breeding.

Conclusion

Hybrid rice is a revolutionary innovation in modern agriculture that harnesses the power of hybrid vigor to offer higher productivity, improve resource-use efficiency and enhance food security. Its ability to provide better yields under different and changing environmental conditions makes it an essential component of sustainable rice production. As food demand increases globally, continued research, technology and development of climate-resilient, high quality hybrid varieties will be critical to unlocking the full promise of hybrid rice for a secure and sustainable future for agriculture.

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Engineering Better Proteins: The Technologies Behind Plant-Based Foods

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Abstract
The global demand for plant-based foods has surged, driven by sustainability, ethics, and health awareness. Plant proteins from legumes, cereals, oilseeds, and pseudocereals are the primary raw materials for meat and dairy analogues, but replicating the texture, flavor, and nutritional quality of animal products remains challenging. This article summarizes key protein engineering strategies—high-moisture extrusion, shear cell processing, enzymatic modification, and fermentation—used to overcome these barriers, and examines how protein structure, functional properties, and processing conditions interact to transform plant proteins into consumer-acceptable foods.

Introduction
Population growth, climate change, and the environmental footprint of animal agriculture have accelerated interest in plant-based alternatives (Khalid et al., 2024; Kim et al., 2024; Nasrollahzadeh et al., 2023). The global market for plant-based meat and dairy alternatives reached roughly $29 billion in 2023 and continues to grow, driven by vegan, vegetarian, and flexitarian consumers who expect products that mirror the sensory and nutritional qualities of conventional meat and dairy (Joshi et al., 2025; Nasrollahzadeh et al., 2023).

Plant proteins are sourced from soybeans, peas, chickpeas, lentils, faba beans, wheat, oats, and emerging sources such as microalgae and duckweed, each with distinct molecular structures and functional properties (Kim et al., 2024). Key barriers to adoption include anti-nutritional factors such as phytates, tannins, trypsin inhibitors, and lectins that reduce digestibility (Rathod et al., 2022); the structural rigidity of plant protein aggregates, which makes replicating fibrous muscle-like texture difficult (Nasrollahzadeh et al., 2023); and off-flavors together with a lack of meat-like umami (Khalid et al., 2024). To address these challenges, the industry has developed technologies including high-moisture extrusion, shear cell processing, enzymatic modification, fermentation, and 3D food printing (Nasrollahzadeh et al., 2023; Elhalis et al., 2024).

Plant Protein Sources and Molecular Characteristics
Plant proteins form complex globular structures stabilized by hydrophobic interactions, electrostatic forces, and hydrogen bonds, which respond dynamically to temperature, pH, and ionic strength during processing (Kim et al., 2024). Soy protein remains the industry benchmark, offering 36–40% protein content and a relatively complete amino acid profile, while pea protein is valued for its high arginine content and allergen-free status; chickpea, lentil, and faba bean proteins add further diversity, and novel sources such as duckweed and microalgae offer high protein yield per unit land area (Joshi et al., 2025; Khalid et al., 2024).

Cultivar selection influences solubility and emulsifying behavior through variation in legumin/vicilin ratios and secondary structure, but the extraction method of pH, solvent, salt, and temperature exerts a more decisive influence on the final isolate's structure and functionality (Kim et al., 2024). Anti-nutritional factors such as phytates, trypsin inhibitors, and lectins must be reduced through processing to make plant proteins nutritionally competitive with animal proteins (Rathod et al., 2022).

Functional Properties in Food Systems
Solubility, emulsification, foaming, gelation, and water/oil-holding capacity together determine the texture, stability, and sensory quality of plant-based products, and are strongly modulated by pH, ionic environment, and processing history (Joshi et al., 2025; Kim et al., 2024). Solubility is foundational, since poorly soluble proteins cannot effectively emulsify or gel, and many plant proteins lose solubility near their isoelectric point or under high ionic strength (Kim et al., 2024).

Emulsification is critical for mouthfeel in meat and dairy analogues, but plant proteins generally emulsify less effectively than whey or egg proteins because their compact globular structure limits interfacial unfolding; heat treatment, pH shifting, and high-pressure homogenization are used to improve this (Kim et al., 2024; Joshi et al., 2025). Gelation, essential for structural cohesion in meat analogues, proceeds through protein unfolding, aggregation, and network formation via non-covalent interactions and disulfide bonding, though plant protein gels generally show lower strength and water-holding capacity than dairy gels; transglutaminase crosslinking, coagulants, and protein blending are common remedies (Kim et al., 2024; Khalid et al., 2024).

Texturization Technologies for Meat Analogues

1. High-Moisture Extrusion Cooking: High-moisture extrusion cooking (HMEC) is the most commercially mature texturization method (Nasrollahzadeh et al., 2023). Plant proteins at 40–80% moisture are processed in a twin-screw extruder under heat, pressure, and shear that unfold and align protein chains into fibrous, muscle-like structures (Joshi et al., 2025). A long cooling die at the extruder exit stabilizes these fibers through disulfide/hydrogen bonding and rising viscosity, producing the anisotropic texture that defines tensile strength, chewiness, and springiness (Nasrollahzadeh et al., 2023). Product quality depends on barrel temperature, screw speed, moisture content, and die geometry, and blending proteins such as wheat gluten with soy, or pea/rapeseed with soy which optimizes fibrous alignment; starch composition (amylopectin vs. amylose) also strongly affects the final structure (Joshi et al., 2025; Nasrollahzadeh et al., 2023).

2. Shear Cell Technology and Emerging Methods: Shear cell technology uses a cylinder-in-cylinder design to apply a well-controlled, constant shear field, offering more precise control over fiber formation than extrusion and enabling fibrous structures at lower moisture contents (Nasrollahzadeh et al., 2023; Joshi et al., 2025). Additional emerging methods include 3D food printing for complex layered geometries (limited in scalability), electrospinning for protein nanofibers with strong water-binding properties, and freeze-structuring for anisotropic porous scaffolds via controlled ice crystal growth (Nasrollahzadeh et al., 2023).

Modification Strategies to Improve Functionality

1. Physical and Chemical Modifications: Heat treatment above the denaturation point exposes hydrophobic groups and improves emulsification and gelation (Joshi et al., 2025). High-pressure homogenization and pH-shifting disrupt globular structures and improve solubility (Kim et al., 2024), while ultrasound treatment uses cavitation to disrupt aggregates and increase surface hydrophobicity (Rathod et al., 2022). High hydrostatic pressure (HPP) processing modifies protein structure and inactivates trypsin inhibitors without excessive heat, improving digestibility and shelf life (Rathod et al., 2022). Chemical modifications such as Maillard conjugation and succinylation can improve solubility and emulsification but face regulatory and clean-label acceptance hurdles, shifting focus toward enzymatic alternatives (Kim et al., 2024).

2. Enzymatic Modification and Crosslinking: Enzymatic hydrolysis using proteases such as alcalase, papain, or bromelain improves solubility, reduces allergenicity, and enhances bioavailability, though excessive hydrolysis can reduce gelation capacity and generate bitter peptides (Rathod et al., 2022). Transglutaminase (TG) catalyzes covalent crosslinking between glutamine and lysine residues, producing heat-stable protein networks with improved mechanical strength and water-holding capacity, and is widely used to bind texturized protein strands in meat analogues (Khalid et al., 2024).

Fermentation as a Protein Engineering Tool

Fermentation using lactic acid bacteria, Bacillus subtilis, yeasts, and molds hydrolyzes proteins into bioactive peptides, reduces anti-nutritional factors, and generates flavor-active volatiles (Elhalis et al., 2024). It improves digestibility by degrading trypsin inhibitors and phytates, and increases free glutamate, contributing meat-like umami flavor often absent in unfermented plant products (Elhalis et al., 2024). Emerging hybrid technologies approaches ultrasound-assisted, high-pressure-assisted, and pulsed electric field-assisted fermentation, as well as cold plasma treatment. Those techniques further enhance microbial productivity, reduce processing time, and inactivate allergens and anti-nutritional factors (Elhalis et al., 2024).

Nutritional Quality, Digestibility, and Bioavailability

Nutritional quality depends on amino acid composition as well as digestibility and bioavailability after digestion; plant proteins are generally considered nutritionally inferior to animal proteins due to incomplete amino acid profiles and digestibility barriers (Rathod et al., 2022). The Digestible Indispensable Amino Acid Score (DIAAS) has replaced the older PDCAAS as the gold standard, since it accounts for amino acid digestibility at the end of the small intestine rather than overall nitrogen digestibility, and reveals significant variability across protein sources and processing methods (Rathod et al., 2022). Protein blending helps close this gap: soy protein supplies lysine and methionine, wheat gluten is rich in sulfur amino acids but low in lysine, and pulse proteins like pea and lentil offer good lysine but lower methionine, so combining sources approaches the completeness of animal protein (Khalid et al., 2024).

Conclusion

Plant-based protein engineering has advanced considerably, driven by consumer demand for sustainable, ethical food and by progress in food processing science. Converting raw plant protein into a commercially viable meat or dairy alternative requires integrated understanding of molecular structure, functional behavior, and processing effects. High-moisture extrusion, shear cell technology, enzymatic modification, and fermentation each contribute distinct capabilities, and their strategic combination is increasingly enabling plant-based products that rival conventional animal foods in texture, flavor, and nutritional completeness. Continued innovation in protein diversification, process optimization, and flavor improvement will be essential to meet growing global demand for sustainable, high-quality food.

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Region-Specific Crop Coefficients: A Foundation for Scientific Irrigation Scheduling in Tamil Nadu

Article ID: 74237

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Abstract

Tamil Nadu is one of the most water-stressed states in India, where agriculture depends on limited rainfall, declining groundwater resources, and increasing competition for water from domestic and industrial sectors. Efficient utilization of available water resources has therefore become essential for ensuring agricultural productivity and sustainability. Among the various tools used for scientific irrigation scheduling, the **crop coefficient (Kc)** plays a crucial role in estimating crop water requirements accurately. Developing **region-wise crop coefficients** for Tamil Nadu is an important step toward improving irrigation efficiency and sustainable water resource management.

Keywords: Crop Coefficient (Kc), Reference Evapotranspiration (ETo), Crop Water Requirement, Irrigation Scheduling, Water Use Efficiency, Precision Agriculture, Lysimeter, Agro-climatic Zones, Climate Change, Tamil Nadu, Sustainable Water Management.

Introduction

Crop water requirement (ETc) is the amount of water needed by a crop to compensate for water lost through evapotranspiration. It is calculated using the equation:

ETc = ETo × Kc

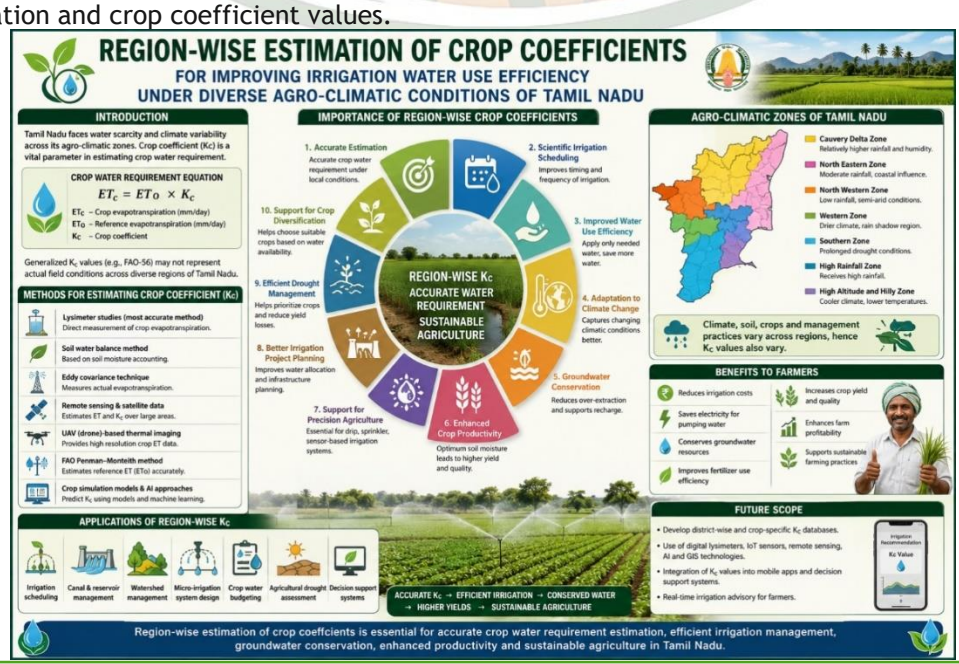
where:

ETc = Crop evapotranspiration (mm/day)
ETo = Reference evapotranspiration (mm/day)
Kc = Crop coefficient

The crop coefficient reflects the combined effects of crop characteristics, canopy development, crop growth stage, and local climatic conditions. Traditionally, Kc values recommended by the Food and Agriculture Organization (FAO-56) are widely used. However, these generalized values may not accurately represent the diverse agro-climatic conditions prevailing across Tamil Nadu.

Need for Region-Wise Crop Coefficient Estimation

Tamil Nadu encompasses seven distinct agro-climatic zones, each characterized by different rainfall patterns, temperatures, humidity levels, wind speed, soil types, and cropping systems. These variations significantly influence crop evapotranspiration and crop coefficient values.



For example:
1. Delta districts receive relatively higher rainfall and humidity.
2. Western districts experience dry climatic conditions.
3. Southern districts often face prolonged drought.
4. Hilly regions possess comparatively cooler climates.

Therefore, adopting a single Kc value for the entire state may lead to inaccurate estimation of crop water requirements.

Importance of Region-wise Crop Coefficients

1. Accurate Estimation of Crop Water Requirement: Region-specific Kc values enable precise estimation of evapotranspiration for crops grown under local climatic conditions. This helps farmers apply the exact quantity of irrigation water required during different growth stages.

2. Scientific Irrigation Scheduling: Accurate Kc values facilitate preparation of efficient irrigation schedules based on crop growth stages rather than fixed irrigation intervals. This improves irrigation timing and reduces water wastage.

3. Improved Water Use Efficiency: Agriculture accounts for nearly 80% of freshwater consumption in Tamil Nadu. Region-wise Kc estimation allows irrigation water to be applied according to actual crop demand, thereby enhancing water use efficiency and conserving scarce water resources.

4. Adaptation to Climate Change: Climate change is altering rainfall distribution, temperature, and evapotranspiration patterns across Tamil Nadu. Locally developed crop coefficients can capture these changing climatic conditions more accurately than generalized FAO values, making irrigation planning more resilient.

5. Groundwater Conservation: Over-extraction of groundwater is a major concern in several districts of Tamil Nadu. Accurate estimation of crop water requirements reduces unnecessary groundwater pumping, thereby contributing to groundwater recharge and sustainable resource management.

6. Enhanced Crop Productivity: Both deficit and excess irrigation adversely affect crop growth and yield. Region-specific crop coefficients help maintain optimum soil moisture throughout the crop growth period, leading to improved crop performance and higher yields.

7. Support for Precision Agriculture: Modern irrigation technologies such as drip irrigation, sprinkler irrigation, sensor-based irrigation, and automated irrigation systems require accurate crop coefficients. Region-wise Kc values enhance the efficiency of these precision irrigation systems.

8. Better Irrigation Project Planning: Government agencies use crop water requirements while designing irrigation projects, canal operation schedules, reservoir management plans, and watershed development programmes. Region-specific Kc values improve the accuracy of water allocation planning.

9. Efficient Drought Management: During drought years, irrigation water must be allocated judiciously. Reliable regional Kc values help prioritize irrigation based on actual crop demand, minimizing yield losses under limited water availability.

10. Support for Crop Diversification: Knowledge of water requirements through accurate Kc estimation helps farmers choose crops that are better suited to local water availability, thereby promoting sustainable cropping patterns.

Agro-Climatic Diversity of Tamil Nadu

Tamil Nadu consists of several agro-climatic zones, including:
1. Cauvery Delta Zone
2. North Eastern Zone
3. North Western Zone
4. Western Zone
5. Southern Zone
6. High Rainfall Zone
7. High Altitude and Hilly Zone

Each zone exhibits unique climatic characteristics influencing crop evapotranspiration. Consequently, crops such as rice, sugarcane, maize, cotton, banana, coconut, vegetables, and pulses require different Kc values under different regional conditions.

Methods for Estimating Region-Wise Crop Coefficient

Crop coefficients can be estimated using several scientific approaches:
1. Lysimeter studies
2. Soil water balance method
3. Eddy covariance technique
4. Remote sensing and satellite observations
5. UAV (drone)-based thermal imaging

6. FAO Penman–Monteith method
7. Crop simulation models
8. Machine learning and artificial intelligence approaches.

Among these, weighing lysimeters provide the most accurate direct measurement of crop evapotranspiration and are considered the standard method for determining crop coefficients.

Conclusion

The estimation of **region-wise crop coefficients** is essential for improving irrigation water management in Tamil Nadu. Due to considerable variations in climate, soil, and cropping systems across the state's agro-climatic zones, generalized crop coefficient values often fail to represent actual field conditions. Developing location-specific Kc values enables accurate estimation of crop water requirements, enhances irrigation efficiency, conserves groundwater, increases crop productivity, and supports sustainable agriculture. Region-wise crop coefficient estimation is therefore a critical component of climate-smart irrigation and efficient water resource management, ensuring long-term agricultural sustainability in Tamil Nadu.

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Plant Tissue Culture: A Revolution in Plant Propagation

Article ID: 74238

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Introduction

One of the biggest issues facing modern agriculture is meeting the growing demand for high-quality planting materials while maintaining sustainable agricultural production. Traditional plant propagation techniques are time-consuming, seasonal, and susceptible to pest and disease spread. Furthermore, there is a need for technology that can produce a large number of healthy and genetically homogeneous plants due to the increasing demand for superior cultivars in horticultural, medicinal, forestry, and industrial crops. In this regard, plant tissue culture has become a ground-breaking biotechnology that has revolutionized plant propagation globally (George *et al.*, 2008).

The *in vitro* cultivation of plant cells, tissues, or organs under aseptic and regulated environmental conditions is referred to as plant tissue culture, or micropropagation. The technology utilizes cellular totipotency, which was put forth by the German botanist Gottlieb Haberlandt in 1902 and holds that, given the right nutrients and environmental circumstances, every living plant cell has the genetic capacity to regenerate into a whole plant (Fehér, 2019). Tissue culture has developed over the last fifty years from a laboratory research method to a commercially viable technology utilized in agricultural development programs, floriculture, horticulture, forestry, and the production of medicinal plants. Millions of tissue-cultured plants are now generated every year all over the world, greatly boosting agricultural output and biodiversity preservation.

The Science Behind Tissue Culture

Plant tissue culture takes advantage of plants' extraordinary capacity for regeneration. An explant is a tiny piece of plant tissue that is removed from a healthy mother plant and grown on a sterile nutritional medium. Mineral salts, vitamins, carbohydrates (often sucrose), agar as a gelling agent, and precisely controlled amounts of plant growth regulators like auxins and cytokinins are typically present in the medium (Murashige & Skoog, 1962). The explant proceeds through cell division and differentiation to create shoots and roots under carefully regulated light, humidity, and temperature conditions. Before being sent to the field, the regenerated plantlets are gradually acclimated to greenhouse conditions until adequate roots has been attained. Tissue culture, in contrast to traditional propagation, allows for the quick multiplication of superior planting material regardless of seasonal constraints.

A Versatile propagating technique	The importance of tissue culture lies in its ability to overcome many limitations associated with conventional propagation.
Rapid multiplication	Thousands of plants can be produced from a single healthy explant within a relatively short period. This is particularly valuable for crops with slow multiplication rates.
Disease-free planting materials	Meristem culture enables the production of virus-free and pathogen-free plants, significantly improving crop health and productivity.
Uniformity	Plants regenerated through axillary shoot proliferation generally retain the desirable characteristics of the mother plant, ensuring true-to-type multiplication.
Year-round production	Since tissue culture is carried out under controlled laboratory conditions, planting materials can be produced throughout the year, independent of climatic conditions.
Germplasm conservation	Rare, endangered, and medicinal plant species can be conserved through in vitro techniques, reducing pressure on natural populations.

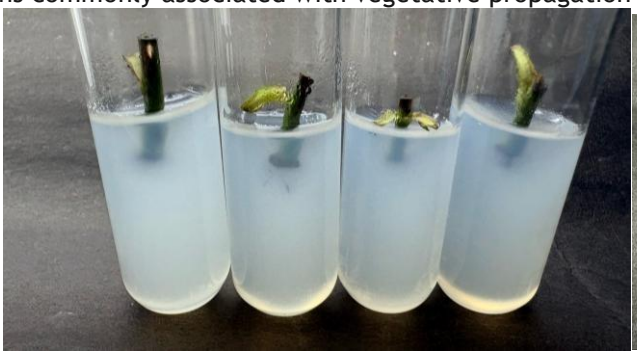
Applications Across Diverse Crops

Plant tissue culture has been successfully applied to decorative, agricultural, forestry, and medicinal crops, demonstrating its versatility. Standardized micropropagation procedures have been created in our lab for rose, chrysanthemum, bamboo, tapioca (*Manihot esculenta*), and vallarai (*Centella asiatica*), each of which has special benefits.

Rose: Multiplying Excellence

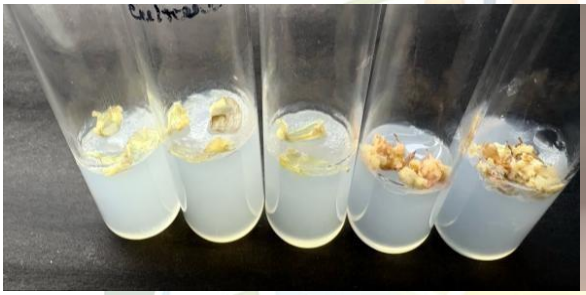
Rose is one of the world's most economically important ornamental crops. Commercial production requires large quantities of uniform, disease-free planting material. Micropropagation enables rapid multiplication of elite cultivars

while maintaining floral quality, colour, fragrance, and growth habit. Tissue-cultured plants also reduce the spread of systemic pathogens commonly associated with vegetative propagation through stem cuttings (Pati *et al., 2006)*.




Chrysanthemum: Supporting the Floriculture Industry

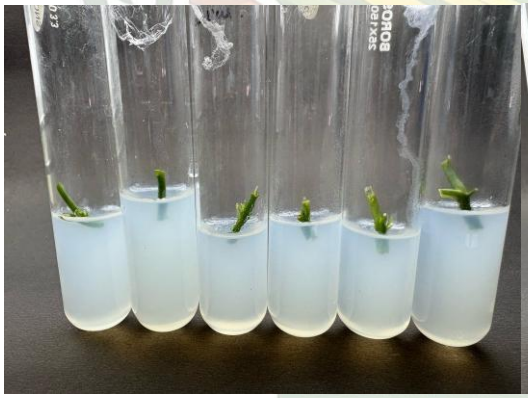
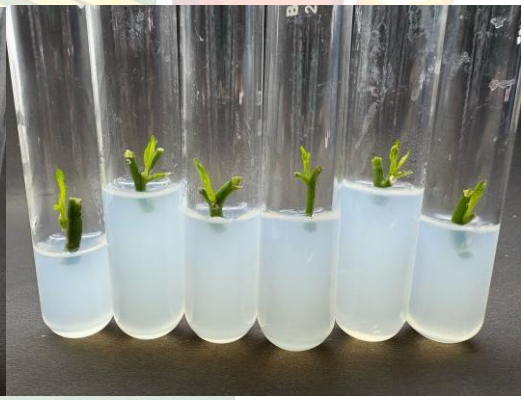
Chrysanthemum is propagated vegetatively and is highly susceptible to viral diseases that accumulate over successive generations. Micropropagation provides an effective means of producing healthy mother plants for commercial nurseries. The availability of disease-free planting material contributes to higher flower yield, improved quality, and enhanced export potential.





Solanum Nigrum

Solanum nigrum (black nightshade) is widely utilized in plant tissue culture due to its medicinal importance, good regeneration ability, and biochemical richness. It serves as both a model plant and a valuable source of secondary metabolites in in vitro studies.

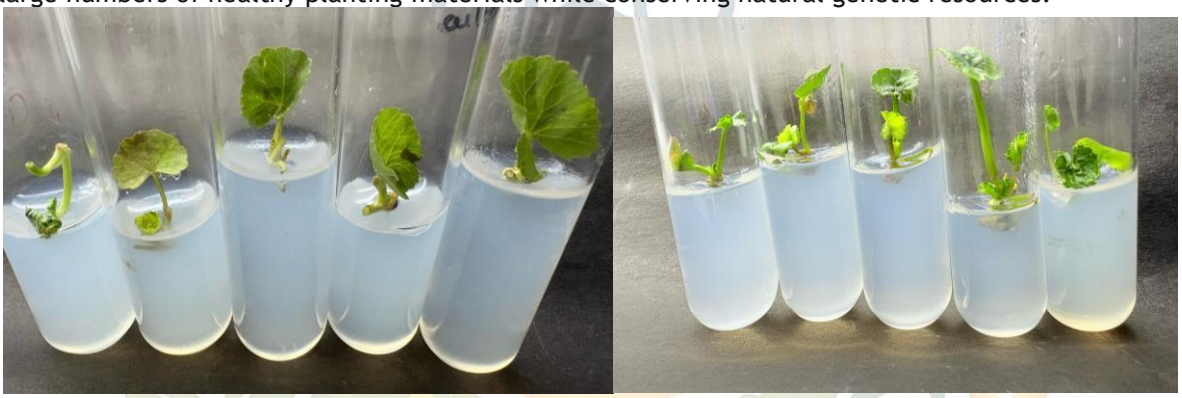
Tapioca: Healthy Planting Material for Better Productivity

Cassava or tapioca is an important food and industrial crop propagated primarily through stem cuttings. Continuous vegetative propagation often leads to the accumulation of pathogens and gradual decline in planting material quality. Micropropagation facilitates rapid multiplication of disease-free plants, ensuring improved field establishment, higher productivity, and efficient dissemination of improved varieties.

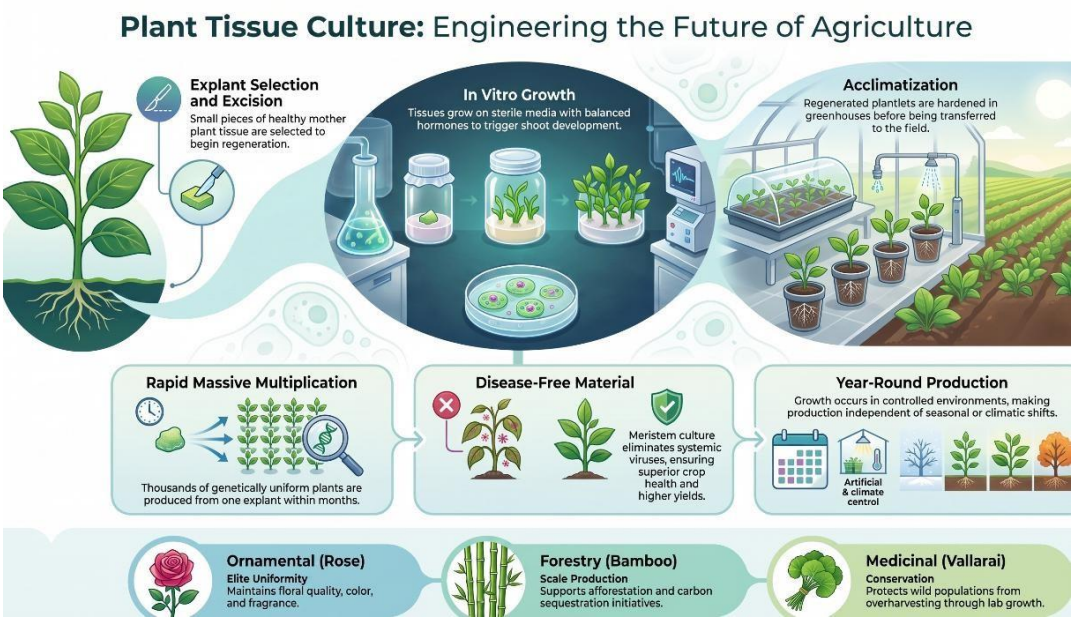


Vallarai: Conserving a Medicinal Treasure

Vallarai (*Centella asiatica*) is widely recognized for its medicinal properties and increasing pharmaceutical demand. Wild populations are declining due to overharvesting. Tissue culture provides an alternative propagation system capable of producing large numbers of healthy planting materials while conserving natural genetic resources.



Beyond Propagation: A Tool for Sustainable Agriculture



Plant tissue culture extends far beyond rapid multiplication. It has become an integral component of modern plant biotechnology. Today, tissue culture supports:

a. Germplasm conservation
b. Production of secondary metabolites
c. Somatic embryogenesis
d. Synthetic seed technology
e. Cryopreservation
f. Genetic transformation

g. Plant breeding programmes
h. Production of climate-resilient crops

The technology also plays a significant role in conserving endangered plant species and supporting sustainable utilization of biodiversity.

Challenges and Future Prospects

Although tissue culture offers numerous advantages, several challenges remain. Contamination by microorganisms continues to be a major constraint in commercial laboratories. Species-specific optimization of nutrient media and plant growth regulators is often required, and acclimatization of plantlets remains a critical stage influencing field survival. Recent advances in temporary immersion bioreactors, LED lighting systems, automation, artificial intelligence, and precision environmental control are making tissue culture more efficient and commercially viable. These innovations are expected to reduce production costs while increasing multiplication rates and plant quality.

Conclusion

Plant tissue culture has revolutionized the way planting materials are produced. By enabling rapid multiplication of healthy, disease-free, and genetically uniform plants, the technology contributes significantly to sustainable agriculture, commercial horticulture, medicinal plant conservation, and forestry development. The successful micropropagation of rose, chrysanthemum, *Solanum nigrum*, tapioca, and vallarai demonstrates the enormous potential of tissue culture to address the growing demand for quality planting materials while conserving valuable plant genetic resources. As agriculture moves towards greater sustainability and climate resilience, tissue culture will continue to play a central role in shaping the future of plant propagation.

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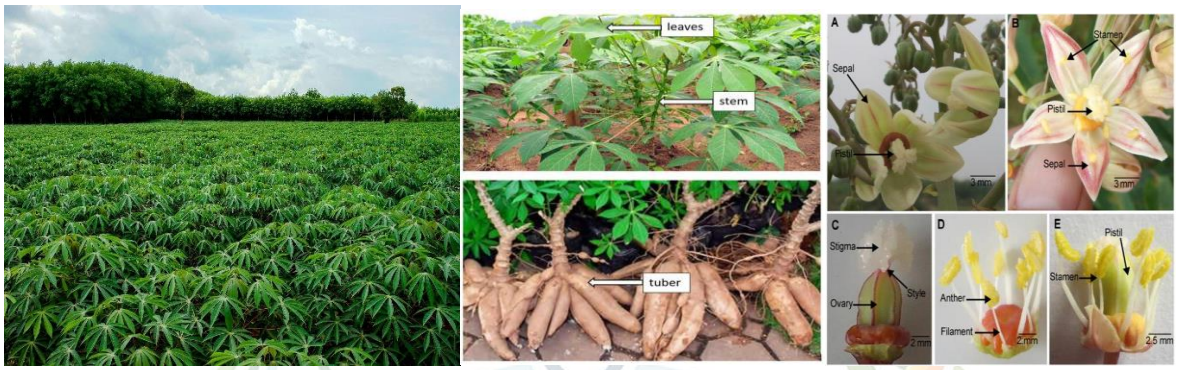
Package of Practices for Cassava Cultivation

Article ID: 74239

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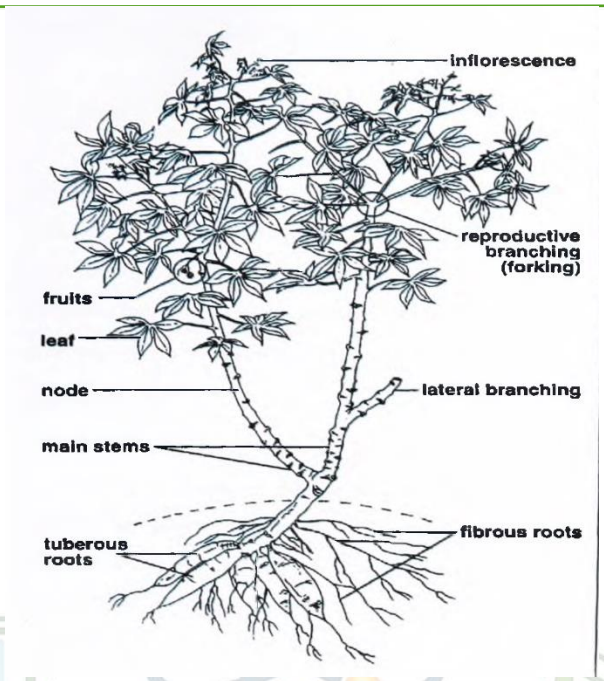
Introduction

Cassava (*Manihot esculenta Crantz*), commonly known as tapioca, manioc, mandioca, yuca, or cassava, is a perennial woody shrub belonging to the family Euphorbiaceae with a chromosome number of 2n = 2x = 36. Native to the tropical regions of South America, particularly Brazil and the southwestern Amazon basin, cassava was introduced to India by the Portuguese during the 17th century. Although botanically perennial, it is cultivated as an annual crop for its enlarged starchy storage roots, which serve as an important source of carbohydrates for human consumption, livestock feed and starch-based industries. Cassava starch is widely processed into tapioca and is extensively used in the food, textile, paper, pharmaceutical, adhesive and bioethanol industries. Owing to its high productivity, ability to grow under marginal soil conditions and remarkable tolerance to drought, cassava is popularly regarded as the "King of Tropical Tuber Crops."

Globally, cassava is the third most important source of dietary carbohydrates in tropical regions after rice and maize and serves as a staple food for more than 800 million people across Africa, Asia and Latin America. According to the latest FAOSTAT data (2024), cassava is cultivated on about 30.4 million hectares worldwide, with an annual production exceeding 354 million tonnes. Nigeria is the largest producer, followed by the Democratic Republic of the Congo, Thailand, Ghana, Brazil, Indonesia, Vietnam and Angola. In India, cassava is cultivated mainly in the southern states, particularly Tamil Nadu, Kerala andhra Pradesh, Telangana and Karnataka, with Tamil Nadu contributing the largest share of national production. During 2023-24, cassava occupied approximately 1.78 lakh hectares with a production of about 6.27 million tonnes, primarily supplying the starch, sago and processing industries in addition to food consumption.

Botany

Cassava (*Manihot esculenta Crantz*), commonly known as tapioca, belongs to the family Euphorbiaceae and is one of the world's most important tropical root crops cultivated for its starchy storage roots. The genus Manihot comprises approximately 98 species, predominantly native to South America, ranging from perennial herbs and subshrubs to shrubs and small trees. Most species contain milky latex and synthesize cyanogenic glucosides as a natural defense mechanism. Phylogenetic studies suggest that cultivated cassava originated primarily from *Manihot esculenta subsp. flabellifolia*, with genetic contributions from closely related wild species such as *M. peruviana*. Cassava is a perennial woody shrub, usually cultivated as an annual crop, attaining a height of 1.5-4.0 m, with some vigorous cultivars reaching 6-7 m. The erect, cylindrical stem is sparsely branched, marked with prominent leaf scars and propagated mainly through stem cuttings, while seeds are used primarily in breeding programmes. The root system consists of fibrous roots, some of which undergo secondary thickening to form enlarged starchy storage roots that serve as carbohydrate reserves. Unlike true tubers, these storage roots lack nodes and internodes.



Leaves are simple, alternate, glabrous and palmately lobed with 5-9 narrow lanceolate lobes, borne on long petioles varying from green to reddish-purple. Cassava bears terminal or axillary panicle-type inflorescences and is monoecious, producing separate male and female flowers on the same inflorescence. Female flowers are borne at the basal portion and open earlier than male flowers (protogyny), promoting cross-pollination. The apetalous flowers possess a petaloid calyx of five fused sepals. Male flowers contain 10 stamens arranged in two whorls surrounding a nectariferous disc, whereas female flowers have a superior tricarpellary, three-locular ovary, each locule containing a single ovule and terminating in three bifid or multifid stigmas. The fruit is an ovoid to globose, three-valved loculicidal capsule (1-2 cm in diameter) that splits open at maturity to release three hard-coated, carunculate seeds. Cassava is predominantly an outcrossing, insect-pollinated (entomophilous) species with a high degree of heterozygosity, providing a broad genetic base for breeding programmes focused on improving yield, starch quality, disease resistance, nutritional value and adaptation to diverse agro-climatic conditions.

Importance

Cassava is one of the world's most important tropical root crops owing to its high starch content, excellent adaptability and multiple food and industrial applications. The storage roots contain 25-40% starch, making cassava one of the richest starch-producing root crops. Although fresh roots contain cyanogenic glucosides, these compounds are effectively reduced to safe levels through proper processing methods such as peeling, soaking, fermentation, drying and cooking. Cassava serves as a vital source of dietary energy for millions of people, particularly in tropical and subtropical regions and is recognized for its high productivity under marginal soils, drought-prone environments and low-input farming systems. Its resilience to several biotic and abiotic stresses makes it an important crop for ensuring food and nutritional security under changing climatic conditions.

The major uses of cassava include:

1. About 70% of global cassava production is consumed as food, either fresh or in processed forms.

2. Fresh storage roots are commonly consumed after boiling, steaming, or mashing, while processed products include chips, flour and starch.

3. Cassava flour is widely used as a partial substitute for wheat and rice flour in various food products.

4. Parboiled and dried chips can be stored for long periods, improving food availability during lean seasons.

5. Cassava starch is the primary raw material for the manufacture of sago, an important food product and baby food. In India, the major sago industries are concentrated in Salem (Tamil Nadu) and the Samalkot region (Andhra Pradesh).

Besides food uses, cassava starch is extensively utilized in the production of ethanol, animal feed, paper, textiles, pharmaceuticals, adhesives, biodegradable plastics and other bio-based industrial products, highlighting its growing economic and industrial importance.

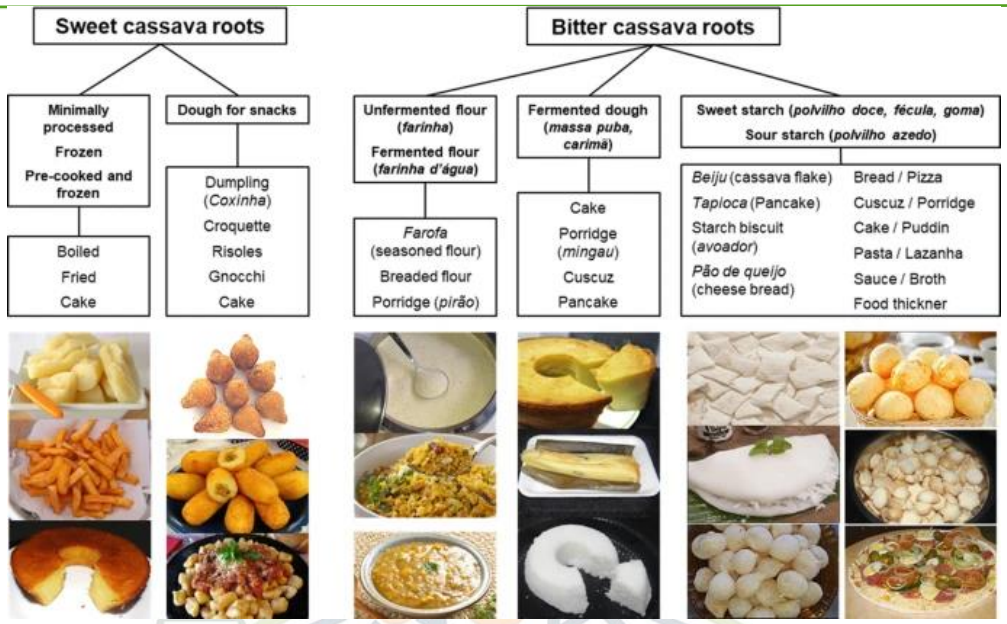


Figure: By products prepared from Cassava

Varieties

Sl.No	Variety	Pedigree	Special Traits	Duration
1.	H-97 (1971)	Hybrid Manjavella X Brazilian selection	Medium tall, drought tolerant & tolerant to CMD	10 months
2.	H-165 (1971)	Hybrid Chadayamangalam vella X Kalikalan	Medium tall, field tolerant to CMD, spider mite andscale insect; good for rotational cropping	8-9 months
3.	H-226 (1971)	Hybrid M4 X Ethakka karupan	Medium tall, tolerant to spider mite & scale insect	10 months
4.	Sree Visakham (1977)	Hybrid Acc No.1501 X S-2312 (exotic)	Carotene rich, compact tubered	10 months
5.	Sree Prabha	TCH	HY table variety for upland & lowland	8-10 months
6.	Sree Annam	-	Flesh dark yellow rich in carotene	9-10 months
7.	Sree Manna	-	Good cooking quality with good taste	9-10 months
8.	Sree Kaveri (2023)	-	Tall, top-branching variety with silver grey stem.	9-10 months
9.	Sree Sakthi (2018)	C33 X CM4574-7	Completely resistant to CMD	9-10 months
10.	Sree Suvarna (2018)	SM1741 X C33	It has medium starch, 25-27% (range: 24-29.8%)	7-8 months
11.	Sree Reksha (2017)	CM79515 X C-18	Tall (275-325 cm), non-branching variety with brown stem and light brown emerging leaf	8-9 months
12.	Sree Pavithra (2015)	Clonal Selection from indigenous germplasm	Medium starch (24.4%) content	9-10 months
13.	Sree Swarna (2015)	Clonal Selection from landrace Arumasa Kappa	Medium starch (25.2%) content	7-8 months
14.	Sree Athulya (2014)	Triploid variety	High extractable starch	10 months

15.	Sree Apoorva (2014)	Triploid variety	High extractable starch	10 months
16.	Sree Sahya (H-2304) (1977)	Multiple cross hybrid (Acc No. 468, 174, 3024, 1310 82, 3939, 3588 & M4)	Tetraploid, Hardy & highly resistant to drought	10-11 months
17.	Sree Prakash (S-856) (1987)	Selection from indigenous germplasm	Suitable for lowland cultivation	7 months (early maturing)
18.	Sree Harsha (1996)	Triploid OP4 (2X) x H-2304 (4X)	1st triploid variety. High yield & dry matter, high starch content, drought tolerant & robust variety	10 months
19.	Sree Jaya (1998)	Selection from indigenous germplasm	Excellent cooking quality	6-7 months (early maturing)
20.	Sree Vijaya (1998)	Selection from indigenous germplasm	Excellent cooking quality	6-7 months (early maturing)
21.	Sree Rekha	Top cross Hybrid (TCH)	HY table variety for upland & lowland	8-10 months
22.	Sree Padmanabha (2006)	Selection from exotic germplasm	First CMD resistant variety	9-10 months
23.	Nidhi (KAU)	Selection from indigenous germplasm (Koombuvelia)	Early maturing	6 months
24.	Kalpaka (KMC-1) (KAU)	Selection from Ramanthala	Early maturing, suitable for coconut gardens in Central Kerala	6 months
25.	Vellayani Hraswa	Selection from indigenous germplasm (COA, Vellayani)	HY, cannot tolerate drought	5-6 months (early maturing)
26.	M4	Introduction	Erect, non-branching, most popular variety in Kerala, very low HCN	10 months
27.	CO 1 (TNAU) (1977)	Clonal selection from a type of Tiruchi	Whitish brown tubers, low incidence of mosaic virus	8.5-9 months
28.	CO 2 (TNAU) (1984)	Clonal selection OP seedling from Thiruvarur type, Tanjore	Low HCN	8-8.5 months
29.	CO 3 (TNAU) (1993)	Clonal selection from seedling progenies of OP seeds from IITA, Nigeria	-	8 months
30.	CO 4 (TNAU) (2002)	Clonal selection from one of the seedling progenies of the hybrid SM1679	-	8.5 months
31.	CO 5 (TNAU	-	Fairly good starch content (28%)	9-10 months
32.	MVD - 1 (Horticulture Dept. of TN)	Clonal selection	Exhibits field tolerance to CMD	-
33.	YTP 1 (2013)	Selection from Thondamuthoor local	Tuber neck is absent. Starch content: 25 to 27%.	9-10 months
34.	YTP 2 (2020)	Selection from Thondamuthoor 1	Flesh colour is white. Starch content: 29.62%	9-10 months

Soil and Climate: Cassava grows well in well-drained, fertile soils, particularly red lateritic loam and sandy loam soils with a pH of 5.5-7.5. The crop performs best under warm, humid tropical and subtropical climates with temperatures ranging from 25-30°C and an annual rainfall of 1000-1500 mm, preferably well distributed. Cassava is tolerant to drought and marginal soils but is sensitive to waterlogging. It can be successfully cultivated up to an altitude of 1,000 m above mean sea level.

Field Preparation: The field should be ploughed 4-5 times to obtain a fine tilth and ensure good root development. The land should be free from weeds and ridges and furrows should be prepared according to the recommended spacing. A soil depth of at least 30 cm is desirable for proper storage root development.

Season and Propagation

Cassava is propagated vegetatively through stem cuttings (setts). Healthy, disease-free and cassava mosaic virus-free plants are selected as the source of planting material. Stem cuttings of 15-20 cm length containing 8-10 nodes are prepared from the middle portion of mature stems. Before planting, the setts are treated with carbendazim (1 g L^{-1}) for 15 minutes to minimize fungal infection. They are planted vertically on ridges with the buds facing upward. Approximately 17,000 stem cuttings are required to plant one hectare. Under rainfed conditions, planting is generally carried out during April-May, while irrigated crops can be planted throughout the year depending on water availability. Biofertilizer treatment with Azospirillum and Phosphobacteria, along with micronutrients such as $ZnSO_4$ and $FeSO_4$, enhances sprouting and early crop establishment.



Mini-Sett Technique

The mini-sett technique is an efficient method for the rapid multiplication of quality planting material. Unlike the conventional method, which uses 20 cm long stem cuttings containing 10-12 buds, the mini-sett technique utilizes two-node cuttings. Since newly sprouted buds begin absorbing nutrients directly from the soil after root establishment, shorter cuttings perform effectively while significantly increasing the multiplication rate. This technique enables rapid production of disease-free planting material, reduces wastage of buds, lowers seed requirements and facilitates the large-scale dissemination of improved cassava varieties (Shruthy and Rajshree, 2020).

Planting

On the sides of ridges and furrows, place the setts vertically with buds pointing upward at the following spacings.

1. Under rainfed condition: **60 × 60 cm (27,777 setts)**
2. Under Irrigated condition: **75 x 75 cm (17,777 setts) and 90 x 90 cm (12,345 setts)**
3. Under Kanyakumari circumstances: **90 x 90 cm (12,345 setts).**



Irrigation: Cassava requires adequate soil moisture during the early stages of crop establishment. The first irrigation is given immediately after planting, followed by a second irrigation on the third day. Subsequently, irrigation is provided at 7-10 days intervals up to the third month and at 20-30 day intervals until harvest, depending on soil type, rainfall and climatic conditions. Proper drainage is essential, as cassava is highly susceptible to waterlogging.

Drip Irrigation: Drip irrigation improves water-use efficiency and enhances storage root yield. Laterals are generally spaced 1.2-1.5 m apart with emitters placed 50-60 cm apart, delivering 3.5-4.0 L h^{-1}. The laterals are laid along the centre of each ridge or raised bed to ensure uniform moisture distribution within the root zone.

Sequential Cropping: Cassava fits well into sequential cropping systems. Short-duration crops such as vegetable cowpea may be grown before cassava and their residues incorporated into the soil as green manure. This practice improves soil fertility, enhances organic matter content and reduces the requirement for farmyard manure and phosphorus fertilizers.

Nutrient Management: Well-decomposed farmyard manure (FYM) at 12.5-25.0 t ha^{-1} should be incorporated during land preparation. Fertilizer application varies with soil fertility and production system; under irrigated conditions, a recommended dose of 90:90:240 kg $N_2O_{52}O$ ha^{-1} is commonly followed, while lower doses are adopted under rainfed conditions. Nitrogen and potassium are generally applied in split doses to improve nutrient-use efficiency. Integration of Azospirillum, Phosphobacteria and micronutrients such as $ZnSO_4$ and $FeSO_4$ enhances crop growth and storage root development. Under drip irrigation, fertilizers can be applied through fertigation at regular intervals.

Intercultural Operations: Gap filling should be completed within 20 days after planting to maintain optimum plant population. Regular weeding and earthing-up during the first five months facilitate better root development and weed control. Plants are thinned to two healthy shoots around 60 days after planting. Short-duration crops such as aggregatum onion, coriander, legumes and leafy vegetables can be successfully grown as intercrops during the initial growth period.

Plant Protection

Cassava is affected by several insect pests, including mites, whiteflies and spiralling whiteflies. Mites cause leaf yellowing, curling and premature defoliation, whereas whiteflies damage foliage and act as vectors of Cassava Mosaic Disease (CMD). Integrated pest management practices such as the use of healthy planting material, removal of alternate weed hosts, installation of yellow sticky traps, conservation of natural enemies, balanced fertilizer application, neem-based biopesticides and need-based insecticide application effectively reduce pest incidence.

Major diseases include Cassava Mosaic Disease (CMD), Cercospora leaf spot and tuber rot caused by Phytophthora palmivora. CMD is characterized by mosaic mottling, leaf distortion and stunted growth and is primarily transmitted by Bemisia tabaci. Cercospora leaf spot can be managed by spraying mancozeb (2 g L^{-1}) at 15-day intervals, while tuber rot is minimized through proper drainage, soil application of Trichoderma viride and need-based application of copper oxychloride.

Physiological Disorders

Iron deficiency and micronutrient-induced chlorosis are common under alkaline soil conditions. Foliar application of $FeSO_4$ (1-2.5%) alone or in combination with $ZnSO_4$ (0.5%), along with lime as a buffering agent, effectively corrects these deficiencies.

Harvesting and Yield

Cassava reaches maturity 9-11 months after planting, depending on the variety and growing conditions. Harvesting is indicated by yellowing and shedding of older leaves, along with cracking of the soil around the base of the plant. Storage roots are carefully lifted using a fork or crowbar to avoid mechanical injury. Under good management practices, average yields range from 20-25 t ha^{-1} under rainfed conditions and 40-50 t ha^{-1} under irrigated conditions.

Post-Harvest Management and Storage



Figure: Processing of cassava starch

Fresh cassava roots are highly perishable and should ideally be processed within 24-48 hours after harvest. The roots are washed, peeled, sliced and dried to produce chips, flour, or starch. Cassava starch is widely utilized in food processing and various industrial applications. For short-term storage, roots should be kept in a cool, well-drained, shaded environment to minimize physiological deterioration and microbial spoilage.

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Molecular Mechanisms and Regulatory Networks of Bacilysin Biosynthesis in *Bacillus* Species: Implications for Biocontrol

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Abstarct

Bacilysin is a dipeptide antibiotic produced by various *Bacillus* species, representing a critical secondary metabolite in biocontrol strategies against plant pathogens. The biosynthesis of bacilysin involves a non-ribosomal peptide synthetase (NRPS)-independent mechanism, with BacA-BacD enzymes catalyzing sequential reactions to form the characteristic dipeptide structure. At the regulatory level, bacilysin production is governed by quorum sensing systems (ComX/ComA), global regulators (Spo0A), and pleiotropic factors (AbrB), which integrate environmental and cellular signals (Wolf *et al.*, 2016). The role of bacilysin as both an antimicrobial agent and a pleiotropic signaling molecule positions it as a multifunctional molecule affecting spore quality, cellular differentiation, and pathogen suppression. Recent genomic and transcriptomic analyses have revealed strain-specific heterogeneity in bacilysin production, highlighting the importance of understanding these regulatory mechanisms for biotechnological applications. This comprehensive review elucidates the molecular mechanisms governing bacilysin biosynthesis, encompassing the structural genes (bac operon), enzymatic pathways, and the complex regulatory networks that coordinate its production.

Keywords: Bacilysin, *Bacillus*, biosynthesis, quorum sensing, biocontrol, regulatory networks.

Introduction

Bacillus species represent one of the most versatile groups of bacteria, capable of producing diverse bioactive secondary metabolites that confer competitive advantages in complex environmental niches. Among these compounds, bacilysin stands out as a unique, structurally simple yet functionally complex dipeptide antibiotic with the molecular formula $C_{12}H_{18}N_2O_5$ and molecular mass of 270.28 g/mol. Antimicrobial peptides (AMPs) are short amino acid sequences synthesized by both prokaryotic and eukaryotic organisms as part of innate immune mechanisms against pathogenic microorganisms. Within the *Bacillus* genus, bacilysin represents a distinctive category of secondary metabolite that differs fundamentally from other characterized AMPs in both its biosynthetic pathway and its pleiotropic effects on cellular physiology (Savary *et al.*, 2019).

The significance of bacilysin extends beyond its direct antimicrobial properties. Bacilysin-deficient mutants exhibit enhanced sensitivity to environmental stressors such as heat, chemical agents, and enzymatic degradation, accompanied by reduced dipicolinic acid content in spores. This multifaceted role positions bacilysin as a critical factor in bacterial survival and competitive fitness in natural environments. The heterogeneous distribution of bacilysin-producing capability among *Bacillus* species and strains, coupled with variable production levels under different cultural conditions, necessitates comprehensive understanding of the molecular and regulatory factors governing its biosynthesis. This knowledge is particularly crucial for agricultural biotechnology applications, where *Bacillus*-based biocontrol products represent environmentally sustainable alternatives to synthetic pesticides (Jain and Kaur, 2020).

Structure and General Characteristics of Bacilysin

Bacilysin is a minimal dipeptide antibiotic composed of L-alanine and L-anticapsin (derived from L-aspartate). Despite its simple dipeptide structure, bacilysin exhibits potent antimicrobial activity against a broad range of microorganisms. The structural simplicity of bacilysin contrasts sharply with its biochemical complexity and regulatory sophistication. Unlike larger antimicrobial peptides, bacilysin's minimal structure allows for rapid synthesis and secretion, enabling

Bacillus strains to respond quickly to environmental pressures and competitive threats. The presence of an epoxide ring within the anticapsin moiety is critical for antimicrobial activity and is generated during the biosynthetic pathway through specific enzymatic modifications (Pinto *et al.*, 2018).

Molecular Mechanisms of Bacilysin Biosynthesis

1. The Bac Operon Architecture: Bacilysin biosynthesis in *Bacillus subtilis* is encoded by a clustered operon containing four structural genes: bacA, bacB, bacC, and bacD. This genetic organization reflects the coordinated synthesis of enzymatic components required for the sequential conversion of substrates to the final dipeptide product. The bac operon is regulated at both transcriptional and post-translational levels. Genetic and biochemical evidence demonstrates that the biosynthetic pathway does not follow the canonical non-ribosomal peptide synthetase (NRPS) mechanism employed by related lipopeptide antibiotics such as surfactin and fengycin. Instead, bacilysin biosynthesis represents a specialized biosynthetic strategy distinct from the multi-carrier thiotemplate model characteristic of NRPS enzymes (Javed *et al.*, 2020).

2. Enzymatic Steps and Gene Functions: BacA encodes a membrane-associated enzyme catalyzing the initial condensation of L-aspartate with an undetermined factor to form the precursor of anticapsin. BacB functions as an intermediate in the modification pathway, facilitating the generation of dihydroanticapsin, which serves as a substrate for downstream enzymatic reactions (Hotta *et al.*, 2010). BacC is identified as an oxidase enzyme catalyzing a critical C7-hydroxyl oxidation step on dihydrobacilysin or its precursor. This oxidation reaction is indispensable for converting the partially synthesized intermediate into anticapsin. BacD functions as the terminal ligase in the biosynthetic pathway, catalyzing the condensation of the oxidized anticapsin with L-alanine to form the mature bacilysin dipeptide. The sequential action of BacA→BacB→BacC→BacD represents an elegant, though mechanistically unconventional, pathway that circumvents the multi-megadalton NRPS complexes employed by other *Bacillus* secondary metabolites.

Regulatory Networks Controlling Bacilysin Biosynthesis

1. Quorum Sensing: The ComX/ComA Pathway: Bacilysin production is fundamentally dependent on bacterial population density through quorum sensing mechanisms. In *B. subtilis*, the ComX/ComA quorum sensing pathway represents the primary regulatory circuit governing bacilysin biosynthesis. ComX is a 10-amino acid modified peptide pheromone that accumulates at high cell densities and serves as an extracellular signal molecule. This pheromone is recognized by ComP, a membrane-bound histidine kinase sensor, which undergoes autophosphorylation upon ligand binding. The phosphorylated ComP (ComP~P) catalyzes phosphoryl transfer to the response regulator ComA, generating the active transcription factor ComA~P. This phosphorylated form of ComA acts as a positive regulator of the bac operon, directly activating transcription of bacilysin biosynthetic genes (Tran *et al.*, 2000). The integration of quorum sensing into bacilysin regulation ensures that costly biosynthetic investments occur primarily when population size justifies the metabolic burden, representing a rational strategy for resource allocation under variable nutritional conditions.

2. The Spo0A Phosphorelay and Sporulation-Linked Regulation: Beyond quorum sensing, bacilysin biosynthesis is tightly coupled to sporulation developmental pathways through the Spo0A phosphorelay system. Spo0A, a master regulatory protein governing sporulation initiation, also influences bacilysin biosynthesis through complex integrative signals. This regulatory connection reflects the biological logic that bacilysin production, as a developmental program associated with stationary phase and nutrient-limiting conditions, shares common triggering signals with sporulation (Wang *et al.*, 2010). The Spo0A phosphorelay integrates signals from multiple sensor kinases through a multi-step phosphoryl transfer cascade: Sensor histidine kinase → Spo0F → Spo0B → Spo0A. This complex signaling architecture allows *Bacillus* to respond to diverse environmental cues including nutritional stress, carbon limitation, and oxygen availability.

3. The Pleiotropic Repressor AbrB: The AbrB (Accessory Regulator) protein functions as a global repressor of stationary phase genes, including genes within the bac operon. AbrB is a Spo0A-repressed gene; thus, as Spo0A~P levels rise during the transition to stationary phase, AbrB expression decreases, allowing derepression of bacilysin biosynthetic genes. This regulatory logic ensures that bacilysin synthesis occurs specifically during stationary phase when nutrient competition intensifies and production of antimicrobial compounds becomes advantageous.

4. Integration of Regulatory Signals and Environmental Sensors: The regulatory networks controlling bacilysin biosynthesis represent an integrative system responding to multiple environmental parameters. Nutrient limitation (triggers both quorum sensing and Spo0A phosphorelay activation. Recent genomic and transcriptomic studies have identified secondary regulators including sigma factors (σH associated with sporulation), transcriptional factors modulating biofilm formation, and trans-acting regulatory RNAs that fine-tune bacilysin biosynthesis in response to complex environmental matrices (Berry *et al.*, 2015).

Implications for Biocontrol Applications

Bacillus species have emerged as predominant biocontrol agents against diverse phytopathogenic fungi and bacteria, with multiple commercial products based on *B. subtilis, B. velezensis*, and related species achieving significant market

penetration. The biocontrol capacity of *Bacillus* strains operates through multiple, often redundant mechanisms: (1) direct antagonism via secreted antimicrobial metabolites including bacilysin, lipopeptides, and polyketide compounds; (2) competition for ecological niches and limiting nutrients; and (3) induced systemic resistance (ISR) in host plants. *In vitro* assays demonstrate that cell-free supernatants from bacilysin-producing *Bacillus* strains inhibit growth of *Fusarium verticillioides, Colletotrichum gloeosporioides, Botrytis cinerea*, and *Phytophthora infestans*. Strains of *B. velezensis* including EA-CB0015 have demonstrated efficacy against Black Sigatoka disease in banana plants caused by *Pseudocercospora fijiensis*, illustrating the practical applicability of bacilysin-producing strains in addressing economically significant plant diseases (Chen *et al.*, 2021). Bacilysin-producing *Bacillus* strains exhibit multiple plant growth-promoting properties including nitrogen fixation, phosphate solubilization, phytohormone production (particularly indole-3-acetic acid and gibberellins), and systemic resistance induction. These pleiotropic beneficial effects amplify the agronomic value of *Bacillus*-based products, providing comprehensive enhancement of plant health, nutrition, and stress resilience (Compant *et al.*, 2010).

Conclusion and Future Research Directions

Bacilysin represents a paradigmatic secondary metabolite exemplifying the sophisticated molecular and regulatory architecture governing natural product biosynthesis in *Bacillus* species. The multifunctional role of bacilysin extending beyond direct antimicrobial action to modulation of spore quality and developmental processes illustrates the systems-level complexity of microbial secondary metabolism. Bacilysin-producing *Bacillus* strains offer environmentally sustainable alternatives to synthetic chemical pesticides, operating through complementary mechanisms of direct pathogen antagonism, ecological competition, and induced systemic resistance. Future advances in structural biology, synthetic biology, and systems biology approaches promise to unlock additional optimization strategies for bacilysin-based biocontrol products. Integration of multi-omics data, predictive modeling of regulatory network behavior, and rational modification of regulatory elements offer realistic pathways toward developing next-generation biocontrol formulations with enhanced reliability, consistency, and efficacy. As global agriculture faces mounting pressures from evolving pathogen populations, resource limitation, and environmental concerns regarding chemical pesticide usage, the optimization and deployment of *Bacillus*-based biocontrol products including bacilysin-producing strains represents a strategic and sustainable approach to crop protection and food security.

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Landraces and Modern Plant Varieties: A Comparative Perspective

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Abstract
Landraces and modern plant varieties represent two distinct yet complementary components of crop genetic resources. Landraces are traditional, farmer-developed populations that possess broad genetic diversity, adaptability to local environments, and resilience to biotic and abiotic stresses. In contrast, modern plant varieties are scientifically bred to achieve higher yield, uniformity, and improved quality through conventional and molecular breeding techniques. While modern varieties have significantly enhanced agricultural productivity and contributed to global food security, their relatively narrow genetic base may reduce resilience to emerging climatic and environmental challenges. Landraces serve as invaluable reservoirs of novel alleles for disease resistance, stress tolerance, and nutritional quality, making them indispensable for future crop improvement. Integrating the rich genetic diversity of landraces with the superior agronomic performance of modern varieties through advanced breeding approaches offers a sustainable strategy for developing climate-resilient and high-yielding crops.

Introduction
The domestication and improvement of crop plants have been fundamental to the development of agriculture and human civilization. Over thousands of years, farmers selected and maintained crop populations that adapted naturally to local environmental conditions, giving rise to what are known as landraces (Ramirez-Villegas *et al*. 2022). These traditional varieties formed the foundation of agricultural production long before the advent of scientific plant breeding. During the twentieth century, advances in genetics and breeding techniques led to the development of modern plant varieties with improved yield potential, uniformity, and resistance to pests and diseases. Today, both landraces and modern varieties play important roles in agriculture, but they differ considerably in their genetic composition, adaptability, productivity, and breeding objectives. Understanding these differences is essential for designing sustainable crop improvement strategies capable of meeting future food security challenges.

Landraces and Modern Varieties: Characteristics, Differences, and Significance
Landraces are genetically heterogeneous populations that have evolved over generations through natural selection and farmer selection under specific agroecological conditions. They are generally well adapted to local climates, soils, and farming practices and often possess remarkable tolerance to drought, heat, salinity, and various pests and diseases. Because they have evolved under diverse environmental conditions, landraces exhibit considerable genetic variability, allowing them to perform reliably under marginal environments where improved varieties may fail. In addition, many landraces possess unique nutritional qualities, distinctive grain characteristics, and cultural significance, making them valuable genetic resources for both agriculture and biodiversity conservation.

In contrast, modern plant varieties are developed through systematic breeding programs that combine desirable traits from selected parents. These varieties are genetically more uniform and stable, ensuring consistent performance across cultivation areas. Modern breeding has successfully improved grain yield, maturity duration, lodging resistance, disease resistance, and product quality. The adoption of improved varieties has been a major contributor to the Green Revolution, substantially increasing food production in many parts of the world. However, the emphasis on uniformity and intensive selection has often resulted in a relatively narrow genetic base, making some modern varieties more vulnerable to newly emerging pests, diseases, and changing climatic conditions.

The differences between landraces and modern varieties extend beyond productivity. Landraces generally produce lower yields under optimal conditions but offer greater yield stability under environmental stress. Modern varieties, on the other hand, can achieve exceptionally high yields when provided with adequate irrigation, fertilizers, and crop management practices, but their performance may decline under adverse conditions. This contrast highlights the importance of conserving landraces as reservoirs of valuable genes that may no longer exist in elite breeding materials (Kumar *et al*. 2025).

Recent advances in **Genomics** have enhanced the utilization of landraces in crop improvement. Technologies such as whole-genome sequencing, marker-assisted selection, genomic selection, and **Genome-Wide Association Studies** enable breeders to identify beneficial alleles present in traditional germplasm and incorporate them into modern breeding programs. These approaches have accelerated the development of varieties that combine the high productivity of modern cultivars with the resilience and adaptability of landraces. Furthermore, emerging technologies such as **CRISPR-Cas9** provide new opportunities to precisely introduce valuable traits from landraces into elite breeding lines without compromising their agronomic performance.

The integration of landraces into pre-breeding programs has become increasingly important in the context of climate change. Rising temperatures, erratic rainfall, and the emergence of new pests and diseases demand crops with greater resilience and broader genetic diversity. Landraces offer a rich source of adaptive traits that can help breeders develop varieties capable of sustaining productivity under these changing conditions. Their conservation, characterization, and systematic utilization are therefore essential for ensuring long-term agricultural sustainability.

Conclusion

Landraces and modern plant varieties each possess unique strengths that contribute to agricultural development. Modern varieties have transformed global food production through enhanced yield and uniformity, while landraces remain irreplaceable reservoirs of genetic diversity, environmental adaptability, and stress tolerance. Rather than viewing them as competing resources, they should be considered complementary components of sustainable crop improvement. The integration of traditional germplasm with advanced breeding technologies provides an effective pathway for developing climate-resilient, high-yielding, and nutritionally superior crop varieties. Conserving landraces and incorporating their valuable genetic diversity into modern breeding programs will be essential for addressing future challenges related to food security, climate change, and sustainable agriculture.

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Potential Biological Agent of *Pantoea* Spp. Against Plant Pathogenic Bacteria

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Abstract

Pantoea is a genus of Gram-negative bacteria that has been obtained from a broad range of environmental habitats. Numerous *Pantoea* strains have been identified from diverse ecological niches and host organisms. Certain isolates produce bioactive compounds with biocontrol potential that effectively suppress a variety of plant pathogens. Members of this genus are capable of synthesizing antagonistic metabolites that provide a competitive advantage over other microorganisms inhabiting the same ecological environments. The biocontrol effectiveness of *Pantoea* species is largely attributed to their ability to produce a wide array of natural antimicrobial metabolites. Their widespread distribution, ecological adaptability, and ease of genetic manipulation make *Pantoea* an excellent potential candidate for the biological control of phytopathogenic bacteria.

Keywords: *Pantoea*, Antagonistic, Ecological, Niches, Metabolites.

Introduction

Plant-pathogenic bacteria pose a major challenge to agricultural productivity by causing diseases that result in substantial economic losses and environmental damage. Biological control has emerged as an effective and sustainable approach and reduces the dependence on chemical pesticides for disease management. Members of the genus *Pantoea* are commonly associated with a wide range of plant species, functioning either as pathogens or as beneficial microorganisms depending on the bacterial strain and the host plant. *Pantoea* comprises Gram-negative, motile, rod-shaped bacteria within the family *Enterobacteriaceae*. Its name, meaning "from all types and sources," reflects the genus' extensive ecological distribution and remarkable diversity. Owing to its widespread occurrence, plant growth-promoting traits, and antagonistic activity against phytopathogenic bacteria, *Pantoea* has gained increasing recognition as a promising biological control agent.

The genus *Pantoea* was established approximately 25 years ago and has expanded to include nearly 20 recognized species exhibiting considerable physiological and ecological diversity. Members of this genus encompass a wide range of plant-associated bacteria, including economically significant phytopathogens as well as beneficial strains with proven potential as biological control agents against plant diseases. The most extensively studied biocontrol *Pantoea* strains produce one or more antimicrobial metabolites that play a key role in enhancing their antagonistic activity against plant pathogens (Smits *et al.*, 2018). Morphologically, *Pantoea* species are Gram-negative, rod-shaped bacteria that typically produce distinctive yellow-pigmented colonies.

Pantoea spp. are naturally associated with plants and are widely distributed across diverse ecological habitats. In addition to plant tissues, members of this genus have been isolated from a variety of soil and aquatic environments worldwide, as well as from animal-associated niches (Ahmed *et al.*, 2025). Beyond their ecological versatility, *Pantoea* species possess significant biotechnological value as bioinoculants and biological control agents by suppressing phytopathogens and enhancing the innate immune responses of plants (Duchateau *et al.*, 2024). Despite the versatile behavior, their role as biocontrol agents and the underlying mechanisms are of increasing interest.

Biocontrol Potential of *Pantoea* Species

Several *Pantoea* species have been recognized as highly efficient biological control agents, offering protection against diverse phytopathogenic microorganisms in numerous crop plants (Walterson and Stavrinides, 2015). A majority of these beneficial isolates belong to *Pantoea agglomerans*, which possess antagonistic activity against a broad spectrum of plant pathogens affecting crops such as grapevine, citrus, and *Prunus* species (Aziz *et al.*, 2016). Some strains of *Pantoea ananatis* have been reported to suppress *Xanthomonas axonopodis* pv. *vesicatoria*, the causal agent of bacterial spot in tomato (Gasser *et al.*, 2012). In addition, *Pantoea dispersa* strains exhibit effective biocontrol activity against *Burkholderia glumae, Xanthomonas albilineans*, and *Pseudomonas syringae* pv. tomato in both monocotyledonous and dicotyledonous crops, including rice, sweet potato, sugarcane, and tomato (Zheng *et al.*, 2021).

1. Role of Antimicrobial Compounds Produced by *Pantoea* spp. in Plant Protection: The biocontrol activity of *Pantoea* spp. primarily depends on the production and release of antimicrobial compounds and specialized metabolites, including volatile organic compounds (VOCs), antibiotics, and biosurfactants. Among these VOCs, 3-methylbutanol, the dominant constituent of the volatilome, together with 2-nonanol, is believed to contribute significantly to antifungal activity. *Pantoea* sp. Dez632 also produces antibacterial VOCs that suppress the motility of *Bacillus pumilus*, the causal agent of beet root rot. Pantocins synthesized by *Pantoea* spp. display potent antibacterial activity against several phytopathogenic bacteria, particularly *Erwinia amylovora*.

A second class of antibacterial metabolites, known as *Pantoea* Natural Products (PNPs), is produced by *Pantoea agglomerans* strains. Among these, PNP-2 and PNP-3, identified from the secretomes of different *P. agglomerans* isolates (Williams and Stavrinides, 2021), exhibit strong inhibitory activity against *E. amylovora*. In addition, biosurfactants, a structurally diverse group of surface-active molecules synthesized by living organisms, are also produced by several *Pantoea* species. For example, N-(2-hydroxyhexadecyl) diethanolamic acid, a biosurfactant produced by *P. brenneri* AS3, demonstrates pronounced antagonistic activity against plant pathogens (Itkina *et al.*, 2021).

2. Competition-Mediated Suppression of Plant Pathogens by *Pantoea* spp.: Bacteria's are capable of restricting the growth of plant pathogens through competition for ecological niches and essential nutrient resources. Several *Pantoea* species demonstrate competitive interactions with phytopathogens, and *Pantoea agglomerans* CPA-2 is among the most extensively studied examples. This strain, originally isolated from the surface of apple fruits, provides effective protection to both apple and pear against important postharvest diseases. In addition, *P. agglomerans* competes successfully with *Pseudomonas syringae* pv. *atrofaciens*, the causal organism of wheat basal bacteriosis, through rapid colonization and effective suppression of pathogen proliferation (Soluch *et al.*, 2021).

3. Defense Priming by *Pantoea* spp.: Priming is a key component of induced resistance, enabling plants to activate stronger defense responses only upon pathogen challenge. Among the various *Pantoea* species, *Pantoea agglomerans* has been the most extensively investigated for its ability to stimulate plant defense mechanisms. The strain PTA-AF2 promotes the activation of late-stage defense responses, including the accumulation of β-1,3-glucanases, chitinases, and stilbene phytoalexins (Aziz *et al.*, 2016). In addition, *P. agglomerans* effectively triggers systemic resistance in radish against bacterial leaf spot caused by *Xanthomonas campestris* pv. *armoraciae*.

Conclusion and Future Perspectives

Pantoea species exhibit considerable potential as biological control agents across a wide range of economically important crops. Their biocontrol activity is mediated through multiple mechanisms, including the production of antimicrobial metabolites, activation of plant defense responses, and competitive exclusion of phytopathogens. Although the diverse lifestyles of *Pantoea* spp. present challenges for their direct field application, selected strains possess significant promise for sustainable disease management. Future research should focus on elucidating the molecular basis of their beneficial and pathogenic interactions, as well as identifying novel antimicrobial compounds and immune-activating mechanisms, to facilitate the development of effective *Pantoea*-based biocontrol formulations.

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Advances in Automated Pest Monitoring and Image-Based Insect Identification in Entomology

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Abstract

Automated pest monitoring and image-based insect identification are rapidly transforming entomology, crop protection, and precision agriculture. Conventional insect surveillance relies heavily on manual trap inspection, visual scouting, taxonomic expertise, and periodic field observations. Although these approaches remain indispensable, they are labour-intensive, time-consuming, subjective, and often unable to provide the frequency of observations required for early pest detection. Recent developments in digital imaging, smart traps, sensors, wireless communication, machine learning, deep learning, cloud computing, and edge artificial intelligence have created new opportunities for continuous, scalable, and data-driven insect monitoring. Automated systems can capture insect images, detect individuals, count trapped insects, classify taxa, estimate population dynamics, and transmit near-real-time information to farmers, researchers, and decision-support platforms. Image-based identification has particularly advanced through convolutional neural networks, object-detection models, transfer learning, and large annotated datasets, enabling the recognition of economically important pests, beneficial insects, pollinators, invasive species, and disease vectors. This review discusses the development, technological foundation, applications, challenges, and future prospects of automated pest monitoring and image-based insect identification in entomology. Particular emphasis is placed on camera-equipped traps, computer vision pipelines, deep-learning models, mobile and edge-based systems, integration with integrated pest management, and the need for robust datasets and field validation. The review highlights that automated insect surveillance is not intended to replace entomological expertise; rather, it can strengthen pest forecasting, improve timeliness of intervention, reduce unnecessary pesticide use, and support sustainable agricultural production.

Introduction

Insects occupy central positions in agricultural ecosystems, natural food webs, public-health systems, and biodiversity networks. While many insect species provide essential ecosystem services such as pollination, biological control, nutrient cycling, and decomposition, numerous others act as serious pests of crops, stored products, forests, livestock, and humans. Accurate monitoring of insect populations is therefore fundamental to entomology and pest management. It enables the identification of pest species, estimation of abundance, tracking of seasonal emergence, recognition of invasion events, assessment of crop risk, and timely implementation of management strategies. In conventional practice, pest monitoring is generally performed through field scouting, sweep-netting, visual inspection, sticky traps, pheromone traps, light traps, pitfall traps, suction traps, and manual counting of captured insects. These methods have contributed enormously to the development of integrated pest management; however, their practical limitations are increasingly evident in large-scale, labour-constrained, and time-sensitive agricultural systems.

Manual trap examination is often conducted at intervals of several days or even weeks. Consequently, sudden increases in pest density may remain undetected during the critical early phase of infestation. Identification may also be difficult when trap catches include damaged individuals, cryptic species, immature stages, mixed taxa, non-target insects, or visually similar species. The quality of monitoring can vary with the observer's experience, availability of trained taxonomists, weather conditions, and the number of traps distributed across the landscape. These limitations have encouraged the development of automated systems that can collect and analyse insect information more frequently and more consistently.

Automated pest monitoring refers to the use of electronic, optical, acoustic, mechanical, sensor-based, or computational technologies to detect, identify, count, classify, or transmit information about insect populations with reduced dependence on repeated manual observation. In recent years, the convergence of affordable cameras, embedded processors, wireless networks, image-analysis software, artificial intelligence, and precision-agriculture platforms has substantially expanded the scope of automated insect surveillance. Camera-equipped traps and computer-vision systems can now generate images of trapped or visiting insects, while deep-learning models can recognise patterns associated with insect morphology, body shape, wing structure, colour, size, texture, and movement. Such systems have become an important frontier in digital entomology and intelligent crop protection (Lima et al., 2020; Teixeira et al., 2023).

Evolution of Automated Pest Monitoring

The initial phase of automated insect monitoring focused mainly on mechanical counting mechanisms and electronic sensors. Devices were designed to detect insect movement, wingbeats, interruptions of infrared beams, changes in electrical conductivity, or entry into trapping chambers. These systems were useful for estimating presence or activity but often lacked the ability to identify insects accurately at species level. Their performance could also be affected by differences in insect size, flight behaviour, trap design, dust accumulation, lighting, moisture, and the presence of non-target organisms.

The introduction of digital cameras represented a major advance because it enabled automated systems to collect visual evidence rather than merely indirect signals. Camera-equipped traps can capture repeated images of sticky surfaces, pheromone lures, light-trap chambers, or insect landing platforms. The images may then be transmitted through mobile networks, Wi-Fi, LoRa-based communication, or other Internet of Things infrastructure. This reduced the need for frequent physical trap visits and allowed remote inspection of pest activity. The use of image sensors also created the possibility of storing permanent records that can be re-examined by specialists, used for model training, or incorporated into long-term pest databases.

A modern automated monitoring system usually combines several components: an attractant or trapping mechanism, an imaging unit, a source of illumination, a power supply, a communication module, a processing unit, and an analytical algorithm. Pheromones, kairomones, food baits, coloured surfaces, ultraviolet light, or floral cues may be used to attract target insects. High-resolution cameras record images of captured insects or insects visiting the device. Image-processing algorithms then identify relevant regions, separate insects from the background, estimate the number of individuals, and classify them into target categories. The information can be delivered to a mobile application, web dashboard, cloud platform, or farm-management system.

The value of these systems lies not only in automatic counting but also in temporal resolution. A traditional trap may be inspected once every week, whereas an automated trap can collect images several times per day or even continuously. This improved frequency makes it possible to detect short-lived flight peaks, identify early seasonal emergence, and relate insect activity to weather variables such as temperature, rainfall, humidity, wind speed, or degree-day accumulation. Automated systems may therefore improve pest forecasting and facilitate more timely management decisions.

Camera-Equipped Smart Traps and Digital Surveillance

Smart traps are among the most visible examples of automated pest-monitoring technology. They are designed to attract, retain, detect, or image insects while producing digital information that can be interpreted remotely. In agriculture, smart traps are especially valuable for pests that are already monitored through pheromone-based systems, such as moths, fruit flies, beetles, borers, weevils, and certain invasive species. A camera-equipped pheromone trap can photograph the sticky surface periodically, allowing insect numbers to be estimated without the need for a person to visit every trap manually.

Camera placement is an important determinant of system performance. Cameras may be positioned above the sticky sheet, inside the trap chamber, beside an entry tunnel, or beneath a transparent landing surface. Uniform illumination is essential because shadows, glare, reflections, and changing daylight may reduce image quality and increase classification errors. Some traps use integrated light-emitting diodes or ring lights to maintain stable imaging conditions. Others use enclosed imaging chambers to reduce the influence of weather and ambient light. The trap background is also carefully selected because contrast between the insect body and the surface can improve segmentation and detection accuracy.

The practical advantage of camera-based monitoring is especially clear in commercial orchards, greenhouses, storage facilities, and large field-crop landscapes where numerous traps are needed. Rather than collecting only cumulative counts, digital traps can produce images that reveal the actual composition of the catch. This is useful when target insects resemble non-target species or when trap contamination makes manual counting difficult. Camera-equipped traps have been extensively explored for monitoring codling moth and other orchard pests, demonstrating the potential of automated imaging to improve the timeliness and efficiency of pest surveillance (Sütő et al., 2022).

However, smart traps are not universally simple to deploy. Insects may overlap on sticky surfaces, become partially obscured by dust or debris, lose scales or body parts after capture, or degrade under heat and humidity. A single image may contain insects at different angles, sizes, and levels of preservation. In addition, target pest abundance may be low during early infestation, while non-target insects may dominate images in some environments. These factors create a challenging visual-recognition problem and explain why the performance of automated monitoring systems must be evaluated under realistic field conditions rather than only on clean laboratory images.



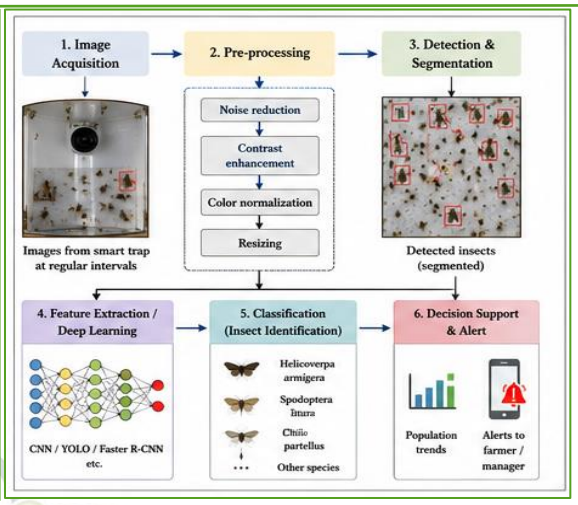


Image Acquisition, Pre-Processing, and Computer Vision

Image-based insect identification begins with image acquisition. The quality of the acquired image strongly influences the reliability of all later analytical stages. Important variables include camera resolution, lens quality, focal distance, depth of field, lighting intensity, exposure time, image compression, background uniformity, and insect orientation. Small insects are particularly difficult to image because they may occupy only a few pixels, while fast-moving insects may appear blurred. In field environments, rain droplets, dust, pollen, trapped leaves, webbing, shadows, and reflections may further complicate image interpretation.

Pre-processing aims to improve image quality and prepare data for automated analysis. Common procedures include resizing, brightness correction, contrast enhancement, noise reduction, colour normalisation, image sharpening, background correction, and cropping. In some systems, an image is divided into smaller sections so that insects can be detected more effectively. Other systems use background-subtraction methods to isolate moving insects from a static surface. Insects captured on sticky traps may be separated from the background through colour thresholding, edge detection, morphological operations, or segmentation algorithms. These traditional methods can work well under controlled conditions, but their performance often declines when background variation is high.

The next step is detection or segmentation. Detection identifies whether insects are present and determines their approximate location. Segmentation attempts to isolate the exact pixels associated with each insect. In early computer-vision systems, insect identification often depended on manually engineered features such as body length, area, wing shape, contour, colour histogram, texture descriptors, or geometric characteristics. Although feature-based systems can be effective for narrowly defined tasks, they are limited when insects vary strongly in orientation, developmental stage, illumination, or background. They also require considerable domain-specific design.

Deep learning has reduced reliance on manually selected features by allowing models to learn visual patterns directly from large labelled image collections. Convolutional neural networks can learn hierarchical representations, beginning with simple edges and textures and progressing toward complex visual traits associated with insect morphology. This ability has made deep learning especially influential in insect classification, object detection, and counting. A systematic assessment of automatic insect detection studies has shown the growing importance of deep-learning approaches for identifying, counting, and locating insects in trap images and other agricultural settings (Teixeira et al., 2023).

Deep Learning for Insect Identification

Deep learning is a branch of machine learning in which multilayer neural networks learn complex patterns from data. In image-based entomology, deep-learning models are trained using labelled photographs of insects, trap catches, crop surfaces, or field scenes. Depending on the purpose, the model may be asked to classify an entire image, identify a single insect, detect multiple insects in a scene, estimate insect density, or distinguish target pests from beneficial insects and non-target species.

Image classification models are useful when each image contains one clearly visible insect or when images have already been cropped into individual specimens. A classifier may assign the image to a species, genus, family, pest group, life stage, or functional category. Object-detection models are more appropriate when multiple insects occur in a single photograph. These models produce bounding boxes around insects and assign a category to each detected individual. This is particularly valuable for sticky-trap images containing numerous overlapping insects. Object-detection frameworks based on region proposal networks, single-shot detectors, and You Only Look Once architectures have been widely adapted for insect detection because they can combine localisation and recognition in a single analytical pipeline.

Transfer learning has become especially valuable in entomological applications. Instead of training a neural network entirely from the beginning, researchers can start with a model that has already learned broad visual features from a large image dataset. The model is then fine-tuned with insect images from the target crop, trap, or region. This approach reduces the amount of labelled data needed for training and can improve performance when datasets are limited. It is particularly helpful for identifying economically important insects for which thousands of high-quality labelled images may not be available.

Deep learning can also support the identification of insect developmental stages. Eggs, larvae, pupae, nymphs, and adults may differ enormously in morphology, colour, size, and habitat. A system trained only on adult insects may therefore fail to recognise immature stages that are often more damaging to crops. Models designed for pest monitoring should ideally include multiple life stages, sexes, seasonal morphs, damaged specimens, and varying environmental conditions. This is especially important for insect pests with cryptic larvae, polymorphic adults, or sexually dimorphic forms.

A further strength of modern image-based systems is their potential to distinguish harmful and beneficial insects. Pest-management decisions should not be based solely on detecting pest presence; they should also account for natural enemies, pollinators, parasitoids, and predators. A system capable of detecting aphids, whiteflies, fruit flies, moths, ladybird beetles, lacewings, hoverflies, spiders, and parasitoid wasps could provide a more ecologically meaningful picture of field conditions. Such information can support conservation biological control and reduce indiscriminate pesticide application.

Applications in Precision Agriculture and Integrated Pest Management

Automated monitoring is increasingly aligned with the principles of precision agriculture. Precision agriculture seeks to manage spatial and temporal variability in crop production through data-driven decision-making. Insect populations are rarely uniform across a farm. Pest hotspots may occur near field margins, irrigation channels, alternate host plants, storage structures, orchards, or areas with particular microclimatic conditions. By deploying multiple smart traps across a production landscape, it becomes possible to create more detailed maps of pest occurrence and population change.

The integration of automated pest monitoring with weather data can significantly enhance forecasting. Many insect species exhibit temperature-dependent development, seasonal emergence patterns, and weather-mediated activity. When smart traps provide frequent observations, their data can be combined with degree-day models, rainfall records, humidity measurements, crop growth stages, and remote-sensing information. This can help predict when a pest is likely to reach an action threshold or when a vulnerable crop stage coincides with peak insect activity. Rather than relying on calendar-based spraying, farmers may be able to make interventions based on actual pest pressure.

In greenhouses, automated image-based monitoring has particular promise because lighting, temperature, and trap placement can be more controlled than in open fields. Whiteflies, thrips, aphids, leafminers, fungus gnats, and other greenhouse pests can be monitored using sticky cards and camera systems. Frequent detection is valuable because pest outbreaks can spread rapidly in protected cultivation. Digital monitoring may also help evaluate the effectiveness of biological-control agents and identify areas where intervention is needed.

In orchards, camera-equipped pheromone traps are relevant for moth pests, fruit flies, borers, and beetles. Continuous monitoring of male moth flights can support decisions about mating disruption, insecticide timing, and larval-control windows. In vegetable crops, image-based systems can detect insects directly on leaves, flowers, fruits, or trap surfaces. In stored-product systems, automated devices can help identify beetles, moths, and other pests in grain stores, warehouses, mills, and food-processing facilities. Invasive insects and disease vectors are another important application because early detection can greatly improve containment and eradication efforts.

Automated identification should nevertheless be considered a decision-support tool rather than a completely autonomous replacement for expert judgement. Models may identify a suspected pest, estimate its abundance, and issue alerts, but field validation remains necessary before high-cost or high-risk interventions are made. Pest management also depends on crop stage, economic threshold, natural-enemy activity, pesticide resistance, local regulations, weather forecasts, and the presence of disease transmission risk. The greatest benefit arises when automated detection is integrated into a broader integrated pest-management framework.

Challenges and Limitations

Despite rapid advances, several scientific and practical challenges remain. The first major challenge is data quality. Deep-learning systems depend on large, accurately labelled datasets. In entomology, this is difficult because insect diversity is enormous, taxonomic expertise is unevenly distributed, and many species are rare or poorly photographed. Images may be labelled at different taxonomic levels, such as order, family, genus, or species, which complicates model development. Misidentification during dataset creation can lead to unreliable predictions. Data imbalance is another major concern because common pests may have thousands of images while rare, emerging, or invasive species have very few.

A second challenge is generalisation. A model trained using images from one trap type, crop, region, camera, or season may perform poorly in another setting. Changes in background colour, illumination, trap design, insect orientation, body condition, or environmental noise may substantially reduce accuracy. A model trained with clean laboratory specimens may not recognise damaged or overlapping insects collected in a sticky trap. Robust systems therefore require diverse datasets that include real-world variation.

A third challenge is the identification of visually similar insects. Closely related species may differ only in small morphological traits that are difficult to capture with ordinary field cameras. Some identifications require microscopic structures, genitalia, wing venation, or molecular evidence. In such cases, image-based systems may be better suited to identifying insects at genus, family, pest-complex, or functional-group level rather than claiming species-level certainty. Confidence scoring and human verification are important safeguards.

Hardware reliability is also important. Smart traps must operate under rain, dust, heat, humidity, wind, insect debris, and inconsistent network connectivity. Power supply can be a limitation in remote agricultural areas. Solar panels, rechargeable batteries, low-power processors, and efficient communication systems can improve practicality, but they add cost and maintenance requirements. In addition, high-resolution image transmission can consume substantial bandwidth. Edge computing, in which images are processed locally on the device, offers a promising solution because only results or selected images need to be transmitted.

Future Prospects

The future of automated pest monitoring is likely to be shaped by stronger integration among imaging, artificial intelligence, sensor networks, robotics, and ecological modelling. Edge artificial intelligence will enable traps to perform insect detection directly in the field, reducing dependence on cloud connectivity and allowing faster alerts. Lightweight neural networks may be deployed on low-power processors, making smart traps more affordable and suitable for smallholders as well as large commercial farms.

Multimodal systems are another important direction. Rather than depending only on images, future devices may combine visual information with acoustic wingbeat signals, infrared sensing, environmental data, pheromone-trap records, and crop imagery. Acoustic monitoring can provide useful information about insect flight activity, while thermal and multispectral imaging may reveal plant stress associated with pest attack. Combining these data sources could improve detection accuracy and provide earlier warnings than any single sensor alone.

The use of drones and autonomous robots may expand the spatial scale of monitoring. Drones can survey large crop areas, inspect canopy regions that are difficult to access, and identify visible symptoms associated with pest infestation. Ground robots can move between crop rows, collect close-range images, and monitor insect populations on leaves, stems, and fruits. Smartphone-based applications are also likely to become more important, especially for extension workers and farmers who require rapid preliminary identification in the field.

Equally important will be the development of open, carefully curated insect-image datasets. Collaborative databases involving entomologists, agricultural universities, pest-surveillance agencies, farmers, citizen-science communities, and technology developers can improve model accuracy and taxonomic coverage. The most useful systems will be those that explicitly acknowledge uncertainty, flag unusual specimens, permit expert correction, and improve continuously as new images are added.

Conclusion

Automated pest monitoring and image-based insect identification represent a major technological advance in contemporary entomology. By combining smart traps, digital imaging, computer vision, deep learning, communication networks, and decision-support systems, these approaches can increase the frequency, scale, and objectivity of insect surveillance. Their most immediate value lies in supporting early detection, improving population monitoring, reducing labour requirements, and enabling more targeted pest-management decisions. Camera-equipped traps and deep-learning models have demonstrated strong potential for detecting and counting insects under both controlled and field conditions, although their reliability depends on image quality, dataset diversity, hardware durability, and careful validation. The technology is particularly promising for precision agriculture and integrated pest management because it can connect pest activity with crop stage, weather conditions, spatial variability, and management thresholds. At the same time, automated systems should complement rather than replace professional entomological knowledge. Taxonomic expertise, ecological interpretation, and field verification remain essential, particularly for rare species, cryptic taxa, and high-stakes pest-management decisions. Continued progress in low-cost sensors, edge artificial intelligence, robust datasets, and multidisciplinary collaboration will determine how rapidly automated insect surveillance becomes a routine component of sustainable crop protection.

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Organic Waste Biodegradation by Microorganisms and Its Agricultural Applications

Article ID: 74244

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Abstract
Agricultural organic wastes represent a valuable renewable resource that can be efficiently recycled through microbial degradation. Microorganisms such as bacteria, fungi, and actinomycetes accelerate the decomposition of lignocellulosic residues, converting them into nutrient-rich composts that improve soil health and crop productivity. Microbial bioconversion enhances nutrient availability, soil fertility, and plant growth while reducing environmental pollution and greenhouse gas emissions associated with residue burning. The use of microbial inoculants and consortia has further improved decomposition efficiency and compost quality, making microbial waste management an important component of sustainable and climate-smart agriculture.

Keywords: Agricultural waste, Microbial degradation, Composting, Microbial consortia, Organic waste recycling, Soil health, Crop productivity, Sustainable agriculture.

Introduction
The search for renewable sources of energy requires a worldwide effort in order to decrease the harmful effects of global climate change, as well as to satisfy the future energy demands (Ahmadi *et al*., 2010). The amount of crop residues available in India is estimated to be approximately 620 million tons (Singh & Prabha.,2017) about 50% of the total residues generated are produced by three crops *viz*. rice, wheat and oilseeds. On an average, crop residues contain about 0.5% N, 0.2% P_2O_5 and 1.5% K_2O.

Crop Residues and their Uses
Crop residues, also referred to as "agricultural, or "farm residue," are comprised of stalks, stem, leaves, husks, seeds, cobs, bagasse etc. left behind after harvesting the crop/s. They can be used for feed, fuel, fertilizer, manure *etc*. Various by products viz. alcohols, SCP, enzymes antibiotics, biogas *etc*. are produced from complex and rigid lignocellulosic biomass by applying pre treatments like chemical, physical and biological.

Bio Degradation and its Acceleration
Biodegradation is the process by which organic substances are decomposed by microorganisms (aerobic/anaerobic) into simpler substances such as carbon dioxide, water, ammonia, methane etc. Inoculation of lignocelluloytic microorganisms is a useful strategy to accelerate the degradation potential of lignocellulosic material of agricultural wastes.

Case Studies
Goyal and Sindhu (2011) studied composting of rice straw using different treatments *viz*. fungal culture, biogas slurry and cow dung. At 90 days of composting, the lowest C:N ratio, the highest cellulose activity and the highest N P K per cent were obtained by fungal inoculation as compared to control.

Ningshen and Daniel (2013) studied bio degradation of coir pith using microbial consortium. The pH steadily decreased with the increase in the number of days of decomposition. The best result was observed with *A. niger* and *Pleurotus sajor caju*. Also there was a steady increase in temperature in the initial phase of decomposition from 29 ºC to 37 ºC up to 15thdays and further a decline in temperature to 29 ºC on the 30thday indicating the active role of microbes in the process.

Osama (2013) revealed that treatment of cotton stalks inoculated with both *P. chrysosporium* and *Azotobacter* (C4) gave the most desirable characteristics of the final product with respect to the narrow C/N ratio, and high nitrogen content. The C/N ratio at the end of the composting period reached 14.17 as compared to non treated compost (20.03).

Dabhi *et. al*. (2014) prepared consortium of four bacterial strains *Cellulomonas cartae, Pseudomonas fluorescence, Pseudomonas putida, Bacillus megaterium* and tested various enzymes viz. FPA (Filter paper assay), CMCase (Carboxy-methly cellulose) and ß-D- glucosidase which showed significant biodegradation of banana waste as compared to single individual bacterial inoculation and application of Banana pseudostem + 500 gm soil + bacterial- fungal consortium recorded significantly lower C:N ratio 90 DAI as compoared to the control.

Viji and Neelanarayanan (2014) observed that mixed culture of three lignocellulolytic fungal strains viz., *Rhizopus oryzae, Aspergillus oryzae and A. fumigatus* gave significant reduction of lignin and cellulose content in paddy straw and produced good quality compost containing higher amount of total N (1.55%), total P (1.57%), total K (1.48%) content as well as the lowest C:N ratio 10:1.

Petre *et al*. (2014) observed that bacterial and fungal pure cultures grown inside different marc (residues of grapes or fruits that have been pressed for wine making) made of apple, cherry and plum wastes. Per cent dry weight loss were checked in mono and co-cultures of *B. subtilis* and *P. ostreatus*. After 648 hr of submerged fermentation, nitrogen content, reducing sugar and protein content were increased which showing effective biodegradation of wastes.

Singh *et. al*. (2015) studied *in vitro* decomposition of above-ground components *viz*. internodes, leaves, chaff and straw of wheat crop by six species of fungi viz. *Fusarium equiseti, Trichoderma lignorum, Stachybotrys atra, Aspergillus flavus, A. niger* and *A. terreus,* wherein, *Stachybotrys atra* was the most efficient decomposer of all the four plant parts followed by *T. lignorum* and *A. niger*.

Choudhary *et al*. (2016) isolated lignocelluloses degrading 11 fungal species and evaluated their lignocellulytic enzymes activity, C:N ratio, dry mass loss, loss of cellulose, hemicelluloses and lignin of paddy crop residues after composting and (RPW 1/3, RPW 1/6, RPWM 2/2 and RZWM 3/2) strains showed higher enzymatic activities and more loss of dry mass and cell wall constituents over the other isolates.

Lemaro *et al.,* (2022) reported that microbial consortium showed significant outcome for composting parameters such as moisture content (65 – 58 %), temperature (25 – 29 °C), pH (5.5 – 5.7) and decrease in mass (25 %) from 25 to 35 d of composting organic kitchen waste.

Crop Production (Growth and Yield)

Rahman *et al*. (2012) revealed that treatment of bio compost (3kg/pot) +NPK produced the highest germination (%), vigour index, growth and yield of chili and the lowest yield and yield contributing parameters were recorded in the control.

Achsah and Prabha (2013) Reported that application of vermicompost made from banana waste by *Eudrilus eugeniae* is an effective biofertilizer facilitate the uptake of nutrients resulting in higher growth and yield of tomato crop.

Sannathimmappa *et al*. (2015) revealed that application of Straw treated with Cow dung slurry (*CDS)* @ 5% + *Trichoderma* (*T.h.*) @ 5 kg/ha + *P.sc* @ 5 kg/ha recorded significantly higher no. of tillers/plant, panicle length, grain and straw yield, while N- fixing and P- solubilizing bacteria recorded higher at time of transplanting and 60 DATP.

Kakde (2015) observed that application of groundnut cake+ soyabean straw + cow dung recorded higher shoot length, root length and total yield as compared to control.

Kumar *et al*. (2017) revealed that application of 20:40:50 kg/ha NPK + 10t/ha NADEP (1) recorded significantly higher no. of branches, no. of pod/plant, seed per pod, wt. of pod and yield (t/ha).

Mangesh and Balbhim (2017) reported that application of vermicompost (6.25 t/ha) recorded higher plant height, length of fruit/plant, dry weight of 100 seeds, fruit yield/plot and grain yield as compared to the control.

Dawood *et al*. (2018) observed that that compost manure @ 1000 kg/ha as well as *Trichoderma* @ 40 kg /ha were found better growth and maximum onion production.

Raihing and Vijayalakshmi (2023) revealed that application of Fruit wastes + cow dung + P. eous + T. asperelloides + Eudrilus eugeniae (5 t/ha) recorded significantly higher No.of pod/plant, pod length and weight of seed as compared to control treatment.

Conclusion

Magnitude of crop residues generated every year all over the world pose a serious problem in terms of disposal and responsible for environmental green house gas emmision. Conversion of such renewable and organic source of raw materials into valuable biological products by microbial bioconversion is the wise and eco-friendly management strategy to deal with agricultural waste management. Several fungi such as *Aspergillus, Penicillium, Trichoderma* and bacteria such as *Bacillus, Cellulomonas, Pseudomonas* are widely used for the agricultural waste management due to their efficacy of hydrolytic enzymes production and degradation of lignocellulosic material. Use of microbial consortium in these process showed more promising results over single inoculation due to synergistic effects of useful microbes. Additionally, use of agricultural waste into quality compost may enhance the properties of soil as well as growth and yield of various crops.

Future Thrust

1. Use of biotechnological advancement into strain improvement and proper bio-conversion of waste material.
2. More research work on organic waste degradation is required.
3. Development of best method or practices for waste use and degradation and their dissemination required to farmer by extension activities.
4. Exploring new potential microbes in the agricultural waste management.
5. Use of best microbial consortium and optimization of microbial formulation.

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Emerging Strategies in Micronutrient Management for Sustainable Crop Production

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Abstract
Micronutrients play a vital role in plant growth, crop productivity, and produce quality despite being required in small quantities. However, intensive cropping, imbalanced fertilizer use, and declining soil fertility have led to widespread micronutrient deficiencies in agricultural soils. Conventional soil application often exhibits low nutrient-use efficiency due to fixation and other soil-related losses. Advanced micronutrient management strategies, including seed treatment, micronutrient-enriched organic manures, foliar application, customized fertilizers, beneficial microorganisms, and nano-fertilizers, offer effective alternatives for improving nutrient availability and crop performance. These approaches enhance nutrient-use efficiency, increase crop yield and quality, improve soil health, and reduce environmental impacts. This chapter discusses the principles, applications, and benefits of these innovative strategies and highlights their role in achieving sustainable crop nutrition and climate-resilient agriculture.

Keywords: Micronutrients, Seed treatment, Organic manure enrichment, Foliar application, Customized fertilizers, Beneficial microorganisms, Nano-fertilizers, Sustainable crop nutrition.

Introduction
In India most of the soils are widely deficient in micronutrients. Therefore, an emphasis are to be given to manage all these deficient micronutrients for their correction through fertilization programme considering right sources, rates and method of application at a right time. The higher agriculture production without balanced use of fertilizer created problems of soil fertility exhaustion and plant nutrient imbalance for not only of major but also for micronutrients. Therefore, there is need to understand advanced micronutrient management strategies for better crop nutrition.

Review of Literature
Seed treatment with micronutrients: Ullah *et al*. (2002) revealed that the seed treatment of $ZnSO_4$ (0.5M) gave significantly the highest field emergence, fresh and dry weight as well as length of root and shoot in mustard.

Anonymous (2003-04) reported that the seed treatment with ZnO (30%) @ 10 ml Zn kg^{-1} seed, $MnCl_2$ (25%) @ 10 ml Mn kg^{-1} seed and ammonium molybdate (12.5%) @ 6 ml Mo kg^{-1} seed improved the grain and straw yield of wheat.

Anonymous (2003-04) revealed that the maximum improvement in pod and haulm of groundnut recorded with the treatment of soil application of 5 kg $ZnSO_4$ ha^{-1}.

Muhammad *et al*. (2007) found that the seed coating with 0.4% Zn significantly increased grains $spike^{-1}$, test weight and biological yield of wheat over control, while higher grain yield was obtained with the 0.1% Zn seed coating in wheat.

David et al. (2008) concluded that the total dry matter and grain yield were higher with seed coated with 0.3% and 0.05%, in chickpea and wheat, respectively.

Mehta (2009) observed that seed treatment with Zn @ 5 g kg^{-1} + Bio-fertilizer (*Azospirillum* + PSB) @ 10 ml kg^{-1} seed + Fungicide (Thiram) @ 3 g kg^{-1} seed gave significantly higher plumule length, Zn content in root, shoot and root weight of maize as well as increased the Zn use efficiency, while highest Zn content in shoot observed under the seed treatment of 5 g Zn kg^{-1}.

Farooq *et al*. (2012) reported that seed treatment with different micronutirent increased grain yield of different crop from 8.42 to 53.68 percent over untreated control.

Organic Manure Enrichment through Micronutrients
Anonymous (2001-02) revealed that 100% RDF+FYM enriched with Zn 5 kg ha^{-1} recorded significantly higher zinc uptake as well as total yield of pearl millet over the control. They also found that 75% RDF+FYM enriched Zn @ 1.5 kg ha^{-1} and 100% RDF+ FYM enriched Zn @ 2.5 kg ha^{-1} recorded significantly higher Zn uptake and total yield, respectively in wheat over the control.

Meena *et al*. (2006) reported that significantly higher mustard yield as well as Fe and Zn uptake were recorded under the treatment En-Zn_2Fe_2 (Zn: 5 kg ha^{-1}& Fe: 10 kg ha^{-1}).

Rathod *et al*. (2012) found that application of NPK + PM Zn 5.0 kg ha^{-1} recorded higher grain yield of wheat as well as green and dry fodder yield of maize.

Patel *et al*. (2016) reveled that significantly highest cumin seed yield was obtained under application of RDF + 1.0 t FYM enriched with 1.5 kg Fe ha^{-1} + 0.75 kg Zn ha^{-1} over rest of the treatment.

Magnur and Kubsad (2020) concluded that significantly higher grain and fodder yield as well as B:C ratio were obtained with treatment $ZnSO_4$ + $FeSO_4$ @ 15.00 kg ha^{-1} each enriched with FYM over the rest of treatment.

Solanki *et al*. (2020) revealed that significantly higher grain and straw yield of wheat were recorded under treatment of RDF + 0.2 t vermicompost ha^{-1} enriched with 5.00 kg Fe and 2.50 kg Zn over only RDF treatment.

Meena *et al*. (2021) reported that seed, stover as well as oil yield of mustard were recorded higher under application of 5 kg Zn + 2 kg B+ 10 kg Fe + 20 kg S Enriched FYM @ 500 kg ha^{-1}.

Foliar Spray of Micronutrients

Muhammad *et al*. (2010) reported that the highest grain and straw yield of wheat were recorded with the foliar application of Zn (2%), Fe (1%), Mn (2%), Cu (1%) and B (1%) at Tiller + Joint + Boot + Ear stage of wheat crop.

Tiwari (2011) revealed that the higher grain yield of wheat and Zn content in straw were found with the treatment of Zn20 soil application + 0.5% foliar spray at ear head initiation & dough stage while straw yield and Zn content in grain were higher under the treatment Zn20soil application + 0.5% foliar spray at ear head initiation & milking stage of wheat.

Ali *et al*. (2015) reported that significantly higher fruit weight and fruit yield of tomato were recorded under the foliar application of 12.5 ppm $ZnSO_4$ + 12.5 ppm H_3BO_3 over rest of treatments.

Dhaliwal *et al*. (2021) found that significantly higher grain yield of Indian mustard was recorded under the application of RDF + foliar spray 0.5 % $FeSO_4.7H_2O$ + 0.5 % $ZnSO_4.7H_2O$ + 1 % Urea at 45 and 60 DAS.

Parthinum *et al*. (2021) revealed that fruit yield of grapes was recorded higher under treatment receiving the foliar spray of chelated EDTA calcium @ 0.2% + boric acid @ 0.1% as compared to other treatments.

Patel *et al*. (2022) reported that application of RDF with 1.5% urea spray + 0.5 % $FeSO_4$ + 0.5 % $ZnSO_4$ at 35 DAS and 50 DAS in groundnut recorded significantly highest pod and haulm yield of groundnut.

Customized Fertilizer

Mudalagiriyappa *et al*. (2015) concluded that grain and straw yields of finger millet were higher with application of 150% (CF) customized fertilizer dose, while net returns was higher with 125% CF dose and B:C ratio (2.35) was highest with the application of 100% CF dose in finger millet.

Singh *et al*. (2018) found that soil test based recommendation (N:P:K:S:Zn:B 120:60:30:30:5:2 kg ha^{-1}) of fertilizer gave higher grain and straw yield of wheat.

Nutrient Mobilization through Microorganisms

Subramanian *et al*. (2009) reported that the Zn content of roots and shoots at 40 and 75 DAS were higher with the application of Zn (5.0 mg kg^{-1}) with inoculation of arbuscular mycorrhizal fungi in maize.

Anonymous (2012-17) found that grain yield of pigeon pea was significantly higher under treatment Fe50+ R-16 while Fe concentration was higher under the treatment Fe50+ Zn25+R-16 over the control.

Vaid *et al*. (2013) observed that highest grain yield of wheat cultivar WH 1021 registered under treatment AX + AB : (*Acinetobacter* sp. SG2 + *Acinetobacter* sp. SG3) whereas in case of VL 804 cultivar, BC + AX : (*Burkholderia* sp. SG1 + *Acinetobacter* sp. SG2) treatment recorded highest grain yield.

Nano Fertilizer

Tiwari (2017) revealed that the grain and stover yield of maize were significantly higher with foliar application of ZnO NPs @1000 ppm, but it was statistically at par with ZnO NPs @2000 ppm.

Prajapati *et al*. (2018) found that higher grain and stover yield of wheat were obtained with the application of ST-ZnO NPs @ 1000 ppm + FS-ZnO NPs @ 1000 ppm over rest of treatments.

Conclusion

Adoption of different advance micronutrient management strategies found beneficial for good quality and higher crop production. In agronomic approaches, pre-sowing seed treatments viz., seed soaking, seed coating and seed priming with micronutrients improved seed germination, plant growth, yield of crop as well as quality of produce. Enrichment of organic manures with the micronutrients increased the crop production and micronutrient concentration in crop produce. Foliar application of micronutrients, use of micronutrient nano particles as well as inoculation with microbes not only increases the crop production but decrease chemical load in soil.

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Sustainable Cocoa Production to Manage Amid Global Shortage

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Introduction

Cocoa is an important horticultural crop obtained from the seeds of the cocoa tree ***(Theobroma cacao L.)***, which grows mainly in tropical regions. These seeds, called cocoa beans, are the main raw material used to make chocolate. After harvesting, the beans are fermented, dried, roasted, and processed into cocoa liquor, cocoa butter, and cocoa powder. These products are widely used in chocolate as well as in bakery products, beverages, cosmetics, and some pharmaceutical products. Because of its many uses and high demand around the world, cocoa plays an important role in agriculture, trade, and the food industry. The scientific name Theobroma cacao means "food of the gods" in Greek.

Global Cocoa Shortage: Causes and Effects

The global cocoa shortage is mainly caused by climate change and extreme weather, crop diseases such as Black Pod Disease and Cocoa Swollen Shoot Virus (CSSV), ageing cocoa trees, low farmer income, limited investment, deforestation, poor soil management, and the increasing global demand for cocoa products. As a result, cocoa and chocolate prices have risen significantly, increasing production costs for manufacturers and reducing their profit margins. Consumers are also affected through higher prices and shrinkflation, where products become smaller while prices remain the same. The shortage has also encouraged greater investment in sustainable cocoa farming to improve long-term production.

Supply Chain and its Importance

The global cocoa supply chain explains how cocoa moves from small farmers to the final chocolate products sold to consumers. It is a long process involving many people and organisations, but the benefits are not shared equally. Farmers do most of the hard work, yet they usually receive the smallest part of the final price of chocolate.

The first step is cocoa farming. Cocoa is mainly grown in tropical regions, especially in West Africa, which produces around 70% of the world's cocoa. Most farmers have small farms and depend on family labour. However, they often face problems like low income, climate change, poor infrastructure and limited access to finance.

After harvesting, the cocoa beans are fermented and dried. Fermentation helps develop the chocolate flavour, while drying removes moisture and prepares the beans for storage and transport. In many areas, farmers do not have proper facilities or training, so the quality of beans can vary. Some farmers also sell their beans quickly because they need money immediately.

Next, farmers sell their cocoa to local traders, cooperatives or buying agents. At this stage, beans from different farms are mixed together, making it difficult to trace where the cocoa originally came from. Farmers usually have very little control over the price they receive.

Large trading companies then buy the cocoa in bulk and export it to other countries. These companies manage transportation, storage and international sales. Since only a few large traders control a major part of the market, they have strong bargaining power, while farmers remain at a disadvantage.

Importance of Cocoa in the Global Economy and Food Industry

Cocoa is one of the most important crops for the global chocolate industry. It provides income to more than five million smallholder farmers and creates employment for millions of people involved in farming, processing, transport, manufacturing, and trade. For many developing countries, especially those in West Africa, cocoa is an important source of export income and supports rural livelihoods. Apart from chocolate, cocoa is also used in bakery products, beverages, dairy products, cosmetics, and pharmaceutical products. This makes cocoa an important commodity for both the global economy and the food industry.

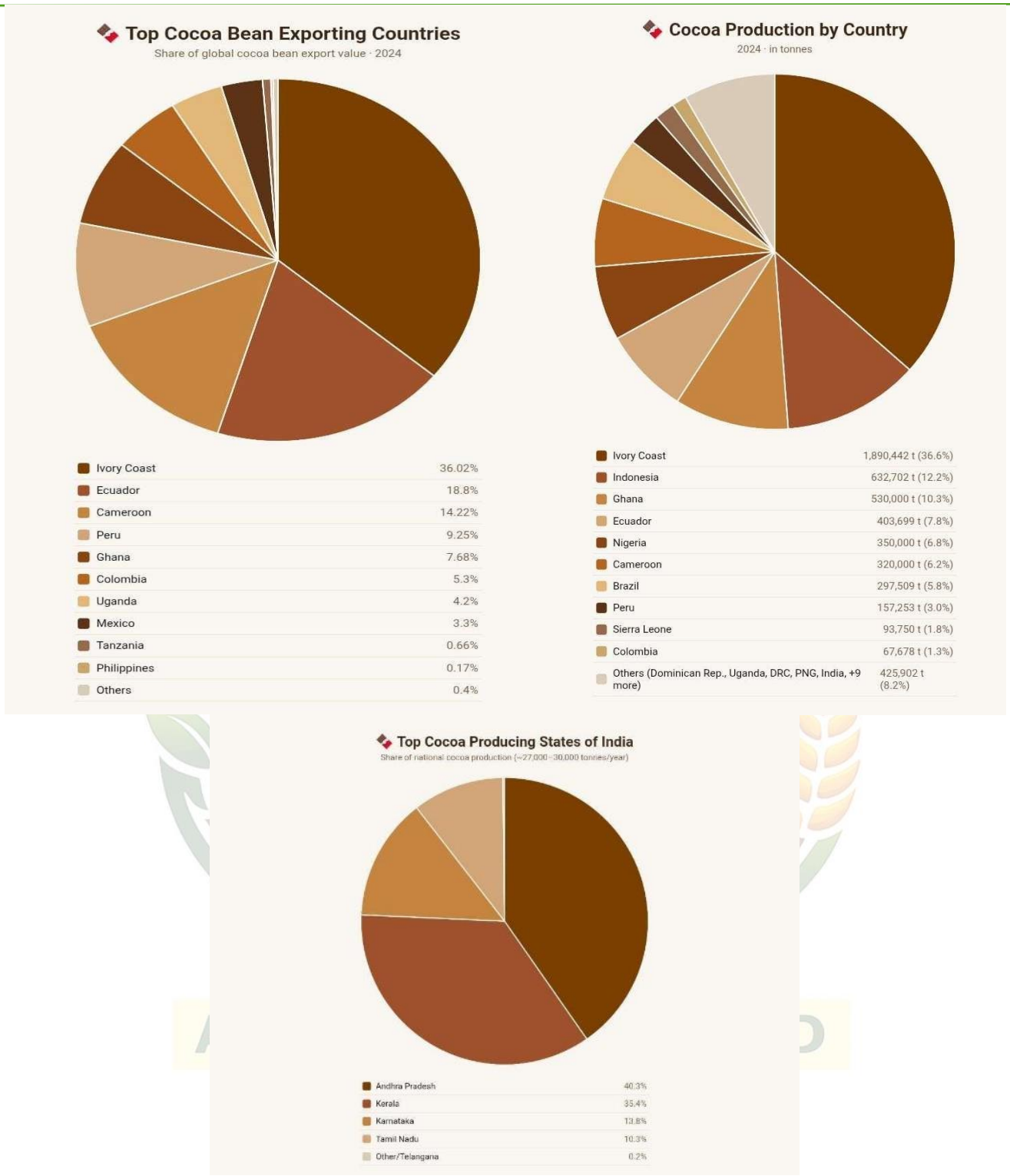


Fig. 1: Cocoa Production in India

Sustainability in Cocoa Production

The global cocoa industry is currently facing significant challenges that threaten the long-term viability of cocoa. Climate change, increasing pest and disease outbreaks, ageing cocoa trees, deforestation, and low farmer incomes have reduced cocoa production in many producing countries, particularly in West Africa. At the same time, the global demand for chocolate and cocoa-based products continues to rise, creating a gap between supply and demand and contributing to higher cocoa prices. These issues highlight the importance of adopting sustainable cocoa production practices to ensure a stable and reliable cocoa supply for the future. Sustainable cocoa production involves cultivating cocoa in ways that protect the environment, improve farmers' livelihoods, and maintain productivity for future generations. It is based on three key principles: environmental sustainability, economic sustainability, and social sustainability. These principles

promote the conservation of forests, soil, water, and biodiversity, while also improving farmers' incomes, encouraging fair labour practices, supporting gender equality, and strengthening rural communities.

Several sustainable farming practices contribute to achieving these goals. Agroforestry, climate-smart agriculture, soil and water conservation, integrated pest and disease management (IPDM), and farmer education and training help improve soil fertility, increase resilience to climate change, reduce crop losses, and enhance cocoa yield and bean quality. These practices also encourage the responsible use of fertilizers and pesticides, reducing negative impacts on the environment while supporting long-term agricultural productivity. Sustainable cocoa production provides numerous benefits for farmers, consumers, and the global cocoa industry. It increases productivity and bean quality, improves farmers' incomes and living standards, protects natural resources, reduces pest and disease losses, strengthens responsible sourcing and traceability, and ensures a more stable and resilient cocoa supply chain. However, achieving sustainability remains challenging due to climate change, persistent crop diseases, ageing plantations, limited financial resources, high implementation costs, deforestation, and inadequate access to training and modern agricultural technologies. Overall, sustainable cocoa production is essential for addressing the global cocoa shortage and ensuring the long-term future of the cocoa industry. Continued support from governments, research institutions, private companies, and farmers is necessary to promote sustainable farming practices, improve productivity, protect the environment, and secure a stable cocoa supply for future generations.

New Techniques and Varieties for Increasing Cocoa Production

Hand pollination in cocoa is an artificial breeding technique used to develop hybrid varieties by crossing selected parent plants with desirable characteristics. The process ensures controlled pollination by preventing unwanted pollen contamination and improving the chances of successful fertilization. In cocoa, emasculation is not required because the crop is naturally self-incompatible. After pollination, the flowers are labelled and monitored for fruit set, while the developing pods are protected until maturity. Although a mature cocoa tree produces thousands of flowers annually, only a small percentage develop into fruits under natural conditions. Hand pollination helps increase hybrid seed production and is most effective when carried out during the morning hours under favourable seasonal conditions.

Seed Garden and Clonal Orchards

Presence of self-incompatibility is observed in many cocoa populations. Self-incompatible but cross-compatible. genotypes are being utilised in hybrid seed production. The purpose of seed garden or clonal orchard is to produce seeds of known parentage and proven performance. Based on earlier progeny trials, best combining parents are selected, multiplied as clones and established as seed gardens or clonal orchards. These well-designed gardens will produce hybrid pods through natural cross pollination. If, the orchards are assembled with two self-incompatible and cross-compatible parents they are called as bi-clonal orchards and if planted with multiple self-incompatible and cross-compatible clones they are designated as poly-clonal orchards. It is important to establish such clonal gardens in research institutes and regional nurseries to meet out the future demand of seedlings.

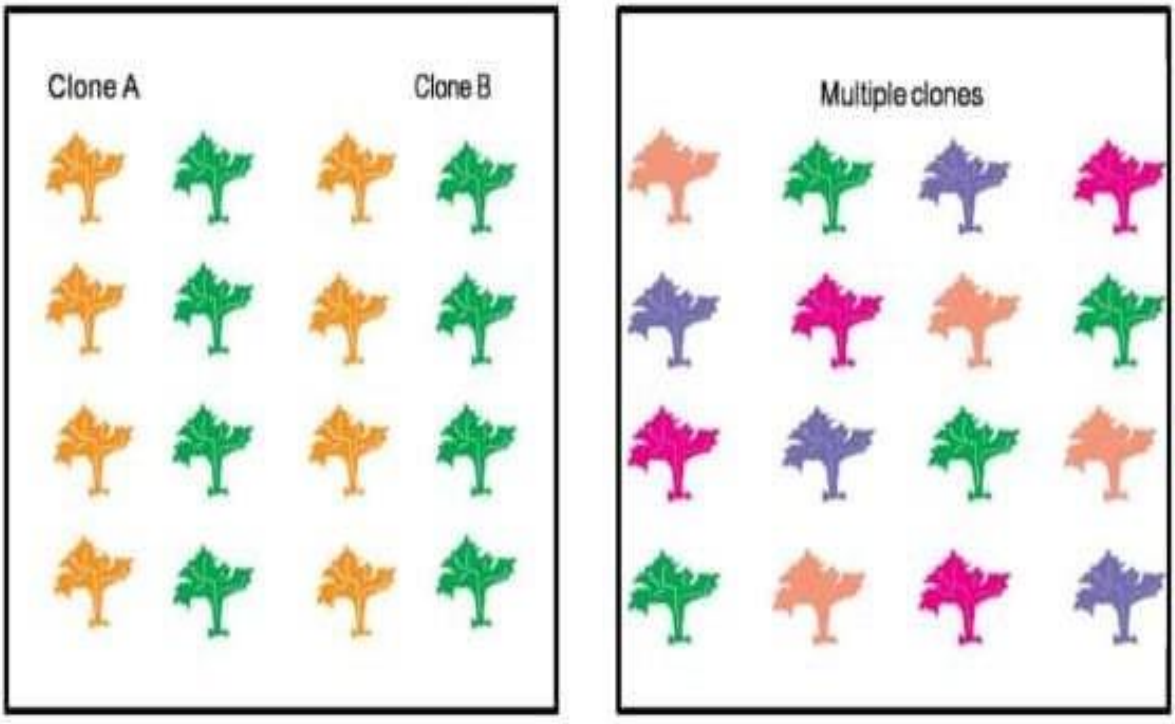


Fig. 2: Seed Garden in Cocoa



Fig. 3: Cocoa Varieties

Nutritional Management

Annual application of 100 g N, 40 g P_2O_5 and 140 g K_2O per tree in two equal splits, first dose in April-May and the second dose in September-October i.e. pre and post monsoon applications is recommended. Fertilizer may be applied uniformly around the base of the tree up to a radius of 30 cm (1 ft) during the first year, forked and incorporated into the soil. For grown up plants the best method is to rake and mix the fertilizers with soil in shallow basins of around 75 cm (2.5 ft). This radius may be increased gradually up to 90 cm (3 ft) after third year. Additional application of potassium in split doses is suggested in plants giving >1 kg dry beans.

Fertilizer (g/plant/year)	I year	II year	III year onwards	Fertigation
Nitrogen	33	66	100	Urea- 107 g Diammonium Phosphate- 145 g Muriate of Potash- 180 g
Phosphorous	13	26	40	
Potash	46	92	140	
Urea	72	144	220	
Rock phosphate	65	130	200	
Muriate of Potash	77	154	230	
Shallow basins	1 ft	2.5 ft	3 ft	

Fig. 4: Fertilizer scheduling in Cocoa

Irrigation

Cocoa plants require continuous supply of moisture for optimum growth and yield. Adequate irrigation is very important in both mono cropping and mixed cropping systems. Summer irrigation at weekly interval is essential in cocoa cultivation which coincides with flowering, fruit set and pod development. With flood/furrow irrigation trees should be irrigated once in five days with 175 litres of water and through drip with 20 litres of water per day per tree.

Pests and Diseases of Cocoa

Cocoa cultivation is affected by many pests and diseases which can reduce the yield as well as quality of beans. Proper field management and regular observation are very important to control these problems before they become serious. Among the diseases, **Black Pod Disease** is considered one of the major diseases in cocoa. It is caused by Phytophthora species. At first, small water-soaked spots appear on the pod and later the whole pod becomes black and starts rotting. This disease mostly spreads during the rainy season. Removal of infected pods, keeping the field clean, proper pruning and spraying 1% Bordeaux mixture at regular interval helps in controlling the disease. Another important disease is **Stem Canker**, which is also caused by Phytophthora.

Charcoal Pod Rot and **Cocoa Dieback** are caused by ***Lasiodiplodia theobromae*** . These diseases result in blackened pods, drying of branches and sometimes complete death of the plant. Regular pruning and destruction of infected branches can reduce the spread.

Many insect pests also attack cocoa. **Tea Mosquito Bug** is one of the most damaging pests. It sucks sap from young shoots, flowers and pods, leaving dark lesions and scars. Shade regulation, pruning and need-based insecticide spray can help in management.

Aphids and **Mealybugs** also suck plant sap from tender shoots and pods. Heavy infestation causes curling of leaves, poor growth and premature shedding of flowers and young pods. Natural enemies help in reducing their population, but severe attack may require neem-based products or suitable insecticides.

Other important pests include **Stem Borer, Cocoa Fruit Borer, Red Banded Thrips, rats and squirrels**, which damage stems or pods and reduce production. Therefore, maintaining proper orchard sanitation, timely pruning, regular monitoring and integrated pest management practices are essential for healthy cocoa cultivation and better yield.

Government and International Initiatives for Sustainable Cocoa Production

Several governments and international organizations have launched initiatives to promote sustainable cocoa production and improve farmers' livelihoods. Government of India gave emphasis on Cocoa development through 2026 post-budget scheme, 'National Cashew and Cocoa Development Programme to improve the challenges like- low productivity, senile plantation, high import dependence, small semi-mechanized units, week farmer-processor linkages, weak post-harvest management and fragmented supply chain. In India, the Mission for Integrated Development of Horticulture (MIDH) and the Directorate of Cashew nut and Cocoa Development (DCCD) support cocoa cultivation through quality planting materials, farmer training, nursery development, irrigation support, and technical guidance. Internationally, the Food and Agriculture Organization (FAO) promotes climate-smart agriculture, disease management, and sustainable farming practices.

Conclusion

The global cocoa shortage has become a major challenge due to climate change, crop diseases, ageing cocoa trees, and low farmer incomes. As the demand for cocoa and chocolate products continues to increase, adopting sustainable cocoa production practices has become more important than ever. Practices such as agroforestry, climate-smart agriculture,

soil conservation, and farmer training can help improve productivity while protecting the environment and supporting farmers' livelihoods. Governments, international organizations, private companies, and farmers must work together to promote sustainable cocoa production and ensure a stable cocoa supply for future generations. With the right policies and continued investment, the cocoa sector can become more resilient, benefiting both producers and consumers worldwide.

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Date Palm Cultivation in the Bundelkhand Region of India

Article ID: 74247

Manoj Gaund[1], Nidhika Thakur[1], Akhilesh Kumar Srivastava[1], Subhash Chandra Singh[1], Prashant Singh[1] and Anita Sahu[1]

[1]Department of Fruit Science, Banda University of Agriculture and Technology, Banda 210001, Uttar Pradesh, India.

Abstract

Bundelkhand's semi-arid climate and thin, moisture-poor soils cut out many conventional fruit crops but suit a species built for exactly these conditions. The date palm (*Phoenix dactylifera*) is among the oldest domesticated fruit trees, historically tied to Middle Eastern and North African oasis farming, and reached India's northwest through settlers and pilgrims returning from Arab lands an early planting at Bhuj is credited to the Maharaja of Kachchh. Today it is grown commercially in Gujarat's Kachchh belt (over 18,000 ha) as well as in Rajasthan, Punjab, Tamil Nadu and Karnataka. The Uttar Pradesh government has already flagged seven Bundelkhand districts Banda, Hamirpur, Chitrakoot, Mahoba, Jhansi, Jalaun and Lalitpur for date palm promotion, citing potential earnings of roughly ₹20,000 per tree.

Botany, Uses and Nutrition

A member of the Arecaceae family, the date palm is dioecious male and female flowers form on separate trees and can live over a century, eventually reaching up to 30 m with a crown 6–10 m across; its pinnate leaves run 4–6 m long with roughly 150 spiny-petioled leaflets. Fruit is eaten fresh (chhuhara) or dried, blended with milk, pressed for pulp-based drinks, or processed into paste and sugar for baking. Leaves go into mats and paper, petioles into brooms, trunks into timber and construction, and crushed seeds into livestock feed. Dried fruit is roughly 70% sugar and 25% moisture, with small amounts of protein, fibre, fat and minerals (table below).

Constituent	Moisture	Sugar	Protein	Fibre	Fat	Minerals	Phosphorus	Calcium	Iron
Share (%)	25	70	2	2.5	2.3	7–10 mg/100g	0.05–0.1	0.3	0.1

Climate and Soil

Sandy, free-draining soil suits date palm best, though it tolerates saline conditions reasonably well. Flowering (February–April) and fruit ripening (May–August) need long, hot, low-humidity summers with temperatures around 25–29°C; the palm can survive anywhere from 0°C to 50°C but stops growing below 6°C, and needs a frost-free winter to fruit reliably.

Varieties

Commercial cultivars fall into early, mid- and late-ripening groups, and separately into soft-fleshed, non-astringent and chhuhara-making types. Representative varieties:

Variety	Fruit character	Yield/tree
Barhee	Soft, widely grown in northern Egypt for home use	100–125 kg
Halawy	Medium fruit, yellow, mildly astringent at doka stage	~150 kg
Hayany	Small fruit, yellow and non-astringent at doka stage	75–100 kg
Khadrawy	Slow-growing, small-to-medium pale-yellow fruit	50–70 kg
Medjool	Large orange-yellow fruit with reddish stippling; firm flesh	75–100 kg
Zahidi	Small-to-medium, tolerant of humidity and rain	100–150 kg

Propagation and Planting

Seed-raised palms take 7–8 years to flower and split unpredictably into male and female plants, so growers instead use rooted offshoots from proven female mothers each mature palm gives 2–3 offshoots every four to six years, weighing 25–35 kg once separated. Tissue culture is used commercially where offshoot supply is limiting. February–March planting gives the best survival in Bundelkhand, letting offshoots establish through the summer, though the July–September monsoon window is also used locally. Pits are commonly spaced 6–8 m apart in commercial blocks (3–4 m in some Indian plantings), with 2–3 male plants included per block to ensure pollination.




Rooted offshoots ready for field planting; red palm weevil damage on a mature stem

Training, Pruning and Nutrition

Palms need no pruning before about five years of age. After that, old and damaged fronds, spent inflorescences and spines are removed each June, and fruit strands are thinned leaving too many leaves raises humidity around the bunches and invites disease, while too few reduces fruit quality. A typical feeding schedule builds up with age: about 20 kg farmyard manure and 100 g each of N, P and K per plant in year one, rising through 30, 40 and 50 kg FYM (with matching NPK increases) by year four, and up to 100 kg FYM with 1,000 g each of N, P and K per plant in mature palms split between an October–November dose (FYM plus half the nitrogen, full P and K) and a January–February top-up of the remaining nitrogen.

Flowering, Pollination and Fruit Set

Flowering starts two to three years after planting creamy-white, broom-like male spathes appear from January, while female spathes are yellowish and longer with fewer strands. Because wind and insect pollination is unreliable, growers hand-pollinate: mature male spathes are shade-dried, and the pollen (viable roughly three months at room temperature, up to a year if frozen) is dusted onto female flowers within two to three days of opening about 3–5 male trees typically service 100 females. A spray of 200 ppm ethephon 10–30 days after fruit set is used to thin bunches down to 1,300–1,600 fruits across 8–10 bunches per palm, improving fruit size and sugar content.




Ripening Stages, Harvest and Post-Harvest

Fruit passes through four recognised stages before harvest:

Local name	Arabic name	Timing after pollination	Fruit condition
Gandora	Chimiri	4–13 weeks	Hard, green
Doka	Khalal	13–17 weeks	Hard, yellow-pink to red; edible
Dang	Rutab	17–21 weeks	Softening at the tip; edible
Pind	Tamer	21–22 weeks	Fully ripe, 60–84% TSS; edible

Bearing typically starts in year four and becomes reliable by year six, averaging around 30 kg per palm under rainfed conditions and considerably more with irrigation. Because India's ripening season overlaps the monsoon, fruit is usually picked early at the doka stage, blanched in boiling water for five minutes, then dried either in an electric oven at 50°C for about 160 hours or in a sun drier to produce chhuhara, with a recovery of roughly 33–35%. Softer khalal-stage fruit is

similarly hot-water-treated but oven-dried at a milder 45–65°C for 60–65 hours. Beyond direct eating, dates go into soft drinks, pickle, jam, jelly and milkshakes.

Pests and Diseases

Red palm weevil and rhinoceros beetle are the two major threats; several secondary pests and two key diseases also need routine monitoring.

Pest / disease	Damage	Control
Red palm weevil	Grubs tunnel inside stem; fermenting odour from damaged tissue	Remove and burn infested tissue; seal fumigant (DDVP/aluminium phosphite) into stem
Black-headed caterpillar	Feeds inside leaf folds; fronds dry and brown, March–May	Remove infected leaves; monocrotophos as root application or 0.04% spray
Rhinoceros beetle	Bores into crown, damaging growing point; worse in monsoon on young palms	Field sanitation; BHC dust in compost pits and at crown/leaf base
Termite	Damages roots and trunk; offshoots wilt and die	Treat pits with 10% BHC before planting; chlorpyriphos drench; BHC around basins
Scale insects	Sap-sucking on leaf base; yellow crust cuts photosynthesis	Remove affected leaves; 0.08% malathion spray
Graphiola leaf spot	Dark pustules with yellow spores on leaves; worse in humidity	Remove and burn affected leaves; Bordeaux mixture or Dithane M-45 (0.2%)

Conclusion

Set against Bundelkhand's heat, water scarcity and degraded soils, date palm offers a long-lived, low-maintenance option once past its establishment years tolerant of drought and salinity, backed by growing government interest, and adaptable through hand pollination and offshoot propagation to local conditions. Careful attention to nutrition scheduling, pruning discipline and pest monitoring, particularly for red palm weevil, will determine how well that potential translates into consistent yields for growers in the region.

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Integrated Nutrient Management (INM) in Coconut Cultivation

Article ID: 74249

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Coconut (*Cocos nucifera* L.) is a perennial plantation crop with a productive lifespan extending up to 60–80 years. Sustaining productivity over such a long period requires a carefully planned nutrient management strategy that maintains soil fertility, ensures balanced nutrition, and minimizes environmental degradation. Integrated Nutrient Management (INM) offers a scientifically sound and economically viable approach by combining inorganic fertilizers, organic manures, and biofertilizers to achieve sustainable coconut production.

Concept and Importance of INM in Coconut

Integrated Nutrient Management is based on the principle that no single nutrient source can meet the entire nutritional requirement of a crop over time. Exclusive reliance on chemical fertilizers may lead to soil degradation, while sole dependence on organic inputs may not meet the crop's nutrient demand, especially in high-yielding systems. Therefore, INM integrates multiple nutrient sources to:

1. Maintain soil fertility and productivity
2. Improve nutrient use efficiency
3. Reduce dependency on chemical fertilizers
4. Enhance soil biological activity
5. Ensure environmental sustainability

In coconut gardens, where continuous nutrient removal occurs through harvest, INM plays a critical role in replenishing soil nutrients and maintaining yield stability.

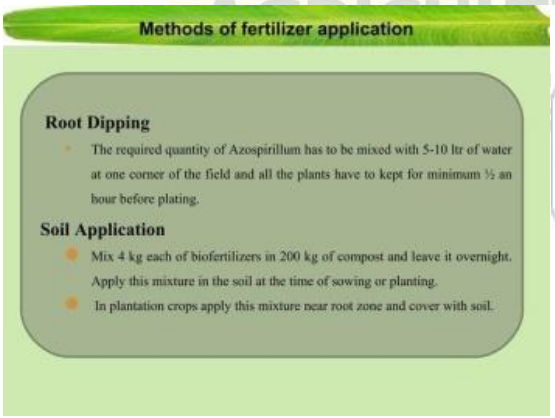
Role of Biofertilizers in Coconut Nutrition

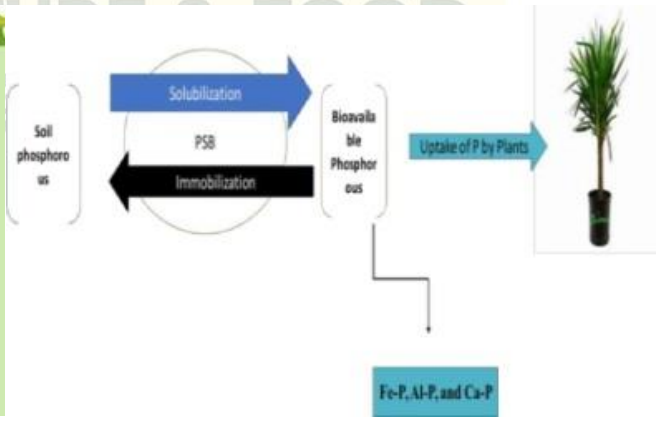
Coconut root zones naturally host beneficial microorganisms, including free-living nitrogen-fixing bacteria. These microbes possess nitrogenase activity, enabling them to convert atmospheric nitrogen into forms usable by plants.
Application of biofertilizers such as **Azospirillum**, which enhances nitrogen availability, and **phosphate-solubilizing bacteria (PSB)**, which convert insoluble phosphorus into plant-available forms, significantly improves nutrient availability and uptake efficiency in coconut.

Application method:

1. Apply near the active root zone (basin area)
2. Apply once every six months
3. Avoid mixing with chemical fertilizers or pesticides
4. Maintain adequate soil moisture for microbial survival

Biofertilizers reduce chemical fertilizer requirements and improve soil biological health, making them an essential component of INM.





INM Effects on Soil Fertility and Yield

Studies on coconut varieties such as East Coast Tall (ECT) have demonstrated that INM practices outperform both organic-only and inorganic-only systems. Key findings include:

1. Sustained availability of nitrogen (N), phosphorus (P), and potassium (K)
2. Improved soil structure and organic carbon levels
3. Enhanced microbial activity
4. Increased nut yield and copra quality

Importantly, research indicates that up to 50% of nitrogen fertilizer can be substituted with composted coir pith (CCP). This not only reduces input costs but also promotes recycling of coconut-based waste, contributing to circular agriculture. In contrast, omission of nutrient inputs leads to rapid nutrient depletion, poor palm vigor, and long-term soil degradation.

Soil Testing: Foundation of Scientific INM

A successful Integrated Nutrient Management (INM) program begins with regular soil testing, which provides critical information on the nutrient status of the soil, helps in the identification of macro- and micronutrient deficiencies, and determines key parameters such as soil pH and salinity levels.

Based on the soil test results, fertilizer recommendations can be customized to the specific needs of the field, rather than relying on blanket applications. This approach ensures balanced nutrient application, prevents over-fertilization, reduces input costs, and minimizes the risk of nutrient leaching and environmental pollution.

Therefore, periodic soil testing (once every 2–3 years) is essential for maintaining soil health and ensuring the long-term sustainability and productivity of coconut gardens.

Mulching as a Supportive Component

Mulching is an essential cultural practice that complements Integrated Nutrient Management (INM) by enhancing soil physical, chemical, and biological properties. It involves covering the soil surface around coconut palms with organic materials, which helps create a favorable microenvironment for root growth and nutrient uptake.

Common mulch materials include coconut husks, dried leaves, straw, and other crop residues.





Benefits of Mulching

1. Conserves soil moisture by reducing evaporation losses
2. Suppresses weed growth and competition
3. Improves soil structure and enhances organic matter content
4. Minimizes nutrient leaching, particularly of micronutrients like boron
5. Promotes microbial activity and overall soil health

In regions with high rainfall, mulching plays a vital role in preventing micronutrient deficiencies and sustaining soil fertility by reducing nutrient losses and maintaining a stable soil environment.

TNAU Coconut Tonic: A Supplementary Nutrient Source

Tamil Nadu Agricultural University has developed TNAU Coconut Tonic, a balanced liquid nutrient formulation containing macronutrients (N, P, K), secondary nutrients (Ca and Mg), and essential micronutrients such as Zn, Fe, and Mn. The tonic is applied at a rate of 200 ml per palm through the root feeding method, with applications recommended once every six months.

This formulation is particularly beneficial for bearing palms under nutrient stress, palms exhibiting deficiency symptoms, and for improving nut set and overall yield. However, it should be emphasized that the tonic is intended as a supplementary input and should not replace the regular fertilizer schedule under an Integrated Nutrient Management (INM) program.

Key Principles of Nutrient Management in Coconut

Effective INM requires adherence to several critical principles:

1. **Balanced Nutrition**: Apply both macro and micronutrients in appropriate proportions
2. **Right Timing**: Apply fertilizers during periods of adequate soil moisture (before rainfall or irrigation)
3. **Split Application**: Divide fertilizer doses into 2–3 splits to improve nutrient use efficiency and reduce losses
4. **Integration of Sources**: Combine organic, inorganic, and biological inputs for sustained fertility
5. **Micronutrient Management**: Pay attention to nutrients like boron and magnesium, which are crucial for nut development
6. **Moisture Management**: Ensure proper irrigation to facilitate nutrient uptake

Economic and Environmental Benefits of INM

Adoption of INM in coconut cultivation offers multiple advantages:

1. Reduced cost of chemical fertilizers
2. Improved yield stability over years
3. Enhanced soil health and structure
4. Increased resilience to climatic stress
5. Reduced environmental pollution

By recycling farm waste (such as coir pith and leaf residues), farmers can significantly cut input costs while improving sustainability.

Conclusion

Integrated Nutrient Management is essential for sustaining coconut productivity in the long term. By combining chemical fertilizers with organic manures, biofertilizers, and supportive practices like mulching and soil testing, INM ensures balanced nutrition, improved soil health, and higher yield efficiency.

Given the perennial nature of coconut, nutrient management decisions have long-lasting impacts. A well-designed INM strategy not only enhances productivity but also safeguards soil fertility, reduces environmental risks, and improves farmer profitability. Therefore, adopting INM is not just a recommendation—it is a necessity for sustainable coconut cultivation.

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Natural Farming for Sustainable Transformation of Indian Agriculture

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Agriculture in the 21st century faces a dual challenge: ensuring food security for a growing population while safeguarding natural resources for future generations. According to FAO (2017), conventional agriculture contributes nearly 20–30% of global greenhouse gas emissions and is a major driver of soil degradation, water pollution, and biodiversity loss. The widespread adoption of intensive farming practices—characterized by excessive chemical inputs, monocropping, and heavy mechanization—has led to declining soil fertility, reduced ecosystem resilience, and increased vulnerability to climate change. In this context, natural farming has emerged as a promising and sustainable alternative that aligns agricultural productivity with ecological integrity.

Natural farming is a holistic approach that emphasizes working in harmony with nature by minimizing external inputs and enhancing biological processes. It relies on locally available resources, promotes biodiversity, and reduces soil disturbance. Unlike conventional systems that depend heavily on synthetic fertilizers and pesticides, natural farming seeks to restore ecological balance while maintaining or even enhancing crop productivity. By integrating traditional knowledge with modern ecological principles, it offers a pathway toward sustainable agricultural transformation in India.

Environmental Concerns of Conventional Agriculture

The intensive use of chemical fertilizers and pesticides in conventional agriculture has significantly impacted soil health and environmental quality. Continuous application of synthetic inputs disrupts soil microbial communities, reduces Soil Organic Carbon (SOC), and weakens nutrient cycling processes (Pimentel et al., 2005). Over time, this leads to soil compaction, reduced water infiltration, and declining productivity.

Monocropping systems further exacerbate these issues by reducing biodiversity and increasing susceptibility to pests and diseases. Such simplified ecosystems lack natural regulatory mechanisms, often resulting in pest outbreaks that require further chemical interventions. Additionally, nutrient runoff from agricultural fields contributes to water pollution, affecting aquatic ecosystems and human health. These challenges highlight the urgent need for sustainable alternatives like natural farming.

Soil Health and Organic Carbon Enhancement

Soil Organic Carbon is a critical indicator of soil health, influencing soil structure, water retention, and nutrient availability. Natural farming practices such as mulching, incorporation of organic residues, intercropping, and reduced tillage significantly enhance SOC levels. Studies have shown that these practices can increase SOC by 25–30% compared to conventional systems (Rao et al., 2019).

Enhanced SOC promotes microbial activity, which plays a vital role in decomposing organic matter and releasing essential nutrients. A biologically active soil not only improves plant growth but also increases resilience against environmental stresses such as drought and nutrient deficiency. Thus, natural farming contributes to long-term soil fertility and sustainability.

Intercropping: Enhancing Resource Use Efficiency

Intercropping is a key component of natural farming systems, involving the cultivation of multiple crops in the same field. This practice enhances resource utilization by exploiting differences in crop growth patterns, root structures, and nutrient requirements. Crops complement each other in utilizing sunlight, water, and nutrients more efficiently than monocultures.

One of the important indicators of intercropping efficiency is the Land Equivalent Ratio (LER), which compares the productivity of intercropping systems with sole cropping. An LER greater than 1 indicates higher productivity per unit area. Intercropping not only improves yields but also reduces pest incidence and enhances soil fertility, thereby minimizing the need for external inputs.

Biodiversity and Ecosystem Services

Natural farming systems promote biodiversity at multiple levels, including soil microorganisms, insects, plants, and animals. This diversity strengthens ecosystem services such as pollination, nutrient cycling, and natural pest control. Diverse cropping systems create habitats for beneficial organisms like predators and parasitoids, which help regulate pest populations naturally (Altieri, 1999).

By fostering ecological interactions, natural farming enhances system resilience and stability. This reduces dependency on chemical pesticides and contributes to environmental conservation. Biodiversity-rich systems are better equipped to withstand climatic variability and biological stresses.

Pest and Disease Management

One of the significant advantages of natural farming is its ecological approach to pest and disease management. Instead of relying on chemical pesticides, it utilizes biological control mechanisms and habitat management strategies. Practices such as intercropping, crop rotation, and multi-layer cropping create complex ecosystems where pests are naturally suppressed by their predators.

Botanical extracts, bio-inputs, and traditional formulations further support plant health and resistance. These methods reduce the risk of pesticide residues, improve food safety, and protect beneficial organisms. As a result, natural farming systems maintain ecological balance while ensuring sustainable crop protection.

Benefits of Mulching

1. Conserves soil moisture by reducing evaporation losses
2. Suppresses weed growth and competition
3. Improves soil structure and enhances organic matter content
4. Minimizes nutrient leaching, particularly of micronutrients like boron
5. Promotes microbial activity and overall soil health

In regions with high rainfall, mulching plays a vital role in preventing micronutrient deficiencies and sustaining soil fertility by reducing nutrient losses and maintaining a stable soil environment.

Water Use Efficiency and Conservation

Water scarcity is a growing concern in Indian agriculture, making efficient water management essential. Natural farming practices significantly improve water use efficiency through techniques such as mulching; cover cropping, and rainwater harvesting. Mulching reduces evaporation losses and maintains soil moisture, while cover crops improve soil structure and infiltration.

Efficient irrigation methods, including drip irrigation, further enhance water productivity by delivering water directly to the root zone. These practices not only conserve water but also improve crop performance under limited water conditions, making natural farming suitable for drought-prone regions.

Climate Change Mitigation and Adaptation

Natural farming plays a crucial role in addressing climate change by both mitigating greenhouse gas emissions and enhancing adaptive capacity. Increased SOC levels contribute to carbon sequestration, thereby reducing atmospheric carbon dioxide levels (Lal, 2004). Reduced dependence on synthetic inputs also lowers emissions associated with their production and use.

Moreover, diversified farming systems are inherently more resilient to climate variability, including droughts, floods, and temperature extremes. By improving soil health and ecosystem stability, natural farming enhances the adaptive capacity of agricultural systems, ensuring sustainable production under changing climatic conditions.

Economic Viability and Farmer Livelihoods

Natural farming reduces input costs by minimizing the use of external inputs such as chemical fertilizers and pesticides. Farmers rely on locally available resources, which lower production costs and increases net returns. Additionally, the growing demand for organic and chemical-free produce offers premium market opportunities. Improved soil health and ecosystem services contribute to stable yields over time, enhancing income security for farmers. Natural farming also promotes self-reliance and reduces financial risks associated with input-intensive agriculture. This makes it particularly beneficial for small and marginal farmers in India.

Conclusion

Natural farming represents a paradigm shift from input-intensive agriculture to a sustainable, ecology-based production system. It offers multiple benefits, including improved soil health, enhanced biodiversity, efficient resource utilization, and reduced environmental impact. By integrating traditional knowledge with scientific advancements, natural farming provides a viable solution to the challenges posed by conventional agriculture.

Large-scale adoption of natural farming models has the potential to transform Indian agriculture by ensuring food security, improving farmer livelihoods, and conserving natural resources. It aligns with the goals of sustainable development and climate resilience, making it a key strategy for the future of agriculture in India and beyond.

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Role of Antibiotics for Managing Plant Pathogenic Bacteria

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Abstract

Plant bacterial diseases are serious challenges to global agriculture. They cause significant yield and quality losses in cereals, fruits, vegetables, legumes, ornamental plants and plantation crops. Antibiotics like streptomycin, oxytetracycline, kasugamycin and gentamicin have played a key in managing these diseases by blocking essential cellular processes, especially protein synthesis. This review covers the major plant pathogenic bacteria, mechanisms of antibiotic action, methods of antibiotic application and the emergence of antibiotic resistance. It also discusses how resistance spreads through genetic mutations and horizontal gene transfer, posing a risk to the long term effectiveness of antibiotic use in managing diseases.

Keywords: Plant pathogenic bacteria, antibiotics, Mechanism of action, Antibiotic resistance.

Introduction

Plant bacterial diseases that affect cereals, fruits, vegetables, legumes, ornamental plants and plantation crops pose major limitations for the global agriculture productivity. These diseases compromises the sustainability of global agricultural systems while at the same time reducing crop productivity and increasing costs of production (Batuman *et al.*, 2024). Destructive plant diseases caused by bacteria pathogens including *Xanthomonas oryzae pv. oryzae*, *Ralstonia solanacearum*, *Erwinia amylovora*, *Pseudomonas syringae*, *Xanthomonas citri subsp. citri* and *Pectobacterium spp.* Increasing temperature, changing precipitation patterns and increasing number of extreme weather events are indicative of climate change, is increasing the incidence, severity and geographical spread of various bacterial diseases, stressing the need for sustained strategies for disease control (Batuman *et al.*, 2024). The absence of efficient chemical bactericides has made controlling bacterial diseases of plants becomes highly challenging. Antibiotics have been very important in ensuring that economic bacterial diseases control since the 1950s (McManus *et al.*, 2002). Antibiotics prevent pathogens by targeting critical processes in bacteria, which include protein synthesis and nucleic acid metabolism (Wilson, 2014; Batuman *et a*l., 2024).

Mechanisms of Action of Major Antibiotics

Streptomycin: Streptomycin, an aminoglycoside antibiotic, by binds permanently to the 30S subunit of the ribosome and the interaction with the 16S ribosomal RNA (rRNA) and S12 ribosomal protein leads to inhibition of bacterial protein synthesis (Wilson, 2014). The binding leads to reduced translation efficiency and inhibits the formation of the translation initiation complex, thus causing error in translation of the mRNA with incorporation of incorrect amino acids in the growing polypeptides (Kotra *et al.*, 2000). The death of bacterial cells and inhibition of protein synthesis occurs due to such aberrant proteins, especially those incorporated into the cytoplasmic membrane (Davis, 1987; Wilson, 2014).

Oxytetracycline: Oxytetracycline is a tetracycline antibiotic through reversible binding to the 30S ribosomal subunit near the A site of the ribosome, affects the process of bacterial protein synthesis by blocking aminoacyl transfer RNA (aminoacyl-tRNA) from binding to the ribosome (Wilson, 2014). The formation of bacterial proteins needed for bacterial survival and metabolic processes is hindered since peptide chain elongation does not take place. Oxytetracycline exerts bacteriostatic effect since its interaction with the ribosome is reversible and does not lead to bacterial cell death (Chopra and Roberts, 2001).

Kasugamycin: Kasugamycin is an aminoglycoside antibiotic has a different mechanism of action compared to other aminoglycosides. By binding to the 30S ribosomal subunit around the decoding region for mRNA and inhibiting the process of interaction of mRNA and initiator tRNA (fMet-tRNA), it inhibits bacterial protein synthesis (Schuwirth *et al.*, 2006; Wilson, 2014). Consequently, protein synthesis cannot begin without disrupting the accuracy of translation or misreading mRNA due to the inability in production of a proper 70S initiation complex (Schuwirth *et al.*, 2006). Kasugamycin has bacteriostatic activity since protein synthesis cannot initiate (Wilson, 2014).

Mechanisms of Antibiotic Resistance in Bacteria

Spread of antibiotic resistance among plant pathogenic bacteria, which has become a major challenge in achieving sustainable control of bacterial diseases in plants (Fair & Tor, 2014). When resistance is acquired through either genetic mutation or through horizontal gene transfer mechanisms such as conjugation, transformation and transduction, the populations of bacteria become highly resistant to antibiotics within a very short period of time (McManus *et al.*, 2002). Four broad categories that can be employed in classifying the factors responsible for the development of antibiotic resistance among PPB includes reduced accumulation of antibiotic within the bacteria due to poor permeability and active efflux, enzymatic inactivation of the antibiotic, Alteration or protection of the antibiotic target site and metabolic avoidance or bypassing of the cellular pathway inhibition is included in these strategies (Blair *et al.*, 2015).

Table 1: Antibiotic resistance mechanisms in plant pathogenic bacteria:

Resistance mechanism	Molecular basis	Antibiotics affected	Key references
Target-site modification	Mutations in ribosomal proteins or 16S rRNA reduce antibiotic binding	Streptomycin, Kasugamycin	Schuwirth *et al.* (2006)
Enzymatic inactivation	Antibiotic molecules are chemically modified	Streptomycin, Gentamicin	Becker and Cooper (2013)
Active efflux pumps	Membrane transporters actively export antibiotics from the bacterial cell	Oxytetracycline, Kasugamycin, Streptomycin	Chopra and Roberts (2001)
Reduced membrane permeability	Alterations in outer membrane porins or lipopolysaccharides decrease antibiotic uptake	Streptomycin, Oxytetracycline, Kasugamycin	Wilson (2014)
Biofilm formation	Extracellular polymeric substances restrict antibiotic penetration and promote bacterial persistence	Streptomycin, Oxytetracycline, Gentamicin	Hall and Mah (2017)
Horizontal gene transfer	Resistance genes are disseminated via plasmids, transposons, integrons, and bacteriophages	Streptomycin, Oxytetracycline, Gentamicin	McManus *et al.* (2002)

Conclusion and Future Perspectives

Antibiotics remained important for managing plant bacterial diseases, especially in high-value crops where effective chemical options are limited. Streptomycin, oxytetracycline, and kasugamycin target bacterial pathogens by blocking key cellular processes, primarily protein synthesis. To prevent the antibiotic resistant development in plant bacteria, antibiotics should be used carefully as part of integrated disease management strategies to maintain their effectiveness and support sustainable crop protection. Future research should aim at creating safer and more specific antibacterial compounds, enhancing precision delivery methods, and promoting responsible antibiotic use in agriculture.

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Harnessing Beneficial Prokaryotic Bacteria for Plant Disease Management: Current Advances and Future Prospects

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Abstract

Plant diseases cause significant crop losses and threaten global food security. Overreliance on chemical pesticides has led to environmental concerns and pathogen resistance, increasing the need for sustainable alternatives. Beneficial prokaryotic bacteria, including plant growth-promoting rhizobacteria (PGPR), endophytic bacteria and actinobacteria suppress pathogens through multiple biocontrol mechanisms while enhancing plant growth and immunity. Recent advances in genomics, microbiome engineering and bioformulation technologies have improved their application in crop protection. This review summarizes their mechanisms, recent developments, challenges and future prospects in sustainable plant disease management.

Keywords: Beneficial prokaryotic bacteria; Plant growth-promoting rhizobacteria (PGPR); Endophytic bacteria; Biological control; Sustainable agriculture.

Introduction

Plant diseases caused by fungal and bacterial pathogens significantly reduce crop productivity, quality and food security worldwide, causing annual yield losses of nearly 20–40% in major crops (Savary *et al.*, 2019). Although synthetic fungicides and bactericides have been widely used for disease control, their excessive application has resulted in environmental pollution, harmful effects on non-target organisms and the rapid development of resistant pathogen populations (Popp *et al.*, 2013).

The increasing incidence of resistance to major fungicides and bactericides has reduced the long-term effectiveness of chemical disease management, highlighting the need for sustainable alternatives (Lucas *et al.*, 2015). Consequently, integrated disease management strategies that combine biological and ecological approaches are receiving increasing attention. Beneficial prokaryotic bacteria, including plant growth-promoting rhizobacteria (PGPR), endophytes and actinobacteria, have emerged as effective biological control agents. These microorganisms suppress pathogens through mechanisms such as antibiotic as well as siderophore production, hydrolytic enzyme secretion, competition for nutrients and induction of systemic resistance, while also enhancing plant growth (Backer *et al.*, 2018). Recent advances in genomics, microbiome research, synthetic biology and multi-omics technologies have improved the understanding and application of bacterial biocontrol agents for sustainable agriculture (Compant *et al.*, 2021; Finkel *et al.*, 2020).

Beneficial Prokaryotic Bacteria Used in Plant Disease Management

Beneficial prokaryotic bacteria are naturally occurring microorganisms that colonize plant roots, tissues, leaves and surrounding soil. They promote plant growth, improve nutrient availability, suppress pathogens, and reduce reliance on chemical pesticides, making them important components of sustainable agriculture (Backer *et al.*, 2018).

Plant Growth-Promoting Rhizobacteria (PGPR): Root-associated bacteria that enhance plant growth, improve nutrient uptake, produce phytohormones and induce systemic resistance against pathogens (Backer *et al.*, 2018).

Endophytic Bacteria: Bacteria living inside healthy plant tissues that suppress pathogens through antimicrobial metabolites and activation of host defense mechanisms (Compant *et al.*, 2021).

Rhizosphere Bacteria: Root-zone bacteria that protect plants by competing with pathogens and producing antibiotics, siderophores and hydrolytic enzymes (Berendsen *et al.*, 2012).

Epiphytic Bacteria: Microorganisms inhabiting plant surfaces that limit pathogen establishment through niche competition and antimicrobial activity (Lindow and Brandl., 2003).

Cyanobacteria: Nitrogen-fixing photosynthetic bacteria that improve soil fertility and help suppress soil-borne diseases (Singh *et al.*, 2016).

Actinobacteria: Especially *Streptomyces* spp., these bacteria produce diverse antibiotics and enzymes effective against many fungal and bacterial plant pathogens (Barka *et al.*, 2016).

Mechanisms of Plant Disease Suppression

Beneficial prokaryotic bacteria suppress plant diseases by multiple direct and indirect mechanisms that inhibit pathogens and enhance plant defense, providing sustainable disease control (Backer et al., 2018). They produce antimicrobial compounds such as surfactins, iturins, fengycins, phenazines, pyrrolnitrin, and 2,4-DAPG that inhibit pathogen growth. These bacteria also compete with pathogens for nutrients and colonization sites, produce siderophores that limit iron availability to pathogens, and secrete hydrolytic enzymes including chitinases and glucanases that degrade fungal cell walls (Lugtenberg and Kamilova., 2009; Barka *et al.*, 2016). In addition, biofilm formation enhances root colonization and survival, while quorum quenching disrupts pathogen communication and virulence (Dong *et al.*, 2001). Beneficial bacteria further induce systemic resistance (ISR) through jasmonic acid- and ethylene-mediated pathways release volatile organic compounds (VOCs) that promote plant growth and suppress pathogens, and improve disease resistance by maintaining a balanced and beneficial plant microbiome (Trivedi *et al.*, 2020).

Current Advances in Beneficial Prokaryotic Bacteria for Plant Disease Management

Microbiome engineering: Manipulates plant-associated microbial communities to improve disease resistance and crop productivity (Trivedi *et al.*, 2020).

Multi-strain consortia: Combines compatible bacterial strains to enhance pathogen suppression, nutrient use, and field performance (Compant *et al.*, 2021).

Synthetic microbial communities (SynComs): Designed microbial mixtures that mimic natural microbiomes for improved disease control and plant growth (Niu *et al.*, 2017).

Genome sequencing: Identifies genes responsible for biocontrol traits, enabling selection of superior bacterial strains (Finkel *et al.*, 2020).

CRISPR-Cas technology: Improves beneficial bacteria by editing genes involved in antimicrobial production, stress tolerance, and root colonization (Barrangou and Doudna, 2016).

Artificial intelligence (AI): Uses genomic and microbiome data to identify promising biocontrol agents and optimize microbial formulations (Xu *et al.*, 2024; Trivedi *et al.*, 2023).

Nanotechnology: Nano-carriers improve bacterial stability, survival, and controlled release during storage and field application (Kumar *et al.*, 2023).

Encapsulation: Biodegradable polymers such as alginate and chitosan protect bacterial cells and enhance shelf life and field efficacy (John *et al.*, 2020).

Challenges and Limitations

Despite their promising role in sustainable plant disease management, the large-scale application of beneficial prokaryotic bacteria remains constrained by several factors. Their performance is often inconsistent under field conditions because environmental variables such as temperature, soil pH, moisture, nutrient availability, and native microbial communities influence bacterial survival, colonization and biocontrol activity (Compant *et al.*, 2021). In addition, the limited shelf-life of microbial formulations and poor establishment due to competition with indigenous microorganisms reduce their effectiveness (Lugtenberg and Kamilova, 2009). Commercialization is further hindered by complex regulatory requirements and biosafety evaluations, while high production costs, inconsistent results and limited farmer awareness slow adoption, particularly in developing countries (Compant *et al.*, 2008).

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Future Prospects

Emerging technologies are expected to improve the efficiency and adoption of beneficial prokaryotic bacteria in sustainable agriculture. Precision agriculture enables targeted application of microbial inoculants for effective disease management (Trivedi *et al.*, 2020). Advances in metagenomics and multi-omics are facilitating the discovery of beneficial microbes and improving understanding of plant–microbe interactions (Finkel *et al.*, 2020; Compant *et al.*, 2021). Microbiome engineering and synthetic biology are supporting the development of superior bacterial strains with enhanced biocontrol potential and stress tolerance (Toju *et al.*, 2018). In addition, nano- and encapsulation-based formulations improve bacterial survival, shelf-life and field persistence (Kumar *et al.*, 2023). Artificial intelligence (AI) is further accelerating the identification and selection of efficient microbial strains using genomic and microbiome datasets (Trivedi *et al.*, 2023). Together, these advances are expected to strengthen sustainable plant disease management while reducing dependence on chemical pesticides.

Conclusion

Beneficial prokaryotic bacteria represent an effective and environmentally sustainable approach to plant disease management. They protect crops through multiple mechanisms. Including pathogen inhibition, activation of plant defense responses and improvement of plant growth and nutrient availability. Recent progress in multi-omics, microbiome research, synthetic biology, artificial intelligence and advanced formulations has accelerated the development of reliable bacterial biocontrol agents. Nevertheless, challenges such as variable field performance, formulation stability, limited shelf life and regulatory constraints continue to limit their large-scale use. Future research should emphasize the development of robust microbial consortia, innovative formulations and precision application methods to improve field efficacy. Overall, beneficial prokaryotic bacteria have significant potential to reduce dependence on chemical pesticides and support sustainable climate-resilient agriculture while enhancing crop productivity and food security.

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Sustainable Utilization of Agricultural Food Waste for Functional Food Development

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Abstract

The generation of agricultural and food processing waste has increased considerably, creating significant environmental and economic challenges. However, these by-products are rich sources of valuable bioactive compounds. Their recovery and utilization offer a sustainable approach for developing functional foods with enhanced nutritional and health-promoting properties. Bioactive compounds can be recovered using conventional and advanced extraction technologies. Emerging non-thermal methods such as ultrasound, microwave, enzyme, pressurized liquid and supercritical fluid-assisted extraction provide higher recovery efficiency, reduced solvent and energy consumption, shorter processing times, and better preservation of heat-sensitive compounds than conventional techniques.

Introduction

Agriculture and food processing industries generate by-products and waste materials such as fruit peels, seeds, pomace, vegetable trimmings, cereal bran and spent residues. But such substances are usually thrown away or used for feeding animals, which causes economic loss and environmental problems. However, recent studies have demonstrated that many agricultural wastes are rich sources of bioactive compounds such as dietary fiber, antioxidants, polyphenols, vitamins, minerals and natural pigments. These valuable components can be exploited to develop functional foods that provide health benefits beyond basic nutrition.

Functional foods are foods that contain biologically active ingredients that have positive effects on health and can prevent diseases. Agricultural by-products are a cheap and sustainable source of such ingredients. For instance, mango peel has carotenoids and phenolic compounds while citrus peels are rich in pectin and flavonoids. Grape pomace contains antioxidants while rice bran is a good source of dietary fibre and essential fatty acids. These materials can be added to food products to boost their nutritional value and reduce food waste.

There are many advantages of using agricultural waste for functional food production. It reduces environmental pollution, lowers disposal costs, creates additional income opportunities for farmers and food processors, and promotes sustainable food systems. Moreover, the global demand for natural and health-promoting foods is increasing, thus providing a growing market for functional food products derived from agricultural by-products. But its potential needs to be addressed with challenges such as proper collection, processing, quality control and consumer acceptance. Technologies such as drying, milling, extraction and encapsulation can help to retain the functional properties of bioactive compounds and improve the quality of the product.

Bioactive Compounds

Agricultural and food wastes are widely recognized as important sources for the recovery of high-value bioactive compounds because they are rich in carbohydrates, proteins, phenolic compounds, dietary fibers, sugar derivatives, organic acids, vitamins and minerals (Barati, 2023). The most prevalent bioactive components found in agricultural waste products are phenolic compounds, which include flavonoids, phenolic acids, tannins, and lignans. These substances have strong antioxidant properties and have been linked to lower risks of cancer, heart disease and neurological conditions. While grape pomace has three to five times more anthocyanins than grape juice, apple pomace has two to four times more phenolic content than apple flesh. Besides fruits and vegetables, polyphenols are also abundant in food wastes generated from other sectors, including cereal and grain by-products (e.g., wheat bran and rice husk), legume hulls, beverage industry residues such as spent tea leaves and coffee grounds, and nut and oilseed processing wastes, including peanut skins and olive pomace (Mia et al., 2025). The content and composition of polyphenols vary considerably depending on the type of raw material, processing techniques, and storage conditions. Dietary fiber is commonly present in food waste derived from discarded fruits, vegetables, grains, and food processing by-products, including peels, skins, and stems. Cellulose, hemicellulose, pectin and lignin are components of dietary fiber that offer several health advantages, such as better digestive health, lower cholesterol and better control of blood sugar. While vegetable pomace offers 40–60% total dietary fiber with advantageous prebiotic qualities, citrus peels contain 60–70% pectin (Dhingra et al., 2012).

Extraction Methods

Valuable phytochemicals like polyphenols, flavonoids, carotenoids, dietary fibers, and bioactive peptides have been isolated using a variety of extraction techniques, including solvent extraction, ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), enzyme-assisted extraction (EAE), pressurized liquid extraction (PLE), and supercritical fluid extraction (SFE) (Fig.1). Traditional extraction methods, including soxhlet extraction, maceration, infusion, percolation, decoction, steam distillation and hydro distillation are widely employed for bioactive compound recovery. Nevertheless, they often require large volumes of organic solvents, involve higher costs and purity requirements, exhibit lower extraction efficiency, demand longer processing times and higher temperatures and may produce hazardous residues. Prior to extraction, food waste generally undergoes pretreatment processes, such as washing, cutting, size reduction and drying to improve the recovery of bioactive compounds.

Emerging extraction technologies are primarily based on non-thermal approaches that enhance the recovery of bioactive compounds while preventing thermal degradation of the waste matrix and minimizing energy consumption. The inherent moisture present in agricultural waste can influence molecular interactions during extraction when exposed to external energy sources. To improve extraction efficiency from high-moisture residues, techniques such as microwave-assisted and ultrasound-assisted extraction are commonly employed. The extraction yield of bioactive compounds is influenced by several factors, including the extraction technique, physicochemical properties of the waste material, solvent type, extraction temperature, processing time and pressure. Compared with conventional methods, non-conventional extraction techniques offer several advantages, such as higher extraction efficiency, shorter processing times, lower solvent and energy consumption and improved preservation of heat-sensitive bioactive compounds. Following extraction, the crude extract contains a mixture of bioactive compounds, which are subsequently identified and quantified to characterize the composition of the extracted bioactive constituents.

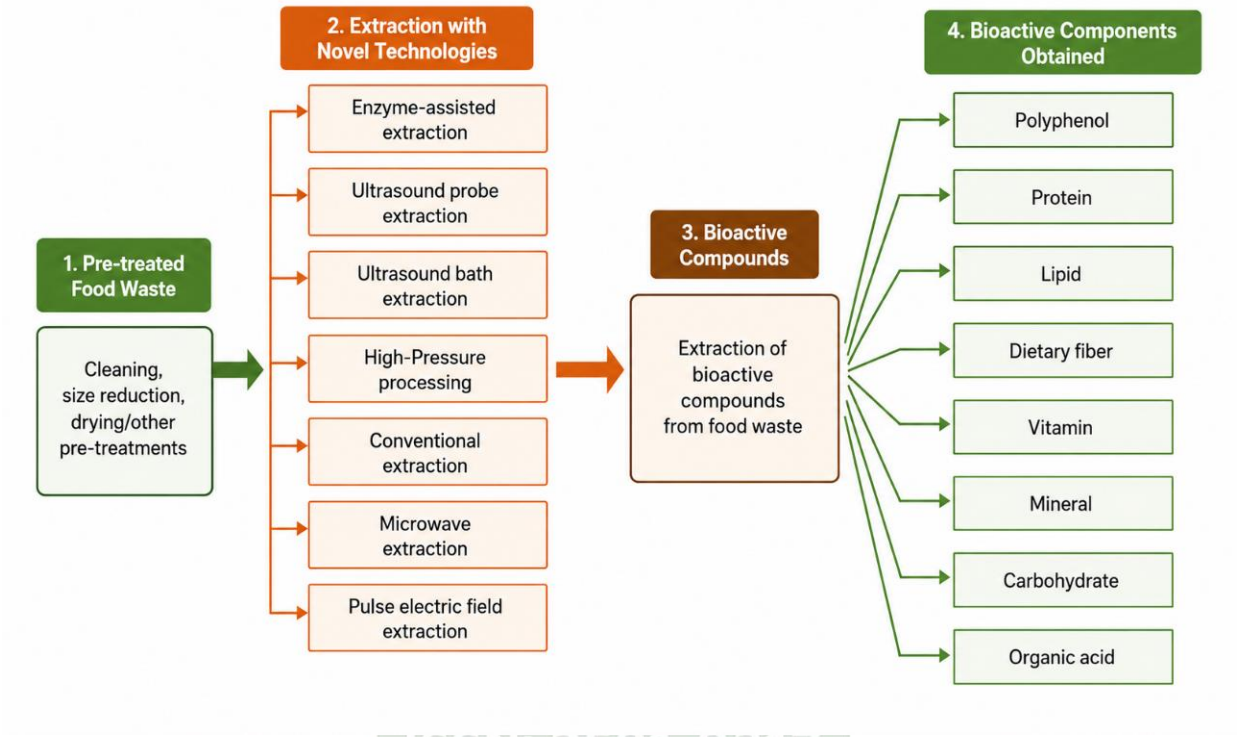


Fig.1. Extraction methods for recovery of bioactive compounds from pretreated food waste

Functional Foods

Agricultural waste can be converted into various value-added functional food products. The fruit peel powders can be used in bakery products such as biscuits, cake and bread to increase the fiber and antioxidant contents. Apple and grape pomace can be utilized for production of beverages, snack foods and cereal bars. Breakfast cereals and health supplements can be made from rice bran. Soups, noodles and extruded products can be enriched with vegetable waste powders. Such applications not only improve the nutritional quality, but also contribute to the circular economy by converting waste into valuable resources. Some of the foods fortified with fruit waste are listed in Table1.

Table1. Use of fruit waste in fortified products:

Product Developed	By product used	Fortification Status
Cookies	Grape Pomace (20-30%)	Dietary fiber, total phenolic content (TPC) and free-radical scavenging activity of cookies increased

Biscuits	Pomegranate peel (1-10%)	Increased functional properties of biscuits by addition of PGP with high dietary fiber, total polyphenol, ß-carotene, calcium and iron.
Icecream	Pomegranate Peel (0.1 and 0.4%)	PGP supplementation significantly increased total acidity, decreased pH, and affected the color of the ice cream. In addition, pomegranate seed oil increased the conjugated fatty acid content, while the combined incorporation of PGP and pomegranate seed oil enhanced the antioxidant and antidiabetic properties of the ice cream.
Idli	Mango seed kernel (MSK) (40%)	Incorporation of 10% MSK into idli significantly increased the moisture content, crude fiber, crude fat, total ash, and energy value. In addition, significant increases in the concentrations of calcium, iron, and magnesium were observed.
Cake	Apple Pomace (25%)	The incorporation of AP in cake increased the total dietary fiber and total phenol content

Conclusion

Agricultural and food processing wastes are valuable resources rather than mere refuse. Their conversion into functional food ingredients provides an effective strategy for waste management, environmental protection and value addition. By adopting suitable processing technologies, these by-products can be transformed into nutritious and marketable products, contributing to sustainable agriculture, food security and rural economic development.

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Phog (*Calligonum polygonoides*): The Desert's Hidden Treasure

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The harsh landscapes of Rajasthan and south-western Haryana are home to many hardy plant species, among them is Phog (*Calligonum polygonoides*). This resilient shrub, belonging to the Polygonaceae family, has sustained desert communities for generations by providing fodder, fuel, food, medicine, and environmental protection. Growing naturally on sand dunes, sandy plains, and field boundaries, Phog is a perennial shrub that usually reaches a height of 2–3 metres, though under favourable conditions it may develop into a small tree. Its well-developed root system penetrates deep into the soil, allowing the plant to survive prolonged drought by efficiently extracting water and nutrients from deeper layers. Flowering occurs during February and March, followed by fruit development in April and May. The fruits are a familiar sight across the arid regions during early summer. However, currently it is vanishing from south-western landscapes of Haryana. Interestingly, natural populations of Phog exhibit considerable variation in growth, plant architecture, and productivity, making it an important species for future improvement and conservation programmes. The ecological value of Phog extends far beyond its direct uses. Its extensive root system firmly binds loose sandy soils, helping to stabilize sand dunes and prevent wind erosion. The plant also contributes organic matter to the soil, improves moisture retention, and supports the overall ecological stability of desert landscapes. Because of these characteristics, Phog has become an important species in land restoration and desertification control programmes across the arid regions of India.

In arid regions where rainfall is scarce and crop failures are common; livestock serve as the primary source of livelihood for farming families. Under these conditions, naturally growing shrubs like Phog become invaluable sources of nutritious fodder. The young succulent shoots, are highly preferred by camels, sheep, and goats. Farmers often combine these shoots with fodder from crops such as moth bean, cluster bean (guar), and sesame to prepare a balanced feed. Nutritionally, these shoots contain approximately 6.5% crude protein, 23% crude fibre, and 62% digestible nutrients, making it an excellent feed resource during dry periods. The fruits are even more nutritious, containing almost twice the protein content of the young shoots along with appreciable quantities of starch. The importance of Phog in livestock production is beautifully reflected in an old Rajasthani proverb: "When Phog blooms, goat milk becomes so abundant that even buffalo owners come asking for buttermilk." This traditional saying reflects the long-held belief that flowering Phog significantly enhances milk production in goats. Apart from domestic animals, Phog also provides forage for several wild herbivores, including deer. Another valuable characteristic is its excellent storage life, allowing fodder to remain useful for extended periods. One of the unique features of Phog is its edible flower buds, locally called Phoglia. These

tender buds have been consumed by desert communities for centuries and are traditionally mixed with curd to prepare a nutritious raita. Phoglia contains nearly 18% protein, making it a rich seasonal food. Recent research has also demonstrated its potential as an ingredient in a variety of vegetable dishes, expanding its culinary possibilities beyond traditional recipes.

Phog occupies an important place in traditional herbal medicine. A decoction prepared from its roots, often combined with catechu, has long been used to treat gum disorders. Local communities also use the juice extracted from its tender branches to soothe eye irritation caused by accidental exposure to the latex of *Calotropis*. Furthermore, Phoglia has traditionally been consumed during the hot summer months to help protect the body against excessive heat and hot desert winds. Fuelwood continues to be the dominant energy source in many desert villages. Approximately 70% of household fuel requirements are met through firewood, while dung cakes contribute about 24%, with the remaining demand fulfilled through crop residues, coal, and kerosene. Among the available woody species, Phog is highly valued because its dry branches produce intense heat with very little smoke. This makes it particularly suitable not only for household cooking but also for commercial applications such as brick kilns and plaster of Paris industries. Across the rainfed areas of north-western Rajasthan, Phog naturally forms living fences around agricultural fields. These bio-fences not only define field boundaries but also protect crops from grazing animals and strong desert winds. Its seeds are easily dispersed by wind and often accumulate along field bunds, where they germinate after receiving sufficient moisture. Farmers generally preserve these naturally emerging seedlings, which gradually develop into dense and durable protective barriers requiring very little management.

Although Phog continues to play a vital role in sustaining desert ecosystems and rural livelihoods, its natural populations are increasingly threatened by excessive harvesting and habitat degradation. Conserving this remarkable species requires coordinated efforts to collect and distribute quality seed, create awareness among rural communities about its multiple benefits, regulate indiscriminate cutting for fuelwood, and encourage scientific harvesting practices. Greater integration of Phog into agroforestry systems, sand dune stabilization programmes, pasture development, and field boundary plantations can simultaneously improve fodder availability, provide sustainable fuelwood, enhance soil conservation, and generate additional income for farmers. Protecting and promoting this native desert shrub is therefore essential for building resilient farming systems and ensuring the long-term sustainability of India's arid landscapes.

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Climate-Triggered Sleeper Bacterial Pathogens: Mechanisms, Impacts, and Agricultural Management Strategies

Article ID: 74255

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Abstract

Sleeper bacterial pathogens—microorganisms that remain dormant or semi-dormant in host tissues until environmental conditions favor their activation—present an emerging threat to global agriculture and food security as climate change alters traditional ecological niches and growing conditions. Rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events trigger the metabolic awakening of latent bacterial infections, leading to sporadic and often severe disease outbreaks in previously resistant or unaffected crops. This review synthesizes current knowledge on climate-triggered bacterial dormancy, the physiological mechanisms of pathogen resuscitation, exemplar pathogens across major crop systems, and integrated management strategies for mitigating climate-induced disease emergence. Understanding the interplay between climatic variables and bacterial quiescence is critical for developing resilient agricultural systems and predicting disease risk in a warming world.

Keywords: sleeper pathogens, bacterial dormancy, climate change, quiescence, agricultural disease, pathogen activation.

Introduction

Global climate change is fundamentally reshaping the epidemiology of infectious diseases across agricultural and natural ecosystems. Rising mean temperatures, altered precipitation regimes, intensified weather extremes, and shifts in seasonal patterns are collectively redefining the ecological boundaries within which plant pathogens thrive (Bebber et al., 2013; Garrett et al., 2006). Among the most consequential yet understudied phenomena are disease emergence events triggered by the activation of dormant or semi-dormant ('sleeper') bacterial pathogens—quiescent microbial populations that persist in host tissues, soil, or plant residues in a metabolically suppressed state until climatic perturbations or biotic cues trigger their sudden resuscitation (Horne & Dayananda, 2015).

The concept of microbial dormancy, while not novel, has historically received limited attention in applied plant pathology, where acute infection cycles dominated research focus. However, accumulating evidence suggests that bacterial quiescence is a sophisticated survival strategy, conferring both persistence in adverse environments and the capacity for rapid phenotypic switching when conditions ameliorate (Lennon & Jones, 2011). Climate variability—particularly temperature oscillations, moisture fluctuations, and nutritional stress—acts as a primary trigger for pathogen resuscitation, potentially explaining the sporadic yet severe outbreak patterns observed in recent decades for pathogens previously considered controlled or geographically limited.

This review examines the intersection of climatic change, bacterial dormancy, and agricultural disease emergence. We synthesize mechanistic understanding of sleeper pathogen activation, review exemplar bacterial species across major crop systems, and evaluate management and adaptation strategies for reducing climate-mediated disease risk.

Bacterial Dormancy: Definitions and Ecological Significance

Bacterial dormancy encompasses a spectrum of physiological states, ranging from reversible growth arrest to deep stationary phase and viable-but-non-culturable (VBNC) conditions. In plant pathology, sleeper pathogens are operationally defined as bacteria capable of persisting in host tissues or soil for extended periods with minimal metabolic activity, without triggering overt disease symptoms, until biotic or abiotic stimuli induce phenotypic reactivation (Horne & Dayananda, 2015). This latency may be enforced externally—e.g., by nutrient limitation, low temperature, or host resistance—or maintained through endogenous regulatory programs that suppress virulence gene expression.

From an evolutionary perspective, dormancy confers significant fitness advantages: reduced metabolic expenditure in nutrient-poor or hostile microenvironments, prolonged persistence permitting trans-seasonal survival or long-distance dispersal via plant material, and avoidance of host immune detection during symptom-free colonization (Dimkpa *et al.*, 2009). These advantages are particularly pronounced in temperate and subtropical zones where seasonal environmental stress—cold winters, dry summers, or marked inter-annual variability—selects for bet-hedging phenotypes capable of rapid resource mobilization when conditions shift favorably.

Mechanistically, dormancy involves coordinated suppression of growth-related gene clusters, including ribosomal biogenesis and cell wall remodeling, coupled with upregulation of stress-response, DNA-repair, and protection systems (proteases, antioxidants, osmolytes). Temperature, moisture, and nutrient signals are sensed via multi-component

regulatory pathways (e.g., the SOS response, stringent response, and nutrient starvation pathways), which collectively drive the transition into quiescence (Lennon & Jones, 2011).

Climate Variables as Triggers for Pathogen Resuscitation

Climate change operates as a multi-dimensional driver of sleeper pathogen activation through several non-mutually exclusive mechanisms:

1. Temperature and Thermal Variability: Rising mean temperatures directly alter metabolic rates and host physiology, potentially awakening pathogens adapted to cooler regimes. More critically, increased thermal variability—larger day-night temperature fluctuations and unpredictable warm spells during traditionally cold seasons—can disrupt dormancy maintenance mechanisms evolved under stable climates (Bebber et al., 2013). Warm-season pulses may trigger premature pathogen activation when host tissues remain immature and metabolically vulnerable, while simultaneous resource depletion (drought stress reducing nutrient translocation) prevents symptom expression and diagnosis, allowing pathogenic populations to expand covertly.

2. Precipitation Extremes and Soil Water Dynamics: Heavy precipitation or irrigation following prolonged drought rapidly elevates soil water potential and oxygen availability in anaerobic microsites, potentially reactivating soil-resident bacterial pathogens from dormancy (Garrett *et al.*, 2006). Simultaneously, waterlogging can damage host root systems, reducing biochemical and physical barriers to pathogenic invasion. Conversely, persistent drought stress may intensify plant carbon and nutrient allocation to reproduction at the expense of systemic acquired resistance, lowering immune thresholds for pathogenic breakthrough.

3. Seasonal Phenology Mismatches: Climate-driven shifts in host phenology—earlier flowering, extended growing seasons, or asynchronous developmental timing relative to natural enemies and competitors—can create phenological windows favoring pathogen establishment when host defenses are compromised (Garrett *et al.*, 2006). Sleeper pathogens persisting from previous seasons may coincide with immature host tissue displaying reduced constitutive defenses or incomplete systemic resistance.

Exemplar Climate-Triggered Sleeper Pathogens in Agriculture

1. *Xanthomonas* spp. - Bacterial Leaf Scorch and Wilt Complexes: Species within the *Xanthomonas* genus, notably *X. citri* subsp. citri (citrus canker), *X. arboricola pv. pruni* (bacterial spot of stone fruits), and *X. axonopodis* pv. phaseoli (common bacterial blight in beans), are well-characterized for their ability to persist as latent infections in asymptomatic host tissues. Elevated temperatures (25–28°C) and humid conditions trigger symptom manifestation and exudative release of inoculum (Schroth *et al.*, 1988). Climate warming in traditionally cooler regions has expanded the geographic range and intensity of *Xanthomonas* outbreaks, while increased rainfall variability creates unpredictable windows of high-humidity favorable for pathogenic breakthrough.

2. *Ralstonia solanacearum* - Bacterial Wilt: This cosmopolitan soil-borne pathogen persists in soil and alternative hosts in a semi-dormant state, with inoculum density declining over time under unfavorable conditions but remaining viable for years (Genin & Denny, 2012). Warm soil temperatures (>20°C), high moisture, and plant stress act synergistically to trigger active pathogenesis. Climate warming in temperate zones has facilitated pathogen establishment in previously marginal regions, while drought-induced plant stress facilitates bacterial translocation and wilt development.

3. *Pseudomonas* spp. - Bacterial Speck and Leaf Spot: *Pseudomonas syringae* pathovars cause economically significant leaf spot and speck diseases on tomato, bean, and cruciferous crops. These pathogens persist epiphytically on leaf surfaces in a quiescent state, becoming pathogenic only when host leaf wetness, nutrient availability (e.g., from pollen or nectar), and temperature synchronize to enable active invasion (Hirano & Upper, 2000). Unpredictable rainfall events creating episodic leaf-wetness periods, combined with warming that accelerates bacterial multiplication, trigger epidemic symptom development on previously asymptomatic host populations.

Agricultural Impacts and Risk Implications

The climate-driven activation of sleeper pathogens poses several critical challenges to agricultural sustainability:

Unpredictability and Disease Forecasting Failure: Dormancy prevents reliable forecasting models calibrated on historical acute-infection cycles. Sleeper pathogen emergence is episodic and decoupled from traditional pre-season disease inoculum assessments, rendering early-warning systems unreliable (Garrett *et al.*, 2006).

Resistance Breakdown: Pathogenic populations persisting in latent form may accumulate genetic variation or undergo phenotypic switching toward virulence-gene upregulation, potentially overcoming host resistance loci when resuscitated.

Reduced Fungicide/Bactericide Efficacy: Dormant cells often display reduced membrane permeability and altered metabolic state, potentially reducing sensitivity to antimicrobial compounds designed to target active growth.

Broad Geographic Risk Expansion: Sleeper pathogens from marginal climatic zones may expand poleward or to higher elevations, establishing novel agricultural disease hotspots in regions with limited endemic immunity or disease management experience.

Management and Adaptation Strategies

1. Genetic Resistance and Breeding: Development of cultivars combining broad-spectrum resistance (e.g., quantitative resistance, R-gene pyramiding) with traits enhancing climate resilience (drought/heat tolerance, phenological plasticity) should be prioritized. Multi-pathogen resistance panels should be screened under stress conditions simulating future climates (Lobell & Asner, 2003).

2. Cultural and Management Practices: Implementation of sanitation protocols to minimize inoculum carry-over (removal of crop residues, disinfection of equipment), rotation with non-host or resistant crops, and management of alternative host plants can reduce the reservoir of dormant pathogens. Conservation of beneficial microbes and natural enemies through diversified cropping systems and reduced tillage may enhance biocontrol of emergent pathogens (Dimkpa *et al.*, 2009).

3. Integrated Pest Management (IPM) and Adaptive Decision-Support: Development of climate-informed disease forecasting models incorporating dormancy dynamics, coupled with real-time environmental monitoring and molecular pathogen detection, can enable proactive management before symptom emergence (Garrett *et al.*, 2006). Bactericide application timing should be refined based on phenological windows and microclimatic triggers of pathogen resuscitation rather than fixed calendars.

4. System-Level Resilience and Adaptation: Diversification of crop portfolios, livestock integration, and infrastructure investments in climate-resilient irrigation and drainage systems can buffer against localized disease catastrophes. Regional cooperation on surveillance networks and rapid information-sharing of emerging disease events enables faster, coordinated response (Bebber *xhe al.*, 2013).

Future Research Priorities

Critical knowledge gaps remain:

1. Quantitative characterization of dormancy thresholds and resuscitation triggers across pathogen species and host-pathogen combinations;

2. Genomic and transcriptomic profiling of dormant versus resuscitated pathogenic populations to identify activation-associated gene networks;

3. Mechanistic modeling of climate-driven pathogen dynamics integrating quiescence, incorporating soil microbiome suppression and plant physiological heterogeneity;

4. Assessment of antimicrobial efficacy against dormant and resuscitating bacterial populations, and development of enhanced formulations penetrating quiescent biofilms;

5. Long-term regional surveillance studies tracking emergence of novel sleeper pathogen phenotypes in response to climate variability.

Conclusion

Climate change is fundamentally altering the epidemiology of bacterial plant diseases through the activation of sleeper pathogens microbial populations persisting in quiescence until climatic perturbations trigger resuscitation. Rising temperatures, precipitation extremes, and phenological mismatches collectively expand the geographic range, temporal unpredictability, and severity of pathogenic breakthrough events. Exemplar pathogens such as X*anthomonas*, *Ralstonia*, and *Pseudomonas* spp. demonstrate the real-world consequences of climate-driven dormancy release, imposing significant threats to global food security and agricultural sustainability.

Effective adaptation requires integrated strategies spanning genetic improvement of host resistance, cultural and management practice optimization, climate-informed decision-support systems, and system-level resilience-building. Investment in research addressing dormancy mechanisms, transcriptomic-genomic signatures of resuscitation, and climate-pathogen modeling is essential for predicting and mitigating emerging disease risks. As climate variability intensifies, understanding sleeper pathogen biology and ecology will become increasingly central to agricultural risk management and crop production security.

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Crown Gall Disease on Rose

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Abstract
Crown gall disease is one of the most destructive bacterial diseases of rose (*Rosa* spp.), causing significant economic losses by reducing plant vigour, flower yield, and nursery quality. The disease is caused by *Agrobacterium tumefaciens* (syn. *Rhizobium radiobacter*), a soil-borne bacterium that infects plants through wounds and transfers T-DNA from its tumor-inducing (Ti) plasmid into the host genome, resulting in gall formation. This review summarizes the causal organism, taxonomy, disease symptoms, epidemiology, molecular mechanism of pathogenicity, biology and survival, detection and diagnostic methods, isolation and identification techniques, and integrated disease management strategies. Recent advances, including PCR-based diagnostics, biological control using *Agrobacterium radiobacter* strains K84 and K1026, genome editing, microbiome-based approaches, and resistant cultivar development, are also discussed. An integrated management approach combining cultural, biological, and molecular strategies is essential for sustainable management of crown gall disease in rose cultivation.

Keywords: Crown gall, *Agrobacterium tumefaciens*, Rose (*Rosa* spp.), Ti plasmid, T-DNA, Biological control, PCR diagnosis, Disease management.

Introduction
Rose (Rosa *spp.*) is one of the most important ornamental flowering plants cultivated worldwide because of its aesthetic beauty, fragrance, and high commercial value in the floriculture industry. Roses are extensively used as cut flowers, landscape plants, potted ornamentals, and for the production of perfumes and cosmetics. The global demand for high-quality rose plants has increased significantly, making healthy nursery production essential. However, several diseases reduce the productivity and quality of roses, among which crown gall is considered one of the most destructive bacterial diseases. The disease has become a major constraint in commercial nurseries because it decreases plant vigour, reduces flower yield and quality, and lowers the market value of planting materials (Vatankhah *et al.*, 2023; Oksel *et al.*, 2024).

Crown gall disease is of great economic importance because infected rose plants exhibit stunted growth, poor rooting, chlorotic leaves, reduced flowering, and in severe cases become unmarketable. The disease has been reported from major rose-growing regions of North America, Europe, Asia, and the Middle East, where it spreads mainly through infected nursery stock, contaminated soil, pruning tools, and wounds created during cultural operations. The causal organism, *Agrobacterium tumefaciens* (syn. *Rhizobium radiobacter*), is a Gram-negative, soil-borne bacterium that infects plants through wounds and transfers a segment of its tumor-inducing (Ti) plasmid DNA into the plant genome. This transferred DNA stimulates the production of auxins and cytokinins, resulting in uncontrolled cell division and the formation of characteristic tumor-like galls on the crown, roots, and stems. Due to its wide host range, long survival in soil, and efficient spread through infected propagative materials, A. tumefaciens remains one of the most economically important bacterial pathogens affecting roses and many other ornamental and horticultural crops (Vatankhah *et al.*, 2023; Oksel *et al.*, 2024).

Causal Organism and Taxonomy
Crown gall disease of rose is caused by *Agrobacterium tumefaciens* (syn. *Rhizobium radiobacter*), a Gram-negative, rod-shaped, aerobic, soil-borne bacterium belonging to the family Rhizobiaceae. The pathogen infects plants through wounds and induces tumor-like galls by transferring a segment of its tumor-inducing (Ti) plasmid DNA into the host plant genome (Oksel *et al.*, 2024; Vatankhah *et al.*, 2023).

Recent molecular studies have shown that the Agrobacterium tumefaciens species complex consists of several closely related genomospecies rather than a single species. (Mafakheri *et al.*, 2019) identified two novel genomospecies associated with rose crown gall, indicating that genetically diverse Agrobacterium strains are responsible for the disease in roses. These findings have improved the taxonomy and accurate identification of crown gall pathogens.

Disease Symptoms
Crown gall disease of rose is characterized by tumor-like swellings (galls) that usually develop at the crown region near the soil line, but may also occur on roots, lower stems, and pruning wounds. Young galls are initially light green or cream coloured and gradually become rough, hard, dark brown to black, and woody with age. Infection occurs only through

wounds caused by pruning, grafting, freezing injury, insects, nematodes, or mechanical injury. Gall formation may appear within 2–3 weeks after infection, although symptoms can develop several months later (Duman *et al.*, 2018).

As the disease progresses, infected plants exhibit reduced vigour, stunted growth, chlorotic leaves, poor root and shoot development, reduced flower production, and increased susceptibility to secondary infections. In severe cases, multiple galls develop on a single plant, resulting in wilting and eventual plant death (Vatankhah *et al.*, 2023).



Fig 1: Later stage crown gall symptoms at the base of a rose plant caused by the bacterium *Agrobacterium tumefaciens* (Source: Duman *et al.*, 2018).

Disease Cycle and Epidemiology

Agrobacterium tumefaciens is a soil-borne bacterium that survives for long periods in infected galls, contaminated soil, plant debris, and the rhizosphere of susceptible plants and weeds. In rose, the bacterium infects plants only through fresh wounds caused by pruning, budding, grafting, transplanting, insect feeding, nematodes, frost injury, or mechanical damage (Duman *et al.*, 2018).

After entering wounded tissues, the bacterium attaches to plant cells and transfers a segment of its tumor-inducing (Ti) plasmid DNA (T-DNA) into the plant genome. The transferred T-DNA stimulates the production of auxins and cytokinins, resulting in uncontrolled cell division and the formation of characteristic crown galls near the crown, roots, or lower stem. Initially, the galls are soft and cream-colored, but they gradually enlarge, become corky, rough, and dark brown with age (Gelvin, 2017).

The pathogen spreads mainly through infected nursery stock, contaminated soil, irrigation water, and pruning or grafting tools. As mature galls crack or decay, large numbers of bacterial cells are released into the soil, where they survive and infect healthy plants through newly formed wounds, thereby completing the disease cycle. Warm temperatures (22–28°C), high soil moisture, frequent wounding, and poor sanitation favour disease development and spread (Agrios, 2005; Duman *et al.*, 2018).

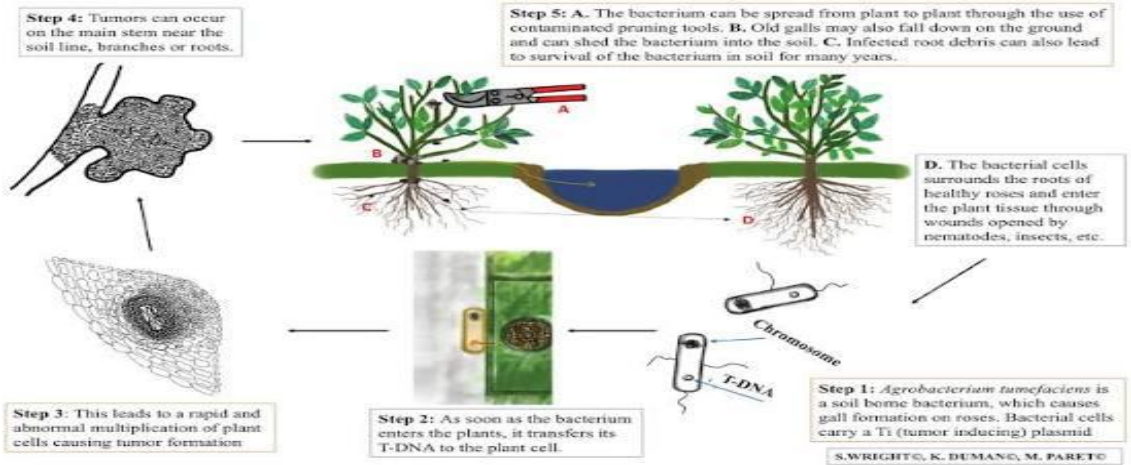


Fig 2: A summary of the disease cycle of crown gall, caused by *Agrobacterium tumefaciens* (Source: Duman *et al.*, 2018)

Molecular Mechanism of Pathogenicity

The pathogenicity of *Agrobacterium tumefaciens* is mediated by the tumor-inducing (Ti) plasmid, which carries the vir genes and T-DNA region. Wounded rose tissues release phenolic compounds such as acetosyringone, which activate the vir genes. The activated Vir proteins transfer the T-DNA into the plant cell through a Type IV secretion system. The T-

DNA integrates into the plant genome and induces the overproduction of auxin and cytokinin, leading to uncontrolled cell division and crown gall formation. It also directs the synthesis of opines, which serve as nutrient sources for the bacterium, enhancing its survival within the gall tissues (Gelvin, 2017; Escobar & Dandekar, 2003; Agrios, 2005).

Biology and Survival of the Pathogen

Agrobacterium tumefaciens is a Gram-negative, aerobic, soil-borne bacterium that survives for long periods in soil, infected plant debris, and symptomless planting material, enabling it to persist and spread in rose nurseries and production fields (Duman *et al.*, 2018; Oksel *et al.*, 2024).

The bacterium enters rose plants through wounds and transfers T-DNA from its Ti plasmid into host cells, leading to gall formation. Its ability to survive in infected tissues and utilize opines produced by transformed plant cells enhances its persistence and successful infection (Vatankhah *et al.*, 2023; Oksel *et al.*, 2024).

Detection and Diagnosis

Crown gall disease is initially diagnosed based on the presence of rough, irregular galls on the crown, roots, or lower stem of rose plants. Young galls are soft, cream-colored, and smooth, while mature galls become hard, woody, rough, and dark brown. Since similar swellings may also result from other causes, laboratory confirmation is recommended (Agrios, 2005).

The pathogen can be isolated from gall tissues on selective media and identified by biochemical and pathogenicity tests. Modern diagnostic methods such as polymerase chain reaction (PCR) targeting vir or Ti plasmid genes provide rapid and accurate detection of pathogenic *Agrobacterium tumefaciens*. Molecular techniques, including real-time PCR, are also widely used for the diagnosis of infected nursery stock and asymptomatic planting material (Gelvin, 2017; Duman *et al.*, 2018).

Isolation and Identification Techniques

Agrobacterium tumefaciens was isolated from fresh crown gall tissues of infected rose plants. Gall tissues were surface sterilized with 0.525% sodium hypochlorite, macerated in 5% sterile saline buffer, and plated on King's B (KB) and 1A media. Pure bacterial colonies were obtained after incubation at 25°C and used for further identification. The isolates were identified by Gram staining, oxidase, catalase, starch hydrolysis, and gelatin hydrolysis tests. Molecular confirmation was performed by PCR using 16S rRNA (8F/1492R), virD2 (VirD2A/VirD2C), and VCF/VCR primers. The amplified 16S rRNA gene sequences showed 100% similarity with *A. tumefaciens* sequences in the NCBI GenBank database, confirming the identity of the pathogen (Oksel *et al.*, 2024).

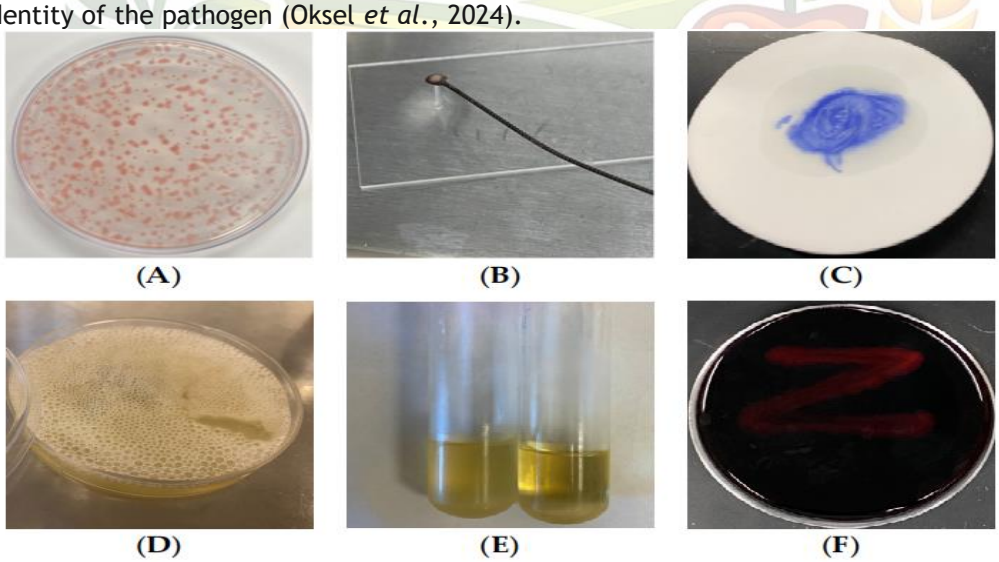


Fig 3: **1.** Identification of the tumorigenic *A. tumefaciens* isolates FBG1034 and FBG1035 using biochemical tests: (**A**) pink to pinkish-red colour colony on 1A medium; (**B**) Gram-negative bacteria based on the Gram staining; (**C**) in the oxidase test, the inoculated filter paper turned violet immediately after adding the reagent; (**D**) in the catalase test, bubbles were formed on the Petri plate after adding H_2O_2; (**E**) the isolates were not produced gelatinases; (**F**) the isolates were unable to hydrolyze starch.

Disease Management

1. Cultural Management: The use of disease-free planting material, pathogen-free soil, and sanitized pruning tools is essential for managing crown gall disease. Wounds caused by pruning, grafting, insects, or cultivation should be avoided because they serve as entry points for *Agrobacterium tumefaciens*. Infected plants should be removed and destroyed, and replanting in infested soil should be avoided for at least three years (Duman *et al.*, 2018; Oksel *et al.*, 2024).

2. Biological Management: Biological control using *Agrobacterium radiobacter* strains K84 and K1026 is the most effective method for crown gall management. (Oksel *et al*., 2024) reported that strain K1026 significantly reduced crown gall incidence, root gall incidence, and gall size in rose by inhibiting the growth of pathogenic *A. tumefaciens*.

3. Chemical Management: Copper-based compounds such as copper octanoate and disinfectants like didecyl dimethyl ammonium chloride can reduce crown gall severity, but they are generally less effective than biological control. Therefore, chemical treatments are recommended as part of an integrated disease management strategy rather than as a sole control measure (Oksel *et al*., 2024).

Future Prospects

The development of resistant rose cultivars remains one of the most promising long-term strategies for managing crown gall disease, although commercially available resistant varieties are still limited. Advances in genome editing technologies, particularly CRISPR/Cas systems, offer opportunities to modify host susceptibility genes and improve resistance against Agrobacterium tumefaciens. In addition, microbiome-based management, including the use of beneficial rhizosphere microorganisms, is emerging as a sustainable approach to suppress pathogen colonization and enhance plant health. Future disease management should focus on integrated and sustainable strategies that combine resistant cultivars, biological control agents, and improved cultural practices to reduce reliance on chemicals. Furthermore, early detection technologies, such as PCR- and qPCR-based molecular diagnostics, will enable rapid identification of latent infections and support timely disease management (Oksel *et al*., 2024).

Conclusion

Crown gall disease caused by *Agrobacterium tumefaciens* remains a major challenge in rose production due to its wide host range, soil persistence, and efficient spread through infected planting material and wounds. Early diagnosis using molecular techniques, combined with the use of disease-free planting material, proper sanitation, and biological control agents such as *Agrobacterium radiobacter* K84 and K1026, can effectively reduce disease incidence. Future research on resistant cultivars, genome editing, and microbiome-based disease management offers promising opportunities for long-term and sustainable control. An integrated disease management approach is essential to minimize economic losses and ensure healthy rose production.

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Role of Biobactericide as a New Environmentally Friendly Approach

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Abstract

In order to manage harmful bacterial illnesses in agriculture, specifically *Ralstonia solanacearum* in crops like potatoes and chillies, this article investigates biobactericides as sustainable, eco friendly substitutes for traditional chemical pesticides. The research investigates a variety of biocontrol strategies, such as microbial antagonists (*Pseudomonas fluorescens*, *Bacillus species*, *Trichoderma*), botanical and essential oil-based formulations (oregano, thyme, and Monarda), and novel tactics like nisin-based vascular therapy and valorisation of agricultural waste materials, in order to address the drawbacks of synthetic chemicals, such as human toxicity, environmental degradation, and the emergence of resistant pathotypes. The study shows that biobactericides boost host plant defence mechanisms and lower antimicrobial resistance while successfully suppressing bacterial plant illnesses. Biobactericides achieve the performance stability and cost-efficiency required for commercial application by utilising Industry 4.0 technologies and circular bioeconomy principles for large-scale production. This results in an affordable, environmentally safe crop protection solution that is in line with the goals of the global one health framework and sustainable agricultural practices.

Key Points: Biobactericides, Pseudomonas, Bacillus, Trichoderma, Essential oils, Waste valorisation, antimicrobial resistance.

Introduction

In order to control extremely destructive bacterial diseases like *Ralstonia solanacearum*, which causes severe wilt disease in economically important crops like potatoes and chilli, conventional agriculture has long relied on synthetic chemical pesticides and intensive treatment medicines (Kalle *et al.*, 2024). However, the ongoing and uncontrolled use of these chemical active components has resulted in acute human toxicity, significant chemical residual concerns, severe environmental degradation, and the quick development of highly resistant or cross-resistant pathotypes (Sabri *et al.*, 2024). As a result, biobactericides have become a very practical and green solution for sustainable crop protection and integrated pest management (IPM) (Soares *et al.*, 2025). This biocontrol framework uses biological systems, microbial antagonists, and minerals from natural sources to combat diseases without leaving long-lasting harmful residues (Kalle *et al.*, 2024). Biobactericides, which combine the natural defences of microbial cells with biodegradable plant-derived matrices to manage bacterial diseases while concurrently mitigating global antimicrobial resistance (AMR), are an essential substitute for conventional chemical toxins as international agricultural policies shift toward strict ecological sustainability (Sabri *et al.*, 2024).

Microbial Antagonists

***Pseudomonas fluorescens**:* *Pseudomonas fluorescens* strain A506 was shown to be able to outcompete *Erwinia amylovora* in pear and apple orchards by space-associated competitive exclusion in early standard methods. In order to identify precise biochemical pathways, modern research has moved beyond straightforward environmental competition. In *Pseudomonas fluorescens* EK007, the production of the non-ribosomal cyclic lipopeptide massetolide A is combined with an explicit Lasparaginase-driven antibiosis to control fire blight. The gacA pathway controls the metabolic synthesis of this lipopeptide, which is heavily impacted by local nutritional sources. Asparagine or cysteine inhibit the antagonist's ability to inhibit *Erwinia amylovora*, while environmental iron increases antibacterial activity (Habibi *et al.*, 2024).

Bacillus sp.: A very promising biotechnological strategy to fight multidrug-resistant (MDR) bacterial diseases is the use of marine-derived Bacillus species as biobactericides, which provide a long-term substitute for traditional antibiotics that are becoming more and more resistant worldwide. Bacillus strains produce special bioactive secondary metabolites like polyketides, lipopeptides, peptides, and alkaloids that have strong antibacterial and antibiofilm properties as a result of microbial adaptive evolution driven by marine environments, especially harsh and high-stress habitats like the Red Sea mangrove sediments in Jeddah, Saudi Arabia. Several active *Bacillus* strains, namely *Bacillus mesophilus* (JRSM 4), *Bacillus xiamenensis* (JRSM 6), *Bacillus halotolerans* (JRSM 7), and *Bacillus subtilis* (JRSM 9), were successfully isolated in recent empirical research. These strains showed notable in vitro inhibitory capabilities against important clinical pathogens, such as *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Escherichia coli*, and *Klebsiella pneumoniae*. With minimum inhibitory concentrations (MIC) as low as 78.125 µg/mL against *S. aureus* and 156.25 µg/mL against *P. aeruginosa*, as well as a minimum bactericidal concentration (MBC) of 312.5 µg/mL for both strains, *Bacillus*

halotolerans (JRSM 7) demonstrated particularly strong antimicrobial efficacy. The ability of these Bacillus species to produce unique antimicrobial peptides (AMPs) like subtilin, bacitracin, bacillomycin, and fengycin, which efficiently disrupt target bacterial cell membranes and dissolve protective biofilms, is crucial to their therapeutic and protective potential. As a result, using these extremophilic marine Bacillus strains as targeted biobactericides creates a useful, novel reservoir for upcoming environmental biotechnology, pharmaceutical research, and sophisticated integrated pest or pathogen management techniques (Hamzah *et al.*, 2025).

Bacillus subtilis: High-yield industrial scale-up of agricultural inputs requires the creation of optimised medium. Nitrogen-source selection is a crucial process variable in the manufacture of biobactericides employing *Bacillus subtilis* ATCC 6633 to mitigate crucifer black rot caused by *Xanthomonas campestris*. The addition of certain inorganic nitrogen salts, specifically sodium nitrite ($NaNO_2$), greatly optimises the production of active secondary metabolites while organic substrates support rapid vegetative cellular growth. This results in large, measurable zones of inhibition against highly aggressive *Xanthomonas* strains isolated from cabbage, kale, and cauliflower (Zahović *et al.*, 2020).

***Trichoderma* Secondary Metabolites:** Anti-infective secondary metabolites, such as polyketides, pyrones, and specialised peptaibols, are abundant in soil-borne fungi of the genus *Trichoderma*. Formulations made from strains such as *Trichoderma pseudoharzianum* (strain T113) exhibit significant broad-spectrum bactericidal properties against *Xanthomonas campestris* and *Ralstonia solanacearum*. The biological mechanism depends on structural envelope damage; exposure to these metabolites causes severe cell wall deterioration, inner membrane disintegration, and total cellular material leakage, according to scanning electron microscopy (Khan *et al.*, 2020).

Botanical and Essential Oil Biobactericides

Oregano and Thyme Essential Oils: Mexican thyme (*Thymus vulgaris*) and oregano (*Lippia graveolens*) essential oils have potent bactericidal effects against *Ralstonia solanacearum*. A 1:1 crude dilution applied in 15 µL aliquots produces structural lysis of the bacterial cell membrane, producing inhibitory zones that either match or surpass traditional streptomycin and ampicillin treatments. This dilution is rich in the active phenolic monoterpene thymol and carvacrol (Rueda-Puente *et al.*, 2018).

Monarda Terpene Complexes: Specialised terpene matrices found in botanical complexes generated from *Monarda didyma* and *Monarda fistulosa* efficiently inhibit the surface-borne growth of leaf-spot pathotypes such as *Pseudomonas syringae* without causing phytotoxicity on host crop foliage (Soares *et al.*, 2025).

New Frontiers in Sustainable Crop Protection

Nisin-Based Vascular Therapy: In order to combat the xylem-limited quarantine pathogen *Xylella fastidiosa* subsp. *pauca*, the class I polycyclic antibiotic nisin A, which is produced by ribosomal processes in *Lactococcus lactis* subsp. *lactis*, has been successfully transferred from food preservation to plant vascular therapy. By immediately attaching to cell-wall lipid precursors (Lipid II) and forming transmembrane holes that instantly cause cellular content extravasation, nisin A develops significant bactericidal activity at a low minimal lethal dosage of 0.6 mg/mL. Nisin effectively translocated throughout the plant's vascular systems, remaining structurally intact and functionally active for up to nine days to stop systemic leaf scorch symptoms without damaging host tissues or beneficial epiphytes, according to liquid chromatography-tandem mass spectrometry (RPLC-ESI-MS/MS) and endotherapy testing (Sabri *et al.*, 2024).

Cattle Bone Waste Valorisation: An environmentally friendly method of managing illness is upcycling organic waste from abattoir operations. Calcium and phosphorus elements are abundant in biobactericides produced by deproteinising beef bones from Limousin and Simmental cattle. When applied *to Ralstonia solanacearum*-infected chilli plants, the powder supplies essential nutrients that fortify host cell walls and modify the osmotic balance of the rhizosphere, promoting the growth of leaves and raising plant height by up to 26 cm while totally preventing wilting symptoms (Kalle *et al.*, 2024).

Agri-Food Waste Valorisation and Industry: By establishing a circular bioeconomy, massive industrial waste streams such as citrus peels, olive pomace, potato processing pulp, and winery grape dregs can be transformed into rich sources of bioactive chemicals for the development of commercial biopesticides. By incorporating industry technologies such automated IoT sensor arrays, big data process analytics, and smart extraction monitoring, processing facilities can overcome previous issues related to natural batch variability. This technological integration, which ensures standard phytochemical profiles (such as constant concentrations of chlorogenic acids, oleuropein, and polymethoxylated flavones), maximises large-scale recovery efficiency, minimises chemical waste generation, and lowers production costs, makes green biopesticides highly competitive with traditional synthetics (Soares *et al.*, 2025).

Table of Biobactericide Availability in India (Directorate of Plant Protection, Quarantine & Storage, 2024):

Agent	Common trade name(s) in India	Recommended dosage	Target bacterial pathogen(s)	Formulation
Pseudomonas fluorescens	Bio-Pf, Stanes Pseudomonas, IPL Pseudomonas, IIHR-PF formulations (manufacturer-specific)	Seed treatment: 10 g/kg seed (WP); Root dip: 10 g/L water; Soil application: 2.5 kg/ha mixed with FYM; Foliar spray: 5–10 g/L	*Xanthomonas* spp., *Ralstonia solanacearum*, *Pseudomonas syringae*, *Erwinia* spp.; also suppresses several fungal diseases	Registered by CIBRC as biofungicide/biopesticide. Formulations listed as Pseudomonas fluorescens 1.0% WP (IIHR-PF-2), 1.5% LF, 2.0% AS, etc. Approved under Section 9(3) of the Insecticides Act.
Bacillus subtilis	Downil®, Bacillus subtilis formulations from Tropical Agrosystem, Shree Pesticides, etc.	Foliar spray: 2–4 g/L; Seed treatment: 5–10 g/kg seed; Soil application: 2–2.5 kg/ha	*Xanthomonas* spp., *Pectobacterium*, *Clavibacter*, *Erwinia* spp. (disease suppression); also controls fungal pathogens	Registered by CIBRC. Bacillus subtilis formulations (1.0% WP, 1.5% AS, 2.0% AS) are listed among approved biofungicides.

Conclusion

The integration of biobactericides into modern standard operating procedures represents a significant advancement in global agronomy, changing the crop protection paradigm from destructive chemical active ingredients toward targeted, environmentally safe interventions (Soares *et al.*, 2025). By utilizing beneficial endophytes, active enzymes, botanical terpene matrices, and mineral resources from agricultural waste, these inputs successfully suppress devastating bacterial plant diseases while strengthening host plant defence architectures (Kalle *et al.*, 2024). Driven by automated Industry process technologies and circular bioeconomy principles, these alternatives achieve the performance stability and cost-efficiency required for mass commercial application (Soares *et al.*, 2025). Ultimately, adopting biobactericides secures the global food supply, protects living soil microbiomes, and directly counters the threat of international antimicrobial resistance, perfectly aligning modern agricultural management with the overarching directives of the global one health framework (Habibi *et al.*, 2024).

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From *Kesar* to Commerce: Value Addition in Mango

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Introduction

Mango (*Mangifera indica* L.), revered as the "King of Fruits" is one of the oldest and most cherished tropical fruits in the world. Native to the Indian subcontinent, mango has been cultivated for over 4,000 years and occupies a prominent place in Indian agriculture, culture, and cuisine. India is the world's largest producer of mangoes, contributing nearly half of global production. The fruit is cultivated across diverse agro-climatic regions, providing livelihood to millions of farmers and supporting a vibrant processing industry. Beyond its delightful taste and aroma, mango is an excellent source of carbohydrates, dietary fibre, vitamins A, C, and E, potassium, antioxidants, carotenoids, and polyphenolic compounds, making it a nutritious component of a healthy diet.

However, despite abundant production, a considerable proportion of mangoes is lost after harvest due to rapid ripening, mechanical damage, microbial spoilage, and inadequate storage and transportation facilities. Post-harvest losses in mango may range from **20-30%**, especially during peak harvest seasons. These losses reduce farmers' income and limit the availability of quality fruits for domestic and export markets. Value addition offers an effective solution to these challenges. Through scientific post-harvest handling, processing, and innovative product development, mangoes can be transformed into a wide range of products such as pulp, juice, nectar, squash, pickles, chutney, dehydrated slices, fruit leather, jams, frozen cubes, powders, confectionery, and fermented beverages. Value addition not only extends shelf life but also improves marketability, creates employment opportunities, supports agro-industries, and contributes to sustainable utilization of the crop.



Fig. 1 Unripe stage of *Kesar* Mango

Kesar Mango Maturity Stages and their Processing Potential

Kesar, popularly known as the "Queen of Mangoes," is one of India's finest mango varieties and the pride of Gujarat. Mainly cultivated in the Gir region, including Junagadh, Gir Somnath, and Amreli districts, it is renowned for its vibrant saffron-orange pulp, rich aroma, natural sweetness, high pulp recovery, and excellent processing quality. These attributes make *Kesar* ideal for producing premium-quality pulp, juices, nectar, fruit leather, frozen products, dairy desserts, and confectionery, while also making it a preferred variety for domestic markets and exports. Below is a scientifically referenced table suitable for a magazine or review article. The Days After Fruit Set (DAFS) are based on research conducted on Indian mango cultivars, including *Kesar* under Gujarat conditions (Jadhav *et al.*, 2021). Commercial harvesting is recommended at the mature green (physiological maturity) stage (approximately 95–100 DAFS) to ensure optimum ripening, superior saffron-orange pulp colour, excellent flavour, and maximum suitability for both fresh consumption and processing (Kanzaria *et al.*, 2015).

Stage	Days After Fruit Set (DAFS)	Characteristics	Recommended Processing/Utilization
Pea Stage 	18–25 DAFS	• Fruits are pea-sized (1–2 cm), dark green, with high acidity and undeveloped seed. • Rapid cell division predominates. 	• Generally not harvested commercially; • Limited use for specialty baby pickles and research. 
Marble Stage 	35–45 DAFS	• Fruits attain marble size (2–4 cm), remain firm and green, with a soft seed and thin pulp. 	• Whole baby mango pickles, • Salted mangoes, • Preserved immature fruits. 
Egg Stage 	60–75 DAFS	• Fruits enlarge rapidly to egg size. • Seed develops while the flesh remains firm and acidic. 	• Tender mango pickles, • Grated mango, chutney, • Dehydrated slices, • Brined products, and • Amchur preparation. 
Mature Green Stage (Physiological Maturity) 	90–110 DAFS (Kesar: 95–100 DAFS)	• Fruits attain full size with a fully developed seed but retain a green peel. • Starch accumulation is complete, enabling normal ripening after harvest. 	• Fresh market, • Export, • Controlled ripening, • Fresh-cut products, • Frozen cubes, and • Processing into pulp, puree, juice, nectar, and concentrates after ripening. 
Full Maturity (Fully Ripe Stage) 	105–125 DAFS	• Fruits develop characteristic colour, aroma, sweetness, and soft texture. • Starch is converted into sugars, and flavour compounds are fully developed. 	• Pulp, puree, juice, nectar, squash, • Jam, jelly, fruit leather, • Dried mango, frozen desserts, • Ice cream, yoghurt, • Bakery fillings, confectionery, • Wine, and vinegar. 

Note: Days after fruit set (DAFS) may vary slightly with cultivar, climate, altitude, and management practices.

Fig. 2 *Kesar* Mango Maturity Stages and their processing potential

Modern Post-Harvest Handling, Industrial Processing, Packaging, Storage, and By-product Utilization

Modern post-harvest management plays a crucial role in preserving mango quality and enhancing its value. After harvesting at the mature green stage, fruits are de-sapped, washed, sanitized, graded, and sorted to remove contaminants and ensure uniform quality. Controlled ripening using ethylene in ripening chambers, along with hot water treatment or approved fungicidal treatments, minimizes post-harvest diseases and promotes uniform ripening. Industrial processing involves peeling, destoning, pulping, refining, pasteurization, aseptic processing, freezing, or drying to produce a wide range of products, including pulp, puree, juice, nectar, squash, fruit leather, frozen cubes, dried mango, jams, and confectionery ingredients. Appropriate packaging using corrugated fibreboard boxes, aseptic bags, PET bottles, retort pouches, and modified atmosphere packaging (MAP), coupled with edible coatings, helps maintain freshness, reduce moisture loss, and extend shelf life during storage and transportation. Scientific cold chain management at recommended temperature and humidity further preserves fruit quality, while emerging technologies such as IoT-enabled monitoring, artificial intelligence-based grading, and non-destructive quality assessment are improving efficiency and traceability throughout the supply chain. Additionally, mango processing generates valuable by-products such as peel and kernel, which are rich in pectin, dietary fibre, antioxidants, starch, and edible fat, and are utilized in functional foods, bakery products, cosmetics, nutraceuticals, animal feed, biochar, compost, and bioenergy production, thereby promoting sustainable, zero-waste utilization of the mango crop.

Modern post-harvest technologies have further enhanced the value chain of mango. Scientific harvesting using clippers and collection bags minimizes mechanical injury, while de-sapping removes latex stains that adversely affect fruit appearance. Subsequent washing, grading, hot water treatment, and sanitization improve fruit quality and reduce microbial contamination. Controlled ripening chambers using ethylene ensure uniform colour development and eliminate the harmful practice of calcium carbide ripening. Advanced storage techniques, including cold storage, modified atmosphere packaging (MAP), controlled atmosphere storage (CA), edible coatings, and refrigerated transportation, help maintain freshness, reduce physiological disorders, and extend shelf life. The adoption of non-destructive quality assessment techniques, optical grading systems, artificial intelligence-based sorting, and IoT-enabled cold chain monitoring is further improving efficiency, traceability, and quality assurance in mango processing.

Value addition has transformed mango into a versatile industrial raw material. Today, mango is processed into a wide range of products including pulp, puree, concentrate, juice, nectar, squash, syrup, ready-to-serve beverages, smoothies, fruit bars, fruit leather, dehydrated slices, freeze-dried cubes, spray-dried powder, frozen pulp, frozen cubes, jams, jellies, marmalade, candies, pickles, chutneys, sauces, dairy beverages, yoghurt, ice cream, bakery fillings, chocolates,

confectionery, and breakfast cereals. Furthermore, by-products generated during processing also offer immense economic potential. Mango peel serves as a rich source of pectin, carotenoids, dietary fibre, and natural antioxidants for food and pharmaceutical applications, while the kernel contains starch, edible fat, and bioactive compounds that can be utilized in bakery products, cosmetics, and nutraceutical formulations. Processing residues can also be converted into livestock feed, compost, biochar, and bioenergy, contributing to sustainable and zero-waste processing systems.

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Defence Mechanisms by Plant Secondary Metabolites Against Bacterial Pathogens

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Abstract

Plants are continuously challenged by a diverse array of bacterial pathogens capable of causing devastating diseases such as leaf spots, blights, wilts, cankers, galls and soft rots. Being sessile organisms unable to physically evade attack, plants have evolved an elaborate innate immune system reinforced by a vast chemical arsenal known as secondary metabolites. Unlike primary metabolites, which sustain basic cellular functions such as respiration and photosynthesis, secondary metabolites are not essential for immediate survival but confer significant ecological and adaptive advantages, particularly in defence against pathogenic microorganisms. This article provides a comprehensive review of the major classes of plant secondary metabolites including alkaloids, phenolics, flavonoids, tannins, terpenoids, saponins, glucosinolates and lectins and elaborates on the diverse biochemical mechanisms through which these compounds inhibit or neutralize bacterial pathogens. These mechanisms include direct antibacterial action through membrane disruption and enzyme inhibition, interference with bacterial quorum sensing and biofilm formation, chelation of essential metal ions, reinforcement of physical barriers through structural metabolites, and activation of systemic defence ignalling pathways mediated by salicylic acid, jasmonic acid and ethylene. The article further discusses the molecular basis of pathogen recognition, the phytoalexin response, the concept of systemic acquired resistance, and specific case studies illustrating metabolite-mediated resistance in economically important crops. Finally, the potential applications of these natural compounds in the development of eco-friendly antibacterial agents, biopesticides and disease-resistant crop varieties are discussed, along with the challenges and future prospects of this rapidly evolving field. A thorough understanding of these natural defence strategies is critical not only for advancing fundamental plant biology but also for addressing pressing agricultural and public health concerns related to bacterial disease management and antibiotic resistance.

Keywords: Plant secondary metabolites, Bacterial pathogens, Phytochemical defence, Alkaloids, Phenolics, Flavonoids, Tannins; Terpenoids, Saponins, Glucosinolates, Antibacterial activity, Phytoalexins, Induced systemic resistance, Quorum sensing inhibition, Plant–pathogen interaction.

Introduction

Bacterial diseases represent one of the most significant constraints to global crop productivity, crop productivity and the role of plant defense mechanisms (Jones. and Dangl,2006) and (Glazebrook,2005) causing substantial economic losses, vegetables, fruits and ornamental plants every year. Pathogenic bacterial genera such as *Pseudomonas, Xanthomonas, Ralstonia, Erwinia (Pectobacterium), Agrobacterium, Clavibacter and Acidovorax* invade host tissues through natural openings such as stomata and hydathodes, or through wounds, and subsequently multiply within the intercellular spaces or vascular tissues, leading to symptoms ranging from localized necrotic lesions to systemic wilting and plant death.

In response to this constant threat, plants have evolved a multi-layered defence system that operates at both the physical and biochemical levels. plant immunity consists of layered defense responses initiated by pathogen recognition and reinforced through induced biochemical defenses (Jones and Dangl 2006). The first layer consists of pre-formed structural barriers such as the cuticle, cell wall and wax layers, while the second layer comprises an active immune response triggered upon pathogen recognition. Central to this active immune response is the production of secondary metabolites low molecular weight organic compounds synthesized through specialized biosynthetic pathways branching off from primary metabolism, including the shikimate, mevalonate, methylerythritol phosphate (MEP) and polyketide pathways.

Secondary metabolites are recognized as major chemical defenses involved in plant adaptation and pathogen resistance (Bennett and Wallsgrove, 1994; Wink, 2003).serve numerous ecological roles, including attraction of pollinators, allelopathic interactions with competing plants, protection against ultraviolet radiation, and, most importantly for this discussion, defence against herbivores and microbial pathogens. Based on their timing of production relative to pathogen attack, these defensive metabolites are broadly classified into two categories: phytoanticipins, which are constitutively present in healthy tissue as pre-formed antimicrobial compounds or their inactive precursors, and phytoalexins, which are synthesized de novo following pathogen recognition and accumulate rapidly at the site of infection.

This article aims to provide a detailed and structured overview of how various classes of plant secondary metabolites contribute to defence against bacterial pathogens, the molecular mechanisms underlying their antibacterial activity, the signalling networks that regulate their biosynthesis, and the practical implications of this knowledge for sustainable agriculture.

Important Points:

1. Dual nature of defence: Plant defence against bacteria operates through both constitutive (pre-formed) and induced (pathogen-triggered) secondary metabolite production, providing layered and adaptable protection.

2. Major classes involved: Alkaloids, phenolic compounds, flavonoids, tannins, terpenoids, saponins, glucosinolates and lectins are the principal groups of secondary metabolites implicated in antibacterial defence.

3. Pathogen recognition: Plant cell-surface pattern recognition receptors (PRRs) detect pathogen-associated molecular patterns (PAMPs) such as bacterial flagellin (flg22) and elongation factor Tu (EF-Tu), initiating PAMP-triggered immunity (PTI).

4. Effector-triggered immunity: Resistant plants possess intracellular nucleotide-binding leucine-rich repeat (NLR) receptors that recognize pathogen effector proteins, triggering a stronger and more localized effector-triggered immunity (ETI), often accompanied by the hypersensitive response (HR).

5. Membrane disruption: Numerous alkaloids, terpenoids and saponins directly interact with bacterial membrane lipids and proteins, increasing membrane permeability and causing leakage of essential ions and metabolites.

6. Enzyme and protein inhibition: Tannins and phenolic acids bind to bacterial extracellular enzymes, adhesins and structural proteins, impairing pathogenicity and virulence factor function.

7. Quorum sensing and biofilm suppression: Certain flavonoids and terpenoids interfere with bacterial cell-to-cell signalling molecules such as N-acyl homoserine lactones (AHLs), thereby suppressing coordinated virulence gene expression and biofilm formation.

8. Metal ion chelation: Phenolics and flavonoids sequester iron and other essential trace metals required for bacterial enzymatic processes, effectively starving the pathogen of critical nutrients.

9. Phytoalexin accumulation: Rapid, localized biosynthesis of phytoalexins such as camalexin, resveratrol and pisatin restricts bacterial multiplication at the infection site.

10. Hormonal signalling crosstalk: Salicylic acid (SA) predominantly governs resistance to biotrophic and hemibiotrophic bacterial pathogens, while jasmonic acid (JA) and ethylene (ET) pathways are more relevant against necrotrophic pathogens, with antagonistic and synergistic crosstalk fine-tuning the overall response.

11. Systemic acquired resistance (SAR): A localized infection can prime the whole plant for enhanced resistance to subsequent bacterial attack, mediated by mobile signals and elevated secondary metabolite production in distal tissues.

12. Agricultural relevance: Understanding these mechanisms is fundamental to breeding disease-resistant cultivars, developing biopesticides, and formulating plant-derived antibacterial agents as alternatives to synthetic chemicals.

Classification of Plant Secondary Metabolites

Plant secondary metabolites relevant to antibacterial defence are broadly classified into several major chemical groups based on their biosynthetic origin and structural characteristics. The table below summarizes the principal classes, representative compounds, and their general mode of antibacterial action. Plant secondary metabolites are broadly classified into alkaloids, phenolics, terpenoids and nitrogen-containing compounds based on their biosynthetic origin (Bennett and Wallsgrove, 1994; Wink, 2003; Yadav *et al.*, 2020).

Class	Representative Compounds	General Mode of Antibacterial Action
Alkaloids	Berberine, Sanguinarine, Nicotine	Membrane disruption; DNA intercalation; efflux pump inhibition
Phenolic acids	Caffeic acid, Chlorogenic acid, Ferulic acid	Enzyme inhibition; membrane damage; metal chelation
Flavonoids	Quercetin, Kaempferol, Catechin	Quorum sensing inhibition; membrane permeabilization
Tannins	Tannic acid, Ellagitannins	Protein precipitation; enzyme inhibition; iron chelation
Terpenoids	Thymol, Carvacrol, Saponins-related sesquiterpenes	Membrane disruption; efflux pump inhibition
Saponins	Avenacin, Tomatine	Membrane permeabilization via sterol binding
Glucosinolates	Sinigrin, Glucobrassicin	Isothiocyanate release; enzyme and protein inhibition

Lectins & PR proteins	Chitin-binding lectins, Thaumatin-like proteins	Cell wall/membrane interaction; hydrolytic activity

Mechanisms of Antibacterial Defense

1. Membrane Disruption: A large proportion of antibacterial secondary metabolites, particularly lipophilic alkaloids, terpenoids and saponins, exert their effects by directly interacting with the bacterial plasma membrane. These compounds insert into the lipid bilayer, altering membrane fluidity and permeability. This leads to leakage of intracellular ions such as potassium, loss of the proton motive force, disruption of ATP synthesis, and ultimately cell lysis. Saponins, for example, form complexes with membrane sterols and phospholipids, creating pores that compromise membrane integrity, while terpenoids such as thymol and carvacrol partition into the lipid bilayer due to their hydrophobic nature, causing similar destabilizing effects. Similar antibacterial membrane-disrupting activities of plant metabolites have been reported by Cowan (1999) and Pandey and Kumar(2013).

2. Inhibition of Bacterial Enzymes and Virulence Factors: Many phenolic compounds and tannins act by binding non-specifically to bacterial proteins, including extracellular enzymes such as pectinases, cellulases and proteases that bacterial pathogens secrete to degrade host cell walls and facilitate colonization. This protein-binding activity, often mediated by hydrogen bonding and hydrophobic interactions, results in enzyme denaturation or inactivation, thereby reducing the pathogen's ability to invade host tissue. Tannins additionally inhibit bacterial adhesins, reducing the pathogen's capacity to attach to host cell surfaces, which is often the first critical step in the infection process. Protein precipitation and enzyme inhibition by phenolics and tannins were extensively reviewed by Cowan (1999)

3. Quorum Sensing and Biofilm Inhibition: Bacterial pathogens rely on quorum sensing, a density-dependent communication system mediated by signalling molecules such as N-acyl homoserine lactones (AHLs) in Gram-negative bacteria, to coordinate the expression of virulence genes and the formation of protective biofilms. Certain flavonoids and terpenoids act as quorum sensing inhibitors, either by structurally mimicking AHL molecules and competitively binding to their receptors, or by degrading the AHL signal itself. This disruption prevents bacteria from reaching the population density threshold required to activate virulence gene expression, effectively attenuating pathogenicity without necessarily killing the bacteria outright, an approach that also reduces the likelihood of resistance development. Plant phenolics capable of modulating microbial signalling have been discussed by Mandal *et al*. (2010).

4. Metal Ion Chelation: Iron and other trace metals are essential cofactors for numerous bacterial enzymes involved in respiration and metabolism. Phenolic compounds and flavonoids possess hydroxyl and carbonyl groups capable of chelating these metal ions, effectively sequestering them from the bacterial environment. This nutritional immunity strategy limits the availability of essential nutrients, thereby suppressing bacterial growth and metabolic activity, particularly in iron-limited conditions such as the plant apoplast. The chelating properties of phenolic compounds contribute significantly to antimicrobial activity.(Cowan, 1999; Sharma *et al.*, 2019).

5. Structural Reinforcement of Physical Barriers: sBeyond their direct antibacterial properties, certain secondary metabolites contribute to defence by reinforcing physical barriers. Lignin and lignin-like phenolic polymers are deposited in cell walls at infection sites, increasing wall rigidity and reducing bacterial penetration and movement through the apoplast. Suberin and callose deposition, often accompanied by phenolic cross-linking, further restrict pathogen spread by sealing off infected cells and vascular tissues. Reinforcement of plant cell walls through phenylpropanoid metabolism has been described by Sharma *et al*. (2019).

6. Phytoalexin Biosynthesis and Accumulation: Phytoalexins are low molecular weight antimicrobial compounds that are synthesized de novo and accumulate rapidly at the site of pathogen attack, often reaching inhibitory concentrations within hours of infection. Classic examples include camalexin in Arabidopsis thaliana, resveratrol and its oligomers in grapevine, and pisatin in pea. These compounds are typically synthesized through the phenylpropanoid or terpenoid pathways and act through mechanisms similar to those described above, including membrane disruption and enzyme inhibition, but are notable for their rapid, localized and pathogen-triggered mode of production. he biosynthesis and role of phytoalexins in disease resistance have been comprehensively reviewed by Ahuja *et al*. (2012) and Dixon (2001).

7. Induction of Systemic Defence Signalling: The production of antibacterial secondary metabolites is tightly regulated by a network of plant hormone signalling pathways. Salicylic acid (SA) is the primary hormone mediating defence against biotrophic and hemibiotrophic bacterial pathogens, activating the expression of pathogenesis-related (PR) genes and promoting the systemic acquired resistance (SAR) response, which confers long-lasting, broad-spectrum protection throughout the plant following a localized infection. Jasmonic acid (JA) and ethylene (ET) pathways, in contrast, are more prominently involved in defence against necrotrophic pathogens and certain insect herbivores, and often act antagonistically to the SA pathway. This crosstalk between hormonal pathways allows plants to fine-tune their defence responses according to the specific lifestyle and mode of attack of the invading pathogen. Hormonal regulation involving salicylic acid, jasmonic acid and ethylene has been reviewed by Glazebrook (2005) and Jones and Dangl (2006).

Class-Specific Antibacterial Mechanisms

1. Alkaloids: Alkaloids are nitrogen-containing heterocyclic compounds, many of which exhibit potent antibacterial activity. Berberine, found in plants such as Berberis species, intercalates with bacterial DNA and inhibits topoisomerase activity, while also disrupting membrane integrity and inhibiting bacterial efflux pumps, thereby enhancing the efficacy of co-administered antimicrobial agents. Sanguinarine, derived from *Sanguinaria canadensis* and other Papaveraceae species, disrupts membrane potential and inhibits key bacterial enzymes involved in energy metabolism the antimicrobial properties of plant. alkaloids have been summarized by Cowan (1999)and Pandey and Kumar (2013).

2. Phenolic Compounds and Flavonoids: Phenolic acids such as caffeic acid, ferulic acid and chlorogenic acid are ubiquitous in plant tissues and exhibit broad-spectrum antibacterial activity through membrane damage, enzyme inhibition and metal chelation. Flavonoids, a diverse subclass of polyphenols, including quercetin, kaempferol and catechins, additionally exhibit quorum sensing inhibitory activity and can act synergistically with other antibacterial metabolites, enhancing overall defence efficacy. Their biosynthesis and defensive functions are closely linked with the phenylpropanoid pathway (Sharma *et al.*, 2019).

3. Tannins: Tannins are high molecular weight polyphenolic compounds classified into hydrolysable and condensed forms. Their strong protein-binding capacity allows them to precipitate bacterial extracellular enzymes and adhesion proteins, while their metal-chelating properties further deprive bacteria of essential nutrients. Tannin-rich tissues, such as bark and unripe fruit, are often significantly more resistant to bacterial colonization than tannin-poor tissues. Their antimicrobial properties were comprehensively reviewed by Cowan (1999).

4. Terpenoids: Terpenoids, including monoterpenes, sesquiterpenes and diterpenes, are synthesized through the mevalonate and MEP pathways. Volatile terpenoids such as thymol and carvacrol, abundant in essential oils, exhibit strong membrane-disrupting activity due to their lipophilicity, while non-volatile terpenoids contribute to structural defence and act as phytoalexins in several plant families. The ecological significance of terpenoids has been discussed by Wink (2003).

5. Saponins: Saponins are glycosylated triterpenoid or steroidal compounds that interact with membrane sterols to form pores, leading to membrane permeabilization. Avenacin in oats and alpha-tomatine in tomato are well-characterized examples that provide constitutive protection against a range of pathogens, including certain bacteria, and are concentrated in tissues most vulnerable to attack, such as roots and young leaves. Preformed antimicrobial saponins were first extensively described by Osbourn (1996)

6. Glucosinolates: Glucosinolates, found predominantly in Brassicaceae family plants, are hydrolysed by the enzyme myrosinase upon tissue damage to release toxic isothiocyanates and other breakdown products. These compounds exhibit strong antibacterial activity through inhibition of bacterial enzymes and disruption of cellular redox homeostasis, contributing to the well-documented pathogen resistance observed in cruciferous crops. The defensive role of glucosinolate derived compounds has been highlighted by Bennett and Wallsgrove (1994).

Examples of Crop Plants

Numerous studies across economically important crops illustrate the practical significance of secondary metabolite-mediated antibacterial defence. In tomato (*Solanum lycopersicum*), elevated levels of chlorogenic acid and rutin have been correlated with enhanced resistance to *Pseudomonas syringae* pv. *tomato*, the causal agent of bacterial speck disease. In rice (*Oryza sativa*), phenolic compound accumulation and lignification at infection sites contribute to resistance against *Xanthomonas oryzae* pv. *oryzae*, the causal agent of bacterial leaf blight. In grapevine (*Vitis vinifera*), resveratrol and its oligomeric derivatives, viniferins, accumulate in response to bacterial and fungal challenge and exhibit demonstrable antimicrobial activity *in vitro*. In Arabidopsis thaliana, camalexin biosynthesis is strongly induced upon infection with *Pseudomonas syringae*, and camalexin deficient mutants exhibit markedly increased susceptibility, providing direct genetic evidence for the role of phytoalexins in bacterial defence.

Applications and Future Prospects

The potential of plant secondary metabolites as eco-friendly antimicrobials and crop protection agents has been emphasized by Pandey and Kumar (2013), Yadav *et al.* (2020) and Zaynab *et al.* (2018).

1. Botanical formulations: Plant extracts containing tannins, alkaloids, and terpenoids offer eco-friendly alternatives to synthetic bactericides.

2. Biopesticides: Secondary metabolites can be developed into sustainable biopesticides with lower environmental impact and reduced resistance risk.

3. Disease-resistant crops: Breeding and genomic approaches can enhance the production of antibacterial metabolites in elite cultivars.

4. Biotechnological applications: Metabolic engineering can increase antibacterial metabolite production in crops or microbial systems.

5. Antibiotic resistance: Plant metabolites with quorum sensing- and efflux pump-inhibitory properties are promising candidates for new antimicrobial drugs.

6. Challenges: Environmental variability, phytotoxicity, high production costs, and limited field validation hinder large-scale application.

Conclusion

Plant secondary metabolites are a vital component of plant defence against bacterial pathogens, acting through diverse mechanisms such as disrupting bacterial cells, inhibiting virulence, preventing quorum sensing and biofilm formation, chelating essential nutrients, strengthening structural barriers, and producing phytoalexins. Their synthesis is tightly regulated by signalling pathways involving salicylic acid, jasmonic acid, and ethylene, enabling plants to mount targeted responses to different pathogens. Evidence from crops such as tomato, rice, and grapevine, as well as Arabidopsis thaliana, demonstrates their significant role in disease resistance and their potential for agricultural applications. As bacterial diseases, climate change, and antibiotic resistance increasingly threaten global food security, plant secondary metabolites represent a sustainable source of natural antibacterial agents. Further research integrating plant biochemistry, genetics, and biotechnology will be crucial for developing innovative biopesticides and enhancing crop protection.

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Scientific Cultivation, Post Harvest Technology and Value Addition of Avocado Fruit

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Abstract

Avocado (*Persea americana* Mill.) has become one of the fastest-growing fruit crops globally due to its superior nutritional value, increasing health awareness, and rising domestic and international demand. The high quality of avocados (e.g., high nutritional content), the growth of consumer awareness, and the global consumption of avocado fruit are all linked. Avocados have many health benefits due to their high content of monounsaturated fatty acids, dietary fiber, vitamins, minerals, antioxidants, and other health promoting and bioactive compounds. After the expansion of avocados from their native growing range, and with the development of new cultivars and planting materials, systems of sustainable orchard management, and efficient irrigation and integrated nutrient management, the expansion of avocados to other subtropical and tropical regions has continued. In many developing countries, many factors, such as irregular bearing, limited pollination, post-harvest losses, diseases, and an inadequate cold-chain system, still limit the production. Avocados require effective post-harvest management, because they are a climacteric fruit that ripens rapidly. Improvement in the controlled atmosphere storage, modified atmosphere storage, edible coatings of fruit, ethylene management, smart packaging, and other advanced post-harvest packaging and storage have improved the shelf life and marketability of avocados. Additionally, a variety of consumer products, such as avocado oil, frozen avocado products, guacamole, functional foods, cosmetics, and nutraceuticals, offer many other value-added and export opportunities. Sustainable alternative use of avocado waste, peels, and seeds, also offer additional benefits to the economy and the environment. This review provides Postharvest technologies, cultivation, added value, and sustainable practices in avocado production and suggests future research directions to improve the profitability of this production.

Keywords: *Persea americana*, avocado cultivation, avocado oil, cold chain, processing, functional foods, sustainable agriculture.

Introduction

Avocado (*Persea americana* Mill.) is one of the most nutritious fruit crops cultivated worldwide and has experienced remarkable growth in production and consumption over the past three decades. Unlike most fruits, it is rich in heart-healthy monounsaturated fatty acids, particularly oleic acid, along with dietary fibre, vitamins A, C, E, K, B-complex vitamins, potassium, magnesium, folate, carotenoids, phytosterols, and antioxidants. These nutritional attributes have established avocado as a functional food, with increasing consumer demand driven by greater awareness of healthy diets and preventive healthcare (Dreher & Davenport, 2013).

Globally, avocado has evolved into a high-value commercial crop owing to urbanization, globalization, improved cold-chain infrastructure, and expanding international trade. Besides fresh consumption, it is widely processed into edible oil, guacamole, frozen pulp, beverages, baby foods, cosmetics, and nutraceuticals, enhancing its economic importance. Scientific studies have also associated avocado consumption with improved cardiovascular health, better lipid profiles, glycaemic regulation, and reduced risks of chronic diseases, leading to its recognition as a "superfruit" (Dreher & Davenport, 2013).

Commercial cultivation is concentrated in tropical and subtropical regions, with Mexico leading global production, followed by Peru, Colombia, Indonesia, Kenya, Chile, Israel, South Africa, the Dominican Republic, and the United States. Cultivation is also expanding in countries such as India, China, Vietnam, Australia, and Ethiopia due to favourable market prospects (Food and Agriculture Organization, 2023). In India, avocado is grown mainly in Karnataka, Tamil Nadu, Kerala, Maharashtra, and several north-eastern and Himalayan states. Although demand is increasing, large-scale commercialization remains constrained by limited quality planting material, inadequate orchard management, poor pollination, weak marketing systems, and insufficient post-harvest infrastructure (Ramos-Aguilar *et al.*, 2019).

Avocado possesses unique physiological characteristics, including ripening only after harvest and climacteric respiration, making proper harvest maturity assessment and post-harvest management essential for maintaining fruit quality (Yahia, 2019). Future growth of the avocado industry will rely on scientific cultivation integrated with precision irrigation, artificial intelligence, remote sensing, molecular breeding, climate-resilient orchard management, improved post-harvest technologies, and sustainable value-addition systems to enhance productivity, profitability, and environmental sustainability (Araújo *et al*., 2018).

Origin, History and Global Distribution

Avocado (*Persea americana* Mill.) originated in the tropical highlands of southern Mexico and Central America and is among the oldest cultivated fruit crops. Archaeological evidence indicates its consumption by ancient civilizations, including the Olmecs, Mayans, and Aztecs, about 8,000–10,000 years ago (Schaffer et al., 2013). Belonging to the family Lauraceae, avocado evolved into three horticultural races—Mexican, Guatemalan, and West Indian—which differ in climate adaptation, fruit characteristics, oil content, and disease tolerance. Most modern commercial cultivars are hybrids of these races (Reints *et al*., 2020).

Following European exploration in the sixteenth century, avocado spread worldwide, while breeding programmes in the nineteenth and twentieth centuries produced improved cultivars such as 'Hass', 'Fuerte', and 'Reed'. Among these, 'Hass' dominates global production and accounts for nearly 80% of international trade owing to its superior fruit quality and storage life (Wolstenholme, 2013). Global production now exceeds 9 million tonnes annually, with Mexico leading production, followed by Peru, Colombia, Indonesia, Kenya, Chile, the Dominican Republic, Israel, South Africa, and the United States (Food and Agriculture Organization, 2023). Growing demand has driven expansion of commercial orchards and adoption of sustainable, climate-smart production systems (Zerihun *et al*., 2021).

Botanical Description, Morphology and Reproductive Biology

Avocado (*Persea americana* Mill.) is an evergreen fruit tree of the family Lauraceae, naturally reaching 10–20 m in height but maintained at 4–8 m in commercial orchards through pruning. It has a spreading canopy, greyish-brown bark, and simple, leathery, dark green leaves that provide year-round photosynthesis. Young leaves are often reddish due to anthocyanins, while leaves of the Mexican race possess a characteristic anise-like aroma (Schaffer *et al*., 2013). The tree develops a shallow, fibrous root system concentrated within the upper 30–60 cm of soil. Because the roots have few root hairs, they depend heavily on mycorrhizal fungi for nutrient and water uptake, making avocado highly sensitive to waterlogging, soil compaction, and poor drainage (Schaffer *et al*., 2013).

Avocado produces terminal panicles bearing numerous small greenish-yellow bisexual flowers. Although flowering is abundant, only a small proportion of flowers develop into fruits due to natural flower and fruit drop. The flowers exhibit protogynous dichogamy, in which female and male functions occur at different times, promoting cross-pollination (Sedgley & Annells, 1981). Cultivars are classified into Type A (e.g., 'Hass', 'Pinkerton', 'Reed') and Type B (e.g., 'Fuerte', 'Bacon', 'Zutano') flowering groups, and interplanting both types improves pollination and fruit set. Honey bees (*Apis mellifera*) are the principal pollinators, while other insects also contribute to pollen transfer (Whiley et al., 2002). After fertilization, fruits develop through cell division, enlargement, and oil accumulation. Unlike most climacteric fruits, avocados mature on the tree but ripen only after harvest, making proper maturity assessment essential for optimum fruit quality and storage.

Flowering Physiology, Fruit Set and Fruit Development

Flowering in avocado is regulated by temperature, photoperiod, carbohydrate reserves, tree age, nutrition, and previous crop load (Whiley *et al*., 2002). Flower initiation occurs several months before anthesis, and each tree may produce hundreds of thousands of flowers. However, less than 0.1% develop into mature fruits because of poor pollination, resource competition, and natural flower and fruit drop (Schaffer *et al*., 2013). Successful fruit set depends on synchronization of flowering, pollen viability, stigma receptivity, insect pollinators, and favourable weather. Cross-pollination generally improves fruit retention, while adverse conditions such as extreme temperatures, rainfall, and strong winds reduce pollination efficiency. After fertilization, fruits develop through rapid cell division, enlargement, and gradual oil accumulation in the mesocarp. Depending on the cultivar, fruits require 6–18 months to mature, often resulting in flowers and fruits at different stages on the same tree (Cáceres-Zambrano *et al*., 2022).

Fruit maturity is commonly assessed by dry matter and oil content, as lipid concentration increases while moisture declines during development (Yahia, 2019). Carbohydrate availability also influences fruit growth, and excessive vegetative flushing can reduce fruit retention. Avocado commonly exhibits alternate bearing, with heavy crop years followed by low yields due to depletion of carbohydrate reserves and reduced flower induction.

Balanced pruning, nutrition, irrigation, and crop load management help stabilize production (Whiley *et al*., 2002). Environmental stresses such as heat and irregular rainfall may also cause disorders including sunburn, fruit drop, internal browning, and poor fruit quality (Dorantes *et al*., 2004).

Climatic Requirements

Avocado grows best in tropical and subtropical regions with moderate temperatures, frost-free conditions, and well-distributed rainfall. Among the three botanical races, the Mexican race is the most cold tolerant, the West Indian race is adapted to warm tropical climates but is frost sensitive, and the Guatemalan race has intermediate adaptability (Schaffer *et al.*, 2013). Optimum temperatures for growth range from 20–28°C. Mild temperatures favour flowering and fruit set, whereas temperatures above 35°C reduce pollination efficiency and those below 10°C during flowering may disrupt flowering synchrony. The crop requires about 1,000–1,600 mm of annual rainfall, although supplemental irrigation is essential in dry regions. Excess rainfall during flowering increases disease incidence and the risk of *Phytophthora* root rot (Builes *et al.*, 2020).

Relative humidity of 60–80% is favourable for growth. Low humidity increases moisture stress and fruit drop, while high humidity promotes fungal diseases. Strong winds reduce pollination, damage branches, and scar fruits; therefore, windbreaks are recommended. Adequate sunlight enhances photosynthesis and fruit quality, but excessive exposure may cause sunburn, making proper canopy management essential (Reints *et al.*, 2020).

Soil Requirements and Land Preparation

Successful avocado cultivation depends largely on proper soil selection because its shallow root system is highly sensitive to poor aeration and waterlogging. Although avocado can grow in various soil types, optimum growth, yield, and fruit quality are obtained in deep, fertile, well-drained soils with excellent aeration. Drainage is more important than soil fertility, as poorly drained soils greatly increase the risk of root diseases, particularly *Phytophthora* root rot (Schaffer *et al.*, 2013). Deep sandy loam or clay loam soils with an effective depth of 1.0–1.5 m is ideal, providing a balance between moisture retention and aeration. Heavy clay soils restrict drainage and promote root diseases, whereas very sandy soils have poor water- and nutrient-holding capacity, requiring intensive irrigation and fertilization. Where drainage is inadequate, raised beds or mounds are recommended to improve root-zone aeration. Avocado performs best in slightly acidic to neutral soils (pH 5.5–6.8). Acidic soils may cause aluminium toxicity and deficiencies of calcium, magnesium, and phosphorus, while alkaline soils commonly induce iron, zinc, manganese, and boron deficiencies, leading to chlorosis, poor growth, and reduced fruit quality. Soil pH should be corrected before planting using lime for acidic soils and sulphur or organic amendments for alkaline soils (Whiley *et al.*, 2002).

High organic matter is essential for improving soil structure, moisture retention, nutrient availability, and microbial activity. Application of well-decomposed farmyard manure, compost, vermicompost, green manures, and cover crops enhances soil health and promotes beneficial mycorrhizal fungi that improve nutrient uptake. Because avocado roots require continuous oxygen, even short-term waterlogging can severely damage roots and increase susceptibility to *Phytophthora cinnamomi*. Orchards should therefore be established on gently sloping land or provided with effective surface or subsurface drainage, raised beds, or mounded rows. Before planting, comprehensive soil testing should assess pH, organic carbon, electrical conductivity, nutrient status, and soil-borne pathogens to guide site-specific nutrient management. Land preparation includes clearing vegetation, removing stones and stumps, deep ploughing, cross-harrowing, and sub-soiling (60–90 cm) where hardpans exist. In hilly areas, contour planting, bench terracing, and cover crops help reduce erosion, conserve moisture, suppress weeds, and improve long-term orchard sustainability (Carr, 2013).

Avocado Races, Cultivars and Genetic Diversity

Cultivated avocado possesses extensive genetic diversity resulting from natural evolution, domestication, and hybridization. Most commercial cultivars originate from three horticultural races—Mexican, Guatemalan, and West Indian—each contributing distinct traits such as fruit quality, climatic adaptation, disease resistance, and yield potential (Schaffer *et al.*, 2013). The Mexican race (*Persea americana* var. *drymifolia*) originated in the cool highlands of central Mexico. It produces small fruits (100–250 g) with thin skins, high oil content, and excellent flavour. Trees are the most cold-tolerant among avocado races, and their leaves release a characteristic anise aroma when crushed. This race is widely used in breeding cold-hardy cultivars (Reints *et al.*, 2020). The Guatemalan race (*P. americana* var. *guatemalensis*) evolved in the highlands of Guatemala. It bears medium to large fruits (250–700 g or more) with thick, rough skins that improve resistance to handling damage. Fruits have high quality and moderate oil content, while trees possess intermediate cold tolerance. Many important commercial cultivars, including 'Hass', have substantial Guatemalan ancestry. The West Indian race (*P. americana* var. *americana*) originated in humid tropical lowlands. It is characterized by vigorous growth, large fruits with smooth skins, lower oil content, and better tolerance to saline soils. Although highly susceptible to frost, it performs well in warm, humid tropical climates and is an important genetic resource for tropical breeding. Most modern commercial cultivars are inter-racial hybrids combining desirable traits from two or more races, resulting in improved adaptability, productivity, fruit quality, and wider climatic suitability compared with the original botanical races (Amare *et al.*, 2019).

Commercial Cultivars

Among commercial avocado cultivars, 'Hass' is the most important, accounting for nearly 80% of global avocado trade. Discovered in California by Rudolph Hass, it is valued for its moderate tree vigour, regular bearing, and wide adaptability. Fruits are medium-sized (200–350 g) with thick, pebbled skin that turns from green to purplish-black when ripe. The creamy flesh has high oil content, rich buttery flavour, and excellent post-harvest keeping quality, making 'Hass' the preferred cultivar for both domestic and export markets (Whiley *et al.*, 2002). 'Fuerte', once the dominant commercial cultivar, remains important in several countries because of its attractive pear-shaped fruits, smooth green skin, pleasant flavour, and long harvesting season. As a Type B flowering cultivar, it is widely used as a pollinizer in 'Hass' orchards. 'Pinkerton' produces elongated pear-shaped fruits with small seeds, high pulp recovery, thick green skin, and excellent eating quality. Trees are precocious, highly productive, and well adapted to subtropical regions (Arias García *et al.*, 2021).

'Reed' is known for its large round fruits, high oil content, excellent flavour, consistent productivity, and late maturity, making it valuable for extending the marketing season. 'Lamb Hass', an improved selection from 'Hass', closely resembles its parent but matures later, extending harvest duration. Its compact, highly productive trees are well suited to high-density orchards (Biazin *et al.*, 2018). Other commercially important cultivars include 'Bacon', 'Zutano', 'Gwen', 'Nabal', 'Sharwil', 'Ettinger', 'Ryan', 'Wurtz', and 'Carmen Hass', each adapted to specific climates and market requirements. Successful cultivar selection should consider climate, flowering type, disease resistance, market demand, harvest season, and pollinizer compatibility. Growing multiple cultivars within an orchard improves pollination, extends the harvesting period, reduces production risks, and enhances overall profitability (Espíndola-Barquera, 2008).

Propagation Techniques

Propagation is fundamental to avocado cultivation because orchard productivity and longevity depend on high-quality planting material. Commercial orchards are established through vegetative propagation, where elite scion cultivars are grafted onto superior rootstocks to produce true-to-type plants with early bearing, uniform growth, superior fruit quality, and improved tolerance to biotic and abiotic stresses (Schaffer *et al.*, 2013). Seed propagation is unsuitable for commercial production due to high genetic variability and delayed bearing (7–12 years), but seedlings remain essential for rootstock production and breeding programmes. Modern propagation emphasizes grafting, clonal rootstocks, improved nursery management, and production of pathogen-free certified planting material.

1. Seed Propagation: Seed propagation is mainly used for producing rootstocks. Seeds should be collected from healthy, fully mature fruits of vigorous trees, washed thoroughly, and sown immediately because avocado seeds are recalcitrant and rapidly lose viability during storage (Whiley *et al.*, 2002). Large, healthy seeds are preferred, and fungicide or Trichoderma treatment helps reduce seed rot and damping-off. Seeds are sown in sterilized, well-drained media with the broad end downward and the upper one-third exposed. Under optimum temperatures of 20–30°C, germination occurs within 3–6 weeks. Seedlings require partial shade initially before gradual exposure to full sunlight. Although unsuitable for commercial orchards, seedling rootstocks are indispensable for grafting elite cultivars.

2. Vegetative Propagation: Vegetative propagation preserves the genetic identity of elite cultivars such as 'Hass', 'Fuerte', 'Pinkerton', 'Reed', 'Lamb Hass', and 'Bacon', ensuring uniform fruit quality, yield, maturity, and market acceptance (Schaffer et al., 2013). Grafted trees also bear much earlier (3–4 years) than seedlings and exhibit more uniform growth and production. Consequently, vegetative propagation is the standard method for commercial avocado cultivation, with grafting being the most widely adopted technique (Viera *et al.*, 2017).

3. Grafting: Grafting involves joining a desirable scion with a compatible rootstock. Successful grafting requires proper cambial contact, adequate moisture, favourable temperature, and protection from desiccation until union occurs. Scions should be collected from healthy, true-to-type, high-yielding mother trees, preferably from mature shoots with dormant buds. Defoliating selected shoots 7–10 days before collection enhances carbohydrate accumulation and improves graft success. Several grafting techniques have been standardized for avocado propagation.

4. Veneer Grafting: Veneer Grafting: Veneer grafting is the most widely used commercial propagation method due to its high success rate, simplicity, and strong graft union formation. Rootstocks aged 6–12 months with stem diameters of 8–15 mm are ideal. A 3–5 cm slanting cut is made on the rootstock, and a matching cut is prepared on the scion. The scion is fitted to ensure close cambial contact and the union is tightly wrapped with polyethylene grafting tape. The graft is protected from drying until healing is complete, with successful unions usually forming within 4–6 weeks under favourable conditions.

5. Cleft Grafting: Cleft grafting is frequently employed when scion and stock possess comparable diameters. The rootstock stem is decapitated and split vertically to form a cleft into which wedge-shaped scions are inserted. Proper alignment of cambial tissues is essential for successful vascular connection. This method generally provides excellent success under nursery conditions when performed during active growth periods.

6. Side Grafting: Side grafting is particularly useful for top-working established trees or when rootstocks are relatively larger than available scions. A slanting incision is prepared on the side of the rootstock stem, into which a correspondingly

shaped scion is inserted. Following successful graft union, the upper portion of the rootstock is gradually removed to encourage scion dominance.

7. Epicotyl Grafting: Epicotyl grafting has gained increasing popularity because it enables rapid production of planting material using very young seedlings. Grafting is performed shortly after seed germination while seedlings remain in their juvenile stage. This technique considerably reduces nursery duration and production costs while maintaining satisfactory graft success under skilled management (Amare *et al.*, 2019).

8. Budding: Unlike several fruit crops, budding techniques generally exhibit lower success in avocado owing to anatomical and physiological characteristics of the bark and cambial tissues. Nevertheless, shield budding and patch budding have occasionally been employed under specialized nursery conditions with variable success. Consequently, grafting continues to dominate commercial propagation systems worldwide.

Nursery Management

Scientific nursery management is vital for producing vigorous, disease-free avocado planting material and ensuring successful orchard establishment. Nurseries should be located on well-drained sites with reliable irrigation, good ventilation, and partial shade during early growth. Growing media should be light, porous, fertile, and free from soil-borne pathogens, with sterilized soil, sand, compost, cocopeat, and perlite commonly used. Root trainers and polyethylene bags with adequate drainage support healthy root development (Amare *et al.*, 2019). Uniform irrigation and balanced fertilization are essential for healthy seedling growth, while micronutrients may be applied where deficiencies occur. Regular sanitation, weed control, and integrated pest management—including biological control agents, botanical pesticides, and careful monitoring—help minimize diseases and insect pests. Before field planting, grafted plants should be hardened by gradually reducing irrigation and increasing sunlight exposure to improve field survival. Commercial planting material should be 8–12 months old, with a healthy fibrous root system, strong graft union, dark green foliage, and complete freedom from pests and diseases (Caro *et al.*, 2021).

Orchard Establishment

Successful commercial avocado production depends on proper orchard establishment, as trees remain productive for over 50 years under good management. Errors made during establishment can reduce yield, fruit quality, and orchard longevity. Therefore, careful planning of site selection, field layout, planting geometry, cultivar and pollinizer selection, irrigation, and soil preparation is essential before planting (Schaffer *et al.*, 2013).

Avocado orchards should be established on gently sloping, well-drained land with good air circulation. Low-lying frost-prone areas and heavy clay soils susceptible to waterlogging should be avoided because avocado roots are highly sensitive to oxygen deficiency and Phytophthora root rot. Gentle slopes improve drainage, air movement, and reduce disease incidence. Before planting, the site should be surveyed for topography, soil depth, drainage, irrigation, road access, and mechanization needs. In windy regions, permanent windbreaks such as *Casuarina equisetifolia, Grevillea robusta, Eucalyptus camaldulensis* or bamboo should be established in advance while maintaining adequate spacing. The orchard layout should allow efficient movement of labour, machinery, and irrigation systems, with farm roads, drainage channels, and irrigation infrastructure completed before planting. Modern orchards increasingly use precision land levelling, GPS-guided planting, and digital mapping to improve efficiency (Thomas *et al.*, 2020).

Planting Season

Selection of the appropriate planting season is critical for successful avocado establishment, as young plants require favourable conditions to develop a strong root system. In tropical regions, planting is best carried out at the onset of the monsoon when adequate soil moisture reduces transplant shock. In India, the recommended planting period is June–August, while February–March planting is also suitable under assured irrigation. In subtropical regions, spring planting after the risk of frost is preferred (Reints *et al.*, 2020). Planting during extreme summer heat or before heavy rains should be avoided, as moisture stress and waterlogging increase seedling mortality. Cloudy weather with moderate temperatures, along with planting during the early morning or late afternoon, provides the most favourable conditions for successful establishment (Rodríguez-Martínez *et al.*, 2022).

Pit Preparation

Pit Preparation: Proper pit preparation promotes rapid root establishment and early tree growth. Generally, pits of 60 × 60 × 60 cm are adequate, while 1 × 1 × 1 m pits are preferred in heavy soils to improve drainage. The topsoil is mixed with 20–30 kg of well-decomposed farmyard manure or compost, neem cake, rock phosphate, and recommended micronutrients before refilling to enhance soil fertility, structure, and root development. In disease-prone soils, Trichoderma harzianum may be added to suppress soil-borne pathogens, while termite control measures should be adopted where necessary. Pits should be prepared 1–2 months before planting to allow soil stabilization. In high-rainfall areas, raised mounds (30–60 cm) are recommended to improve drainage and reduce root diseases (Thomas *et al.*, 2020).

Spacing Systems

Plant spacing influences tree population, light interception, canopy architecture, nutrient competition, irrigation efficiency, and overall orchard management. The optimum spacing depends on cultivar vigour, rootstock, soil fertility, climate, pruning intensity, and mechanization requirements (Whiley *et al.*, 2002).

Traditional avocado orchards generally use square planting at 8 × 8 m to 10 × 10 m, accommodating about 100–156 trees ha^{-1} while ensuring adequate sunlight penetration and machinery movement. Moderately vigorous cultivars are commonly planted at 7 × 7 m or 8 × 6 m to enhance early productivity without excessive canopy competition, whereas semi-dwarf rootstocks permit closer spacing. Rectangular planting systems facilitate mechanized operations such as mowing, spraying, pruning, harvesting, and transport by combining wider row spacing with closer within-row spacing. On sloping land, contour planting reduces soil erosion, slows runoff, and improves water infiltration. Triangular and hexagonal systems accommodate slightly higher tree populations and improve light distribution but are less suitable for mechanized orchard management, limiting their adoption in modern commercial orchards (Farooq *et al.*, 2019).

High-density planting is an important innovation in avocado production, driven by rising land costs, labour shortages, and the need for higher productivity. Depending on cultivar vigour and rootstock, spacings of 6 × 4 m to 5 × 3 m accommodate 300–600 trees ha^{-1}, compared with 100–150 trees ha^{-1} under conventional systems (Reints *et al.*, 2020). Higher tree density accelerates canopy development, increases early light interception, and improves cumulative yields, resulting in earlier economic returns. However, sustained productivity requires intensive canopy management through regular pruning, hedging, topping, and thinning to prevent overcrowding and maintain light penetration. Efficient drip irrigation with fertigation is essential to meet the higher water and nutrient demand, while dwarfing rootstocks, compact cultivars, and precision technologies further improve orchard efficiency. Although establishment costs are higher, increased early yields often make high-density systems economically viable for commercial avocado production (Thomas *et al.*, 2020).

Pollinizer Arrangement

Efficient pollination is essential for profitable avocado production because of its protogynous dichogamous flowering habit. Although some cultivars are partially self-fertile, cross-pollination generally improves fruit set and yield (Sedgley & Annells, 1981). Commercial orchards therefore combine compatible Type A cultivars ('Hass', 'Pinkerton', 'Gwen', 'Reed') with Type B cultivars ('Fuerte', 'Bacon', 'Zutano', 'Ettinger'). A common practice is to plant one pollinizer tree for every 8–10 main cultivar trees or dedicate every fourth or fifth row to pollinizers, depending on orchard conditions (Etissa, 1999). Managed honey bee colonies (5–10 ha^{-1}) are introduced during flowering to enhance pollen transfer, while native pollinators and flowering cover crops further improve pollination efficiency, biodiversity, and orchard productivity (Toukem *et al.*, 2020).

Scientific Planting Methods

Only healthy grafted plants with vigorous root systems and well-healed graft unions should be selected for planting. Nursery containers should be watered before transplanting to remove plants without disturbing the root ball. The graft union should remain 15–20 cm above the soil surface to prevent scion rooting and reduce disease risk. Plants should be placed upright in the centre of the pit, and soil should be gently firmed around the roots. Immediate irrigation helps establish good soil–root contact. In windy areas, staking is recommended to support young trees. Organic mulch conserves moisture, suppresses weeds, and improves soil fertility but should be kept away from the trunk to prevent collar rot (Reints *et al.*, 2020).

During the first year, regular irrigation, balanced nutrition, weed control, and protection from livestock, rodents, and sunburn are essential. White tree guards or trunk paints may be used in hot regions to reduce sunburn. Regular monitoring for pests, diseases, and nutrient deficiencies ensures healthy establishment and vigorous canopy development.

Nutrient Management

Balanced nutrient management is essential for avocado productivity, fruit quality, and orchard longevity. Nutrient requirements vary with tree age, cultivar, rootstock, soil fertility, crop load, and climate. Efficient nutrient management combines soil testing, leaf analysis, organic manures, inorganic fertilizers, fertigation, and precision monitoring to optimize yield while minimizing environmental impacts (Schaffer *et al.*, 2013).

Nitrogen is the most important nutrient for vegetative growth, flowering, and fruit production. Deficiency causes chlorosis, poor growth, and low yields, whereas excess promotes excessive vegetative growth, delays fruit maturity, and reduces fruit quality. Nitrogen should therefore be applied in split doses during active growth. Phosphorus supports root development, energy transfer, flowering, and early fruit growth, while potassium is essential for fruit enlargement, carbohydrate transport, oil accumulation, and fruit quality. Calcium improves cell wall strength, fruit firmness, and storage life, whereas magnesium is required for chlorophyll formation and photosynthesis. Sulphur and micronutrients such as zinc, boron, iron, manganese, copper, and molybdenum are also essential. Zinc deficiency reduces shoot growth,

boron is critical for pollination and fruit set, and iron deficiency commonly causes interveinal chlorosis in alkaline soils (Sotomayor *et al.*, 2019).

Leaf nutrient analysis, combined with soil testing, is the most reliable method for diagnosing nutrient status and guiding fertilizer application. Organic sources such as farmyard manure, compost, vermicompost, green manures, biochar, and crop residues improve soil fertility, structure, microbial activity, and water-holding capacity. Biofertilizers, including nitrogen-fixing bacteria, phosphate-solubilizing microbes, potassium-mobilizing bacteria, and mycorrhizal fungi, further enhance nutrient uptake and use efficiency. Integrated Nutrient Management (INM), combining organic manures, chemical fertilizers, and biofertilizers, is the most sustainable strategy for maintaining soil fertility, improving nutrient-use efficiency, enhancing fruit quality, and reducing environmental pollution (Whiley *et al.*, 2002).

Weed Management

Weeds compete with avocado trees for water, nutrients, light, and space, especially during orchard establishment. They also harbour pests and diseases and interfere with irrigation and harvesting. Effective weed control is therefore essential for maintaining orchard productivity. Young orchards require intensive weed management because their root systems are weak. Manual weeding, mechanical cultivation, organic mulching, cover crops, and selective herbicides can be integrated according to orchard age and management needs (Duarte *et al.*, 2016). Organic mulches suppress weeds, conserve soil moisture, and improve soil health, while leguminous cover crops enhance nitrogen fixation and reduce erosion. However, vigorous cover crops should be managed to avoid competition with young trees. Herbicides should be used carefully, applying non-selective products only within tree rows and avoiding drift onto avocado foliage. An Integrated Weed Management (IWM) approach that combines cultural, mechanical, biological, and chemical methods provides the most effective and sustainable long-term weed control (Sora, 2023).

Intercropping

Intercropping during the juvenile phase of avocado orchards enhances land-use efficiency and provides additional income before trees reach full bearing. Since young avocado trees occupy only a small proportion of available land during the first several years, suitable intercrops may be cultivated between rows without adversely affecting tree growth **(Whiley *et al.*, 2002)**. Leguminous crops such as cowpea, green gram, black gram, soybean, and groundnut are particularly suitable because they improve soil fertility through biological nitrogen fixation. Short-duration vegetables including cabbage, cauliflower, onion, garlic, carrot, radish, beetroot, and leafy vegetables may also be cultivated where irrigation is available. Medicinal and aromatic plants such as lemongrass, citronella, turmeric, ginger, and aloe vera have shown promise as intercrops owing to their relatively shallow root systems and economic value. However, competitive perennial crops should be avoided as tree canopies expand **(Whiley *et al.*, 2002)**.

Mulching

Mulching constitutes one of the most beneficial orchard management practices for avocado cultivation. Organic materials including straw, dried grasses, sugarcane trash, wood chips, compost, coconut husk, and shredded pruning residues are commonly applied around tree basins. Mulching conserves soil moisture by reducing evaporation, moderates soil temperature, suppresses weeds, minimizes erosion, improves infiltration, and gradually contributes organic matter through decomposition **(Whiley *et al.*, 2002)**. Enhanced microbial activity beneath mulch also promotes nutrient cycling and improved soil health. In warm climates, mulching reduces extreme soil temperatures that may damage shallow feeder roots. During dry seasons, it substantially decreases irrigation requirements while maintaining favourable root-zone moisture conditions (Lovatt *et al.*, 2015).

Training, Pruning and Canopy Management

Canopy management is essential for balancing vegetative growth and fruit production in avocado. Without proper management, trees become excessively tall with dense canopies that hinder harvesting and reduce light penetration. Training begins soon after planting by developing a strong framework with well-spaced scaffold branches. Early removal of weak, crossing, diseased, and poorly oriented shoots establishes a desirable canopy structure (Whiley *et al.*, 2002).

Maintenance pruning regulates tree size, improves light distribution and air circulation, facilitates harvesting, and removes dead, diseased, or overcrowded branches, thereby promoting healthy fruiting wood and reducing disease incidence. High-density orchards require more intensive pruning through hedging, topping, and side pruning to maintain manageable tree size. In old orchards, rejuvenation pruning restores productivity by stimulating new vegetative growth, although yields decline temporarily during recovery. Proper canopy architecture enhances photosynthesis, flowering, fruit size, colour, and overall productivity by ensuring uniform light penetration. Thus, scientific canopy management is a key practice for sustaining long-term yield and fruit quality (Schaffer *et al.*, 2013).

Flowering Biology, Floral Physiology, Pollination, Pollinizers, Fruit Set and Fruit Development

Avocado (*Persea americana* Mill.) exhibits protogynous dichogamy, where the female and male phases of the same flower occur at different times, promoting cross-pollination. Cultivars are classified into Type A (e.g., 'Hass', 'Reed') and Type

B (e.g., 'Fuerte', 'Bacon') flowering groups with complementary flowering patterns. Flowering is influenced by genotype, carbohydrate reserves, nutrition, temperature, soil moisture, and previous crop load. Although a mature tree produces thousands to millions of flowers, only 0.05–0.2% develop into fruits. Optimum temperatures (20–25°C), balanced nutrition, and adequate boron and zinc favour flowering and fruit set.

Pollination is mainly carried out by the European honey bee (Apis mellifera), with 5–10 bee colonies per hectare recommended in commercial orchards. Fruit set depends on effective pollination, fertilization, carbohydrate supply, and favourable environmental conditions, while drought and nutrient stress increase natural fruit drop. Fruits develop through cell division, enlargement, and oil accumulation, maturing on the tree but ripening only after harvest. Dry matter and oil content are the most reliable maturity indices. Integrated management involving compatible pollinizers, bee populations, balanced nutrition, irrigation, pruning, and stress management improves fruit set, fruit quality, and yield stability (Onsomu *et al.*, 2018).

Crop Regulation, Alternate Bearing, Fruit Thinning, Crop Load Management and Physiological Disorders

Crop regulation is essential for maintaining consistent yield, fruit quality, and orchard longevity in avocado. Because vegetative growth, flowering, and fruit development occur simultaneously, competition for carbohydrates, nutrients, and water often affects fruit retention and subsequent flowering. Effective management maintains a balance between vegetative and reproductive growth (Lovatt *et al.*, 2015).

Alternate (biennial) bearing is a major constraint, especially in 'Hass', where a heavy crop year is followed by poor flowering and low yield. Heavy fruit loads deplete carbohydrate reserves, while hormones produced by developing seeds suppress floral initiation, reducing the following season's crop (Whiley *et al.*, 2002). Environmental stresses such as drought, nutrient deficiency, salinity, pests, diseases, and delayed harvesting further aggravate this problem. Scientific management minimizes alternate bearing through balanced nutrition, efficient irrigation, timely harvesting, and annual canopy pruning. Moderate nitrogen with adequate potassium, calcium, boron, and zinc promotes regular flowering, while prompt harvesting reduces competition between mature fruits and developing floral buds. Proper pruning improves light penetration and air circulation, enhancing flower bud formation. Precision irrigation using soil moisture sensors and automated scheduling helps maintain optimum soil moisture, reducing stress and improving regular annual production (Bender *et al.*, 2001).

Fruit Thinning & Crop Load Management

Routine manual fruit thinning is generally unnecessary in commercial avocado orchards because natural physiological fruit drop removes most flowers and young fruits. However, under exceptionally heavy fruit set, selective thinning may improve fruit size, reduce limb breakage, and minimize alternate bearing. Natural thinning occurs through successive drops of unfertilized flowers, weakly fertilized fruits, and excess developing fruits during periods of intense competition for assimilates. These processes usually regulate crop load effectively under normal conditions.

When fruit load is excessive, early removal of overcrowded, malformed, damaged, or diseased fruits improves fruit quality and reduces stress on trees. Chemical thinning has limited commercial use due to the crop's complex reproductive physiology and inconsistent responses to plant growth regulators. Crop load management aims to maintain an optimum balance between fruit number and tree capacity. Excessive crop loads reduce fruit size, delay maturity, deplete carbohydrate reserves, and promote alternate bearing, whereas light crop loads reduce productivity. Balanced crop loads improve fruit size, oil content, marketable yield, and regular annual flowering through integrated pruning, nutrition, irrigation, pollination, and harvest management. Precision technologies such as remote sensing, drone imaging, machine vision, and artificial intelligence are increasingly used to assess crop load and optimize orchard management (Lovatt *et al.*, 2015).

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Physiological Disorders

Physiological disorders represent non-pathogenic abnormalities arising from environmental stress, nutritional imbalance, genetic factors, or improper orchard management. Although these disorders are not caused by infectious organisms, they frequently reduce fruit quality, storage life, and market value.

1. Sunburn: Sunburn is a common physiological disorder in avocado caused by intense sunlight and high temperatures. Exposed fruits develop yellow, brown, or black necrotic patches, often with internal tissue damage, reducing market value and increasing susceptibility to fungal infection. Management includes maintaining adequate canopy cover, avoiding excessive pruning, ensuring proper irrigation during hot periods, and applying reflective kaolin sprays to lower fruit surface temperature.

2. Chilling Injury: Chilling injury occurs when avocados are stored below cultivar-specific temperature limits. Symptoms include peel pitting, internal browning, uneven ripening, vascular discoloration, increased decay, and poor flavour. Proper cold-chain management using recommended storage temperatures and controlled atmosphere storage effectively minimizes chilling injury while preserving fruit quality (Yahia, 2019).

3. Irregular Fruit Shape: Environmental stress during flowering and early fruit development frequently produces malformed fruits exhibiting curved necks, asymmetrical growth, or distorted shapes. Inadequate pollination, temperature fluctuations, nutrient deficiencies, and hormonal imbalance have all been implicated in irregular fruit development. Maintaining optimum pollination conditions, balanced nutrition, and adequate irrigation during early fruit growth substantially reduces fruit malformation.

4. Lenticel Damage: Lenticels are small natural openings present on avocado fruit surfaces that facilitate gas exchange. Under humid conditions followed by rapid drying, lenticels may crack or become enlarged, resulting in rough fruit surfaces and reduced cosmetic quality. Mechanical injury during harvesting and handling may further aggravate lenticel damage. Careful harvesting, gentle handling, rapid cooling, and maintenance of optimum relative humidity during storage help minimize lenticel disorders.

5. Fruit Cracking: Fruit cracking occasionally occurs following sudden fluctuations in soil moisture, particularly when prolonged drought is followed by heavy rainfall or excessive irrigation. Rapid water uptake causes expansion of internal tissues beyond the elasticity of the peel, producing longitudinal cracks that render fruits unmarketable. Uniform irrigation scheduling and mulching effectively reduce fluctuations in soil moisture, thereby minimizing cracking incidence.

6. Internal Browning: Internal browning represents one of the most economically important physiological disorders affecting stored avocado fruits. Browning may occur within vascular tissues, pulp, or seed cavity and often becomes evident only after fruit ripening. Chilling injury, delayed harvesting, mechanical damage, calcium deficiency, and prolonged storage contribute to disorder development. Maintenance of recommended storage temperatures, balanced calcium nutrition, careful harvesting, and minimization of mechanical injury substantially reduce internal browning (Schaffer *et al.*, 2013).

7. Stem-End Disorders: Premature softening and discoloration around the stem attachment region frequently occur following improper harvesting or delayed cooling. Excessive moisture loss through the pedicel region accelerates ripening and increases susceptibility to fungal pathogens. Harvesting fruits with short pedicels, immediate pre-cooling, and maintenance of high relative humidity reduce stem-end disorders.

Pest Management of Avocado

1. Thrips: Thrips, especially *Scirtothrips perseae*, feed on young leaves, flowers, and developing fruits, causing silvery leaf discoloration, distorted shoots, flower damage, and brown fruit scars that reduce market value. Infestations are favoured by warm, dry weather and excessive nitrogen fertilization. Management includes regular monitoring, conservation of natural enemies (predatory mites, Orius spp., lacewings, ladybird beetles, and spiders), pruning for better air circulation, and selective insecticide application only when economic thresholds are exceeded.

2. Scale Insects: Scale insects, including greedy scale (*Hemiberlesia rapax*), black scale (*Saissetia oleae*), and brown soft scale (*Coccus hesperidum*), infest avocado leaves, shoots, twigs, and fruits by sucking plant sap. Heavy infestations weaken trees, reduce photosynthesis, cause premature leaf fall, and lower fruit quality. Soft scales produce honeydew that encourages sooty mould, reducing photosynthesis and fruit marketability. Management relies mainly on biological control through parasitoid wasps, ladybird beetles, lacewings, and predatory mites. Pruning infested branches, balanced fertilization, horticultural oils, and avoiding unnecessary broad-spectrum insecticides help maintain effective control.

3. Mealybugs: Mealybugs infest young shoots, leaf axils, flower clusters, fruit stalks, and roots, causing sap loss, reduced vigour, fruit drop, and fruit deformation. Honeydew secretion promotes sooty mould, while ants protect mealybug colonies and increase infestations. Management includes controlling ants, conserving parasitoids (Anagyrus spp.), releasing the predatory ladybird Cryptolaemus montrouzieri, removing heavily infested plant parts, and using selective insecticides only when necessary.

4. Aphids: Although aphids rarely become major pests in mature avocado orchards, young nursery plants and newly flushing shoots may occasionally experience significant infestations. Aphids feed on tender tissues, causing curling, distortion, reduced shoot growth, and transmission of certain viral diseases. Natural enemies including ladybird beetles, lacewings, syrphid flies, parasitoid wasps, and predatory bugs usually maintain aphid populations below damaging levels. Excessive nitrogen fertilization should be avoided because it promotes succulent growth attractive to aphids.

5. Fruit Borers: Fruit borers constitute serious pests in several avocado-growing regions. Larvae penetrate developing fruits, feeding internally on pulp and seeds while rendering fruits unsuitable for marketing. Entry holes often become infected by secondary fungal pathogens, accelerating fruit decay. Integrated management includes orchard sanitation, destruction of infested fruits, pheromone trapping where available, timely harvesting, conservation of egg parasitoids, and judicious insecticide application based upon monitoring results.

6. Stem and Branch Borers: Stem borers and branch borers attack woody tissues, producing tunnels that weaken structural integrity, reduce nutrient transport, and predispose trees to secondary infections. Severe infestations may result in branch dieback or complete tree decline. Regular inspection of trunks and scaffold branches enables early

detection of borer activity. Removal and destruction of heavily infested branches, maintenance of tree vigour, sealing of pruning wounds, and appropriate insecticidal treatments contribute to effective management.

7. Leaf-Feeding Caterpillars: Several lepidopteran larvae feed on avocado foliage, causing defoliation during severe outbreaks. Young trees are particularly susceptible because extensive leaf loss reduces photosynthetic capacity and delays canopy development. Conservation of natural enemies, including parasitoid wasps and predatory birds, together with microbial insecticides based on *Bacillus thuringiensis* (Bt), provides environmentally compatible management. Chemical interventions should be reserved for severe infestations exceeding economic thresholds.

8. Mites: Mites: Mites are important avocado pests, especially under hot, dry conditions. Species such as avocado brown mite (*Oligonychus punicae*), persea mite (*Oligonychus perseae*), and eriophyid mites feed on leaves, causing chlorosis, bronzing, defoliation, and reduced photosynthesis. Severe infestations expose fruits to sunburn and lower productivity. Management includes conserving predatory phytoseiid mites, avoiding unnecessary insecticides, maintaining adequate irrigation to reduce dust, and applying selective acaricides only when economic threshold levels are reached.

9. Root Weevils: Root weevils damage avocado by feeding on foliage during the adult stage while larvae attack roots beneath the soil surface. Root injury reduces water and nutrient uptake, predisposing trees to drought stress and root diseases. Biological control using entomopathogenic nematodes and fungi has demonstrated promising results in suppressing larval populations. Cultural practices including orchard sanitation, weed management, and maintenance of healthy root systems further reduce damage.

10. Nematodes: Plant-parasitic nematodes, particularly root-knot nematodes (*Meloidogyne* spp.) and lesion nematodes (*Pratylenchus* spp.), occasionally infest avocado roots, causing gall formation, reduced root function, nutrient deficiencies, and stunted growth. Damage becomes more severe when nematode infestations interact with *Phytophthora* root rot. Use of nematode-free nursery stock, crop rotation before orchard establishment, organic amendments, biological antagonists, and resistant rootstocks constitute effective management strategies.

Diseases of Avocado and Integrated Disease Management

Avocado (*Persea americana* Mill.) is susceptible to a wide range of fungal, oomycete, bacterial, algal, and physiological diseases that affect every stage of production, from nursery propagation to post-harvest storage. Disease incidence varies according to cultivar, rootstock, climatic conditions, orchard sanitation, irrigation practices, and overall orchard management. Among these, diseases caused by soil-borne pathogens are particularly destructive because they impair root function, reduce nutrient uptake, weaken tree vigour, and ultimately lead to severe yield losses or tree mortality. Scientific disease management therefore requires an integrated strategy involving preventive cultural practices, resistant rootstocks, biological control, accurate diagnosis, regular monitoring, and judicious fungicide application (Schaffer *et al.*, 2013).

1. Phytophthora Root Rot: Phytophthora root rot, caused by *Phytophthora cinnamomi*, is the most destructive avocado disease worldwide. The soil-borne oomycete infects feeder roots, reducing water and nutrient uptake, and spreads through contaminated soil, irrigation water, nursery plants, machinery, and runoff (Whiley *et al.*, 2002). Infected trees show chlorosis, wilting, sparse canopy, poor growth, root decay, branch dieback, fruit drop, and eventual death, especially in poorly drained, waterlogged soils. Management includes well-drained sites, raised beds, proper irrigation, and certified disease-free planting material. Tolerant rootstocks such as 'Dusa', 'Duke 7', 'Toro Canyon', and 'Thomas', biological agents (Trichoderma spp., Bacillus subtilis, mycorrhizae), and phosphonate fungicides provide effective control (Schaffer *et al.*, 2013).

2. Anthracnose: Anthracnose, caused mainly by Colletotrichum gloeosporioides, is a major pre- and post-harvest disease of avocado. Infection occurs during fruit development but remains latent until ripening, when dark, sunken lesions develop (Yahia, 2019). Warm, humid conditions favour disease development. The pathogen survives on infected twigs, leaves, mummified fruits, and debris. Severe infections extend into the pulp, making fruits unmarketable. Management includes orchard sanitation, canopy pruning, balanced fertilization, careful harvesting, pre-harvest fungicide sprays, and post-harvest hot water treatment, rapid cooling, proper storage, and hygienic packing-house practices.

3. Stem-End Rot: Stem-end rot is an important post-harvest disease of avocado caused by Lasiodiplodia theobromae, Botryosphaeria dothidea, Neofusicoccum parvum, and Phomopsis spp. Infection occurs before harvest but symptoms develop during ripening as soft brown decay spreading from the stem end into the fruit. Disease is more severe in overmature, injured fruits and under poor storage conditions. Management includes orchard sanitation, timely harvesting, careful handling, removal of infected twigs, balanced irrigation, maintenance of tree vigour, rapid pre-cooling, an uninterrupted cold chain, and approved post-harvest fungicide treatments (Yahia, 2019).

4. Cercospora Spot: Cercospora spot, caused by Pseudocercospora purpurea (syn. Cercospora purpurea), affects leaves, fruits, and young twigs, particularly under warm, humid conditions. Symptoms include small purple-brown leaf lesions and dark, rough, corky spots on fruits that reduce market quality and predispose fruits to anthracnose infection. The pathogen survives in infected plant debris and spreads through rain splash and wind. Management involves orchard sanitation, pruning for improved air circulation, balanced nutrition, and timely fungicide applications, especially copper-based protectants, during periods of high humidity.

5. Scab: Avocado scab, caused by *Elsinoë perseae*, primarily affects young leaves, shoots, and fruits. Initial symptoms appear as small raised corky lesions that later enlarge into irregular rough scabby patches. Although scab seldom affects internal fruit quality, severe external blemishes substantially reduce marketability. Young tissues are particularly susceptible during humid weather. Continuous rainfall during early fruit development significantly increases disease incidence. Integrated management involves pruning for improved air circulation, destruction of infected plant material, balanced nutrition, and preventive copper-based fungicide sprays during flowering and early fruit development.

6. Powdery Mildew: Powdery mildew caused by *Oidium* species occasionally affects avocado flowers, young leaves, and tender shoots, particularly under conditions of high humidity accompanied by moderate temperatures. White powdery fungal growth develops on susceptible tissues, reducing photosynthesis and occasionally interfering with successful fruit set. Regular monitoring during flowering enables early disease detection. Adequate canopy ventilation, avoidance of excessive nitrogen fertilization, and timely fungicide application where necessary effectively suppress disease development.

7. Verticillium Wilt: Verticillium wilt caused by *Verticillium dahliae* occurs mainly where avocado is planted following susceptible crops such as tomato, potato, eggplant, cotton, or sunflower. The pathogen survives in soil for many years through persistent microsclerotia. Symptoms include sudden wilting of branches, unilateral leaf chlorosis, vascular discoloration, branch dieback, and gradual decline. Unlike *Phytophthora* root rot, feeder roots generally remain healthy. Management relies primarily upon preventive measures including careful site selection, avoidance of susceptible previous crops, removal of infected branches, and maintenance of vigorous tree growth. No completely effective chemical control currently exists.

8. Algal Leaf Spot: Algal leaf spot caused by *Cephaleuros virescens* develops under warm, humid conditions. Circular orange, reddish, or rust-coloured velvety spots appear on leaf surfaces. Severe infections reduce photosynthetic area and occasionally cause premature defoliation. Canopy thinning to improve air circulation, sanitation, and copper fungicide applications generally provide satisfactory control.

9. Bacterial Diseases: Bacterial diseases are relatively less important in avocado compared with fungal pathogens. However, bacterial cankers and leaf spots occasionally occur following mechanical injuries, hail damage, pruning wounds, or insect feeding. Preventive measures include sanitation, disinfection of pruning equipment, avoidance of unnecessary injuries, balanced nutrition, and removal of infected branches. Copper bactericides may provide partial protection under favourable disease conditions.

10. Post-Harvest Diseases: Post-harvest diseases account for substantial economic losses throughout avocado supply chains. Anthracnose and stem-end rot remain the two dominant post-harvest pathogens worldwide, although secondary infections caused by *Alternaria*, *Rhizopus*, *Penicillium*, and *Botrytis* species occasionally occur during prolonged storage. Successful post-harvest disease management begins in the orchard. Healthy fruits harvested at optimum maturity exhibit greater resistance than immature or over-mature fruits. Gentle harvesting techniques minimizing mechanical injuries significantly reduce infection opportunities. Rapid pre-cooling immediately after harvest slows pathogen growth while maintaining fruit quality. Storage at recommended temperatures together with maintenance of high relative humidity minimizes disease development. Modern post-harvest technologies including controlled atmosphere storage, modified atmosphere packaging, edible coatings, biological antagonists, ultraviolet treatment, ozone application, and hot water treatments further reduce post-harvest losses (Yahia, 2019).

Harvest Maturity and Harvesting

Harvest maturity is reached when avocado fruits have completed physiological development and can ripen normally after harvest. Immature fruits show poor flavour, low oil content, uneven ripening, and rubbery texture, while over-mature fruits ripen rapidly and have reduced storage life. As skin colour is unreliable in many cultivars, dry matter content (21–25%, depending on cultivar) is the most reliable maturity index because it closely reflects oil content and eating quality. Fruit size, days from flowering, and seed maturity provide supportive information but should not be used alone. Commercial harvesting therefore combines dry matter, oil content, fruit size, flowering age, and market requirements to ensure optimum fruit quality (Sommaruga & Eldridge, 2020).

Harvesting is critical because bruises, cuts, and stem-end injuries accelerate respiration, moisture loss, pathogen infection, and post-harvest losses. Fruits should be harvested during the cool hours of the day, selecting only mature, healthy fruits while discarding immature, diseased, or damaged ones. Fruits should be clipped with 5–10 mm pedicels to reduce stem-end rot, and harvesting poles should be used for tall trees to prevent impact injury. Harvested fruits must be handled carefully, packed in ventilated crates, protected from direct sunlight, and quickly transported or shaded to remove field heat and maintain quality.

Post-Harvest Physiology

Understanding post-harvest physiology is essential for extending avocado shelf life and maintaining quality. As a climacteric fruit, avocado continues to respire after harvest and undergoes a rapid increase in respiration and ethylene production during ripening (Blakey *et al.*, 2014). Ethylene promotes softening, colour change, aroma, and flavour

development, while enzymes degrade cell walls to produce the characteristic creamy texture. Unlike most fruits, avocado accumulates little sugar during ripening, with flavour mainly derived from its high oil content. High temperatures accelerate ripening and decay, whereas low temperatures may cause chilling injury. High relative humidity reduces moisture loss and shrivelling. Mechanical injuries increase respiration and susceptibility to anthracnose and stem-end rot. Proper harvest maturity, pre-cooling, controlled or modified atmosphere storage, edible coatings, ethylene management, and an efficient cold chain help prolong storage life and preserve fruit quality (Yahia, 2019).

Processing and Value Addition of Avocado

The expansion of avocado cultivation has increased demand for processing and value addition. Besides fresh consumption, surplus and lower-grade fruits are processed into avocado oil, frozen pulp, guacamole, beverages, bakery ingredients, dairy alternatives, nutraceuticals, cosmetics, and pharmaceutical products (Yahia, 2019). Value addition reduces post-harvest losses, extends shelf life, increases farmer income, stabilizes prices, generates employment, and creates export opportunities while improving resource utilization (Dorantes *et al.*, 2004).

1. Avocado Pulp Processing: The edible mesocarp, comprising about 60–75% of fruit weight, is the primary raw material for processing. Fruits are washed, graded, sanitized, peeled, deseeded, and pulped under hygienic conditions. Fresh pulp is highly prone to enzymatic browning caused by polyphenol oxidase and peroxidase. To maintain colour and quality, processors use anti-browning agents such as citric and ascorbic acids, vacuum or modified atmosphere packaging, edible coatings, high-pressure processing, and rapid freezing.

2. Avocado Oil: Avocado oil is one of the most valuable processed products because of its nutritional and commercial importance. Unlike most vegetable oils extracted from seeds, it is obtained directly from the pulp, which is rich in oleic acid and other monounsaturated fatty acids. Oil extraction involves pulp separation, conditioning, mechanical pressing or centrifugation, followed by clarification and filtration. Cold-pressed extra virgin oil retains antioxidants, carotenoids, tocopherols, phytosterols, and natural flavour compounds, while refined oil offers excellent oxidative stability and a high smoke point. Regular consumption has been associated with improved cardiovascular health by lowering LDL cholesterol and maintaining HDL levels (Dreher & Davenport, 2013). The oil is also widely used in creams, lotions, shampoos, soaps, lip balms, sunscreens, and pharmaceutical ointments.

3. Guacamole: Guacamole is the most popular avocado-based processed food, prepared from mashed avocado blended with onion, tomato, chilli, lime juice, coriander, salt, and spices. Commercial production requires strict control of browning and microbial spoilage. Technologies such as vacuum packaging, modified atmosphere packaging, refrigerated storage, freezing, and especially high-pressure processing (HPP) preserve flavour, colour, texture, and nutritional quality. Growing demand for healthy ready-to-eat foods has expanded the global guacamole market.

4. Frozen Products: Freezing is an effective method for preserving avocado pulp while retaining flavour, colour, nutrients, and functionality. After extraction, pulp is treated with anti-browning agents and rapidly frozen using blast or individual quick-freezing systems. Frozen pulp is widely used in smoothies, desserts, sauces, baby foods, bakery products, and institutional catering, while frozen slices and cubes are supplied to restaurants and food service industries.

5. Avocado Beverages: Increasing demand for functional beverages has encouraged development of avocado smoothies, milkshakes, yoghurt drinks, fruit blends, and protein beverages. These products supply healthy fats, dietary fibre, potassium, vitamin E, carotenoids, and phytochemicals while providing a naturally creamy texture. Blending avocado with fruits, cocoa, coffee, or plant-based milks enhances flavour and nutritional value. Fortified beverages containing probiotics, plant proteins, and omega-3 fatty acids are emerging market segments.

6. Bakery and Confectionery Products: Avocado pulp is increasingly used as a partial substitute for butter and hydrogenated fats in bread, cakes, muffins, cookies, brownies, and pastries. It improves nutritional quality by increasing dietary fibre, antioxidants, potassium, folate, and healthy lipids while enhancing crumb softness and freshness. Spray- or freeze-dried avocado powder is also used in bakery mixes, instant beverages, infant foods, and nutritional supplements.

7. Nutraceuticals and Functional Foods: Avocado is an important source of nutraceutical ingredients because it contains carotenoids, tocopherols, phytosterols, lutein, zeaxanthin, glutathione, phenolics, dietary fibre, and monounsaturated fatty acids (Dreher & Davenport, 2013). These bioactive compounds are incorporated into capsules, dietary supplements, functional beverages, and specialized formulations aimed at supporting cardiovascular health, metabolic disorders, obesity management, and healthy ageing. Avocado also enhances absorption of fat-soluble vitamins and carotenoids from other foods.

8. Cosmetic and Pharmaceutical Applications: The cosmetic industry extensively utilizes avocado oil and extracts in moisturizers, anti-ageing creams, sunscreens, soaps, shampoos, conditioners, massage oils, and dermatological products. Vitamin E, phytosterols, chlorophyll derivatives, and essential fatty acids promote skin hydration, collagen synthesis, wound healing, and antioxidant protection. Avocado-derived compounds are also being investigated for anti-inflammatory, antimicrobial, antioxidant, hepatoprotective, gastroprotective, anticancer, and immunomodulatory properties, although many applications remain under clinical evaluation.

Economics of Avocado Cultivation

Avocado is one of the most profitable fruit crops due to its increasing global demand and long productive life of 30–50 years under scientific management (Schaffer *et al.*, 2013). Although orchard establishment requires substantial initial investment, long-term returns are highly attractive. Commercial production from grafted trees usually begins in the third or fourth year, with economic yields achieved from the sixth year onward. Scientifically managed orchards can produce 10–20 tonnes per hectare, while high-density planting with precision irrigation further improves productivity. Value addition through products such as avocado oil, frozen pulp, guacamole, nutraceuticals, and cosmetics enhances profitability by utilizing surplus fruits and reducing dependence on fresh markets. Smallholders can further increase income through intercropping during the juvenile stage, while Farmer Producer Organizations (FPOs), cooperative marketing, and value-chain integration improve market access and overall returns.

Marketing and Export Potential

Global avocado consumption continues to rise, with North America, Europe, East Asia, Australia, and the Middle East serving as major export markets, while Mexico remains the leading exporter (Food and Agriculture Organization, 2023). Export success depends on high-quality fruits meeting standards for maturity, quality, phytosanitary safety, and traceability, supported by efficient grading, packaging, certification, and cold-chain management. India has strong potential for avocado cultivation due to favourable agro-climatic conditions and increasing domestic demand. Expanding certified nurseries, scientific production, post-harvest infrastructure, processing, cold-chain facilities, and export-oriented value chains, along with adoption of Good Agricultural Practices (GAP), Global G.A.P. certification, digital traceability, and GI branding, will strengthen its global competitiveness.

Conclusion

Avocado (*Persea americana* Mill.) is one of the world's most valuable fruit crops owing to its high nutritional value, health benefits, and increasing consumer demand. High productivity and fruit quality depend on scientific cultivation practices, including improved cultivars, quality planting material, balanced nutrition, efficient irrigation, canopy management, pollination, and integrated pest and disease management. Proper maturity assessment, careful harvesting, pre-cooling, grading, packaging, and cold-chain management reduce post-harvest losses and extend shelf life. Value-added products such as avocado oil, guacamole, frozen pulp, nutraceuticals, cosmetics, and pharmaceuticals further enhance its economic importance. Future growth will depend on climate-smart production, precision horticulture, biotechnology, AI, and efficient value chains. In India, coordinated efforts in research, extension, and infrastructure can expand avocado cultivation, improve farmer income, strengthen nutritional security, and promote export potential.

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PCR Techniques for Detection of Plant Pathogenic Bacteria

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Abstract

Plant pathogenic bacteria are responsible for significant economic losses in agriculture by reducing crop yield and quality. Rapid, sensitive, and accurate detection of these pathogens is essential for effective disease management, quarantine, and biosecurity. Polymerase Chain Reaction (PCR) has emerged as one of the most reliable molecular diagnostic techniques due to its high specificity, sensitivity, and ability to detect pathogens directly from infected plant tissues, seeds, and bacterial cultures without prior isolation. This review highlights the principle, essential components, workflow, and various PCR-based techniques, including conventional PCR, nested PCR, multiplex PCR, real-time PCR (qPCR), reverse transcriptase PCR (RT-PCR), digital PCR (dPCR), colony PCR, touchdown PCR, and hot-start PCR. The article also discusses the applications of PCR in plant disease diagnosis, seed health testing, epidemiological studies, and quarantine inspection, along with its advantages, limitations, and recent advances such as portable PCR, microfluidic PCR, CRISPR-based detection, lab-on-a-chip technology, and AI-assisted molecular diagnostics. PCR-based technologies have significantly improved the speed and accuracy of pathogen detection, making them indispensable tools for modern plant disease diagnosis and sustainable crop protection.

Keywords: Plant pathogenic bacteria, Polymerase Chain Reaction (PCR), Molecular diagnostics, Disease diagnosis, Real-time PCR (qPCR), Digital PCR (dPCR), Plant pathology, Pathogen detection, Seed health testing, Biosecurity.

Introduction

Plant pathogenic bacteria cause serious diseases in many economically important crops, resulting in significant yield and quality losses. Early, rapid, and accurate detection is essential for effective disease management, quarantine, and prevention of pathogen spread through infected seeds and planting materials. Conventional diagnostic methods such as culturing, biochemical tests, and pathogenicity assays are reliable but are often time-consuming and less sensitive, particularly when pathogens occur in low populations or in symptomless plants (Palacio-Bielsa *et al.*, 2009).PCR (Polymerase Chain Reaction) has become one of the most important molecular diagnostic tools because it enables rapid, sensitive, and specific detection of plant pathogenic bacteria without requiring prior culturing. PCR-based techniques are now widely used in plant pathology laboratories for disease diagnosis, surveillance, and biosecurity (Palacio-Bielsa *et al.*, 2009; Visnovsky *et al.*, 2020).

Principle of PCR

Polymerase Chain Reaction (PCR) is a molecular technique used to amplify a specific DNA sequence, enabling rapid and sensitive detection of plant pathogenic bacteria. The process involves repeated cycles of DNA denaturation, primer annealing, and DNA extension, resulting in the exponential amplification of the target DNA fragment. PCR has become an essential tool in plant pathology because of its high sensitivity, specificity, and rapidity (Mullis & Faloona, 1987; Palacio-Bielsa et al., 2009).

DNA Extraction: The first step in PCR is the extraction of high-quality DNA from infected plant tissues, bacterial cultures, or seeds. The extracted DNA serves as the template for amplification.

Denaturation: The reaction mixture is heated to approximately 94–95°C to separate the double-stranded DNA into two single strands.

Annealing: The temperature is lowered to 50–65°C, allowing specific primers to bind (anneal) to complementary sequences on the target DNA.

Extension: The temperature is increased to 72°C, where Taq DNA polymerase synthesizes new DNA strands by extending the primers.

Amplification Cycles: The denaturation, annealing, and extension steps are repeated for 25–40 cycles, resulting in exponential amplification of the target DNA sequence.

Detection of Amplified Product

The amplified PCR products (amplicons) are commonly analyzed by agarose gel electrophoresis, where DNA bands of the expected size confirm the presence of the target pathogen. In real-time PCR, amplification is monitored directly through fluorescent signals without the need for gel electrophoresis (Palacio-Bielsa et al., 2009).

Components of PCR

PCR requires several essential components that work together to amplify a specific DNA sequence. Each component plays a crucial role in ensuring efficient and accurate DNA amplification (Mullis & Faloona, 1987; Green & Sambrook, 2019).

Template DNA: Template DNA is the extracted genetic material from infected plant tissue, bacterial culture, or seeds. It contains the target DNA sequence that is amplified during PCR.

Primers: Primers are short synthetic oligonucleotides that bind specifically to complementary sequences on the target DNA. They determine the specificity and starting point of DNA amplification.

Taq DNA Polymerase

Taq DNA polymerase is a thermostable enzyme isolated from *Thermus aquaticus*. It synthesizes new DNA strands by extending the primers during the extension step at **72°C**.

dNTPs: Deoxynucleotide triphosphates (dATP, dCTP, dGTP, and dTTP) serve as the building blocks required for the synthesis of new DNA strands.

$MgCl_2$: Magnesium chloride ($MgCl_2$) acts as an essential cofactor for Taq DNA polymerase and is required for optimal enzyme activity and efficient DNA amplification.

Buffer: PCR buffer maintains the appropriate pH and ionic strength of the reaction mixture, ensuring the proper functioning of DNA polymerase throughout the amplification process.

Thermal Cycler: A thermal cycler is an automated instrument that precisely controls the temperature changes required for DNA denaturation, primer annealing, and extension during repeated PCR cycles.

Types of PCR Used in Plant Pathology

Several PCR-based techniques have been developed to improve the sensitivity, specificity, and speed of detecting plant pathogenic bacteria. The selection of a PCR method depends on the objective of diagnosis, the type of sample, and the required level of accuracy (Palacio-Bielsa et al., 2009; Venbrux et al., 2023).

Conventional PCR: Conventional PCR is the most widely used technique for detecting plant pathogens. It amplifies a specific DNA fragment, and the amplified product is visualized by agarose gel electrophoresis. It is simple, reliable, and suitable for routine laboratory diagnosis.

Nested PCR: Nested PCR involves two successive rounds of amplification using two sets of primers. This method provides higher sensitivity and specificity than conventional PCR and is particularly useful for detecting pathogens present in very low concentrations.

Multiplex PCR: Multiplex PCR uses multiple primer pairs in a single reaction to detect two or more pathogens simultaneously. It reduces analysis time, reagent consumption, and laboratory costs.

Real-Time PCR (qPCR): Real-time PCR monitors DNA amplification in real time using fluorescent dyes or probes. It provides rapid, highly sensitive, and quantitative detection of plant pathogenic bacteria without the need for post-PCR gel electrophoresis.

Reverse Transcriptase PCR (RT-PCR): RT-PCR is used to amplify complementary DNA (cDNA) synthesized from RNA. Although it is mainly applied for RNA viruses, it is also useful for studying bacterial gene expression and RNA-based analyses.

Digital PCR (dPCR): Digital PCR divides the reaction mixture into thousands of individual partitions, allowing absolute quantification of target DNA molecules. It offers extremely high sensitivity and precision, especially for detecting low levels of pathogens.

Colony PCR: Colony PCR enables direct amplification of DNA from bacterial colonies without prior DNA extraction. It is a rapid method for confirming bacterial identity in microbiological studies.

Touchdown PCR: Touchdown PCR begins with a high annealing temperature that is gradually reduced in subsequent cycles. This approach improves primer specificity and minimizes non-specific amplification.

Hot-Start PCR: Hot-start PCR uses modified DNA polymerase that remains inactive at room temperature and becomes active only after heating. This technique reduces non-specific amplification and improves the accuracy of PCR results.

PCR Workflow

The PCR workflow consists of a series of steps that enable the rapid and accurate detection of plant pathogenic bacteria. A systematic workflow ensures reliable amplification and correct identification of the target pathogen (Palacio-Bielsa et al., 2009; Green & Sambrook, 2019).

Sample Collection

Plant samples showing disease symptoms, such as infected leaves, stems, roots, fruits, seeds, or bacterial cultures, are collected under sterile conditions to avoid contamination.

DNA Extraction

Genomic DNA is extracted from the collected samples using suitable extraction methods or commercial kits. The quality and purity of DNA are important for successful PCR amplification.

PCR Amplification

The extracted DNA is mixed with PCR reagents, including primers, Taq DNA polymerase, dNTPs, $MgCl_2$, and buffer. The reaction is carried out in a thermal cycler through repeated cycles of denaturation, annealing, and extension to amplify the target DNA sequence.

Gel Electrophoresis

The amplified PCR products are separated on an agarose gel and stained with a DNA-binding dye. The DNA bands are visualized under UV or blue-light illumination to verify successful amplification.

Example

PCR Detection of Plant Pathogenic Pseudomonas Visnovsky et al. (2020) developed a highly specific PCR assay for the rapid detection of plant pathogenic Pseudomonas by targeting the trehalose phosphatase (treA) gene. Species-specific primers were designed to amplify a 655 bp DNA fragment, which was found only in pathogenic Pseudomonas strains. The assay was evaluated using a wide range of bacterial isolates and showed 100% specificity, with no amplification from non-pathogenic bacteria or other plant-associated microorganisms. It also demonstrated high sensitivity, allowing reliable detection directly from infected and symptomless plant tissues without the need for bacterial isolation. The PCR assay provides a rapid, accurate, and dependable method for identifying plant pathogenic Pseudomonas and is valuable for plant disease diagnosis, q uarantine testing, and biosecurity programs.

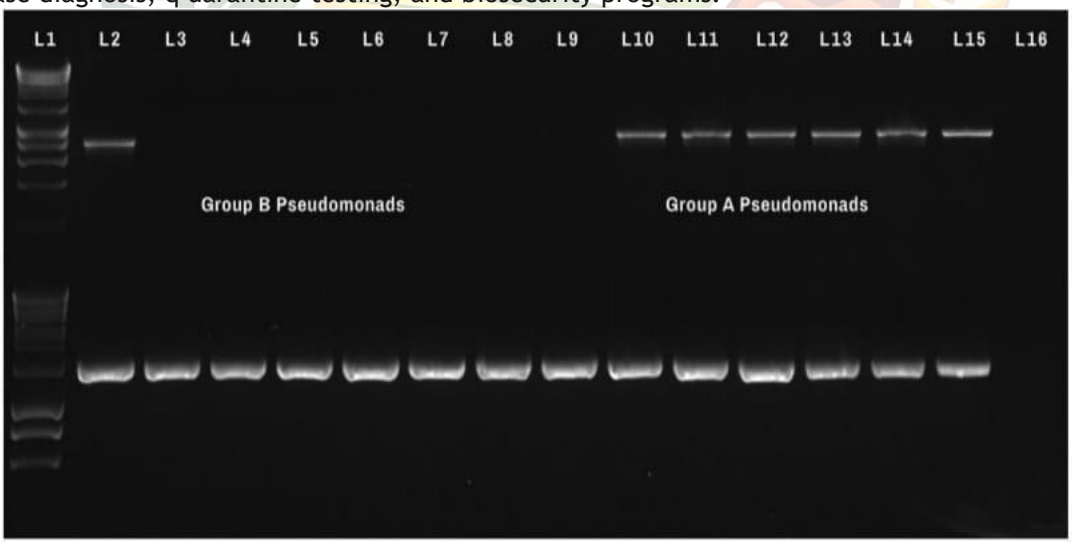


Fig. Specificity of trehalose phosphatase PCR using G1_m16F/R primers. A 655 bp amplicon was detected only in Group A (pathogenic) Pseudomonas isolates (L10-L15), while Group B (saprophytic) isolates (L3-L9) showed no amplification. Thelower gel shows the 16S rDNA internal control PCR confirming bacterial DNA amplification. L16: no DNA control. (Source: Wang & Wang, 1996)

Result Interpretation

The presence of a DNA band of the expected size confirms the detection of the target bacterial pathogen. In real-time PCR (qPCR), amplification results are interpreted using fluorescence signals and cycle threshold (Ct) values instead of gel electrophoresis.

Applications of PCR in Detection of Plant Pathogenic Bacteria

PCR is widely used for the rapid and accurate detection of plant pathogenic bacteria, including disease diagnosis, seed health testing, quarantine inspection, epidemiological studies, disease surveillance, and identification of virulence and resistance genes (Palacio-Bielsa et al., 2009; Visnovsky et al., 2020; Srinivasa et al., 2012).

Advantages of PCR

PCR offers several advantages for the detection of plant pathogenic bacteria due to its speed, sensitivity, and accuracy (Palacio-Bielsa et al., 2009).

1. **Highly Sensitive:** Detects very small amounts of pathogen DNA.
2. **Highly Specific:** Uses specific primers for accurate pathogen identification.
3. **Rapid Detection:** Provides results within a few hours.
4. **Detects Unculturable Bacteria:** Identifies bacteria that cannot be cultured easily in the laboratory.
5. **Small Sample Requirement:** Requires only a small amount of DNA or plant tissue for analysis.

Limitations of PCR

Despite its advantages, PCR has some limitations that may affect its routine use in plant disease diagnosis (Palacio-Bielsa et al., 2009; Venbrux et al., 2023).

1. **Expensive Equipment:** Requires specialized instruments such as a thermal cycler.
2. **Skilled Manpower Required:** Proper training is needed to perform PCR and interpret results.
3. **DNA Contamination:** Contaminated samples can produce false-positive results.
4. **PCR Inhibitors:** Compounds present in plant tissues may inhibit DNA amplification.

Cannot Distinguish Live and Dead Cells: Conventional PCR detects DNA from both living and dead bacteria, which may lead to overestimation of pathogen presence.

Recent Advances in PCR-Based Detection

Recent advances in molecular diagnostics have improved the speed, sensitivity, and accuracy of detecting plant pathogenic bacteria (Venbrux et al., 2023).

1. **Real-time qPCR:** Enables rapid and quantitative detection of pathogens using fluorescent signals.
2. **Digital PCR (dPCR):** Provides highly sensitive and absolute quantification of target DNA.
3. **Portable PCR:** Allows on-site detection of pathogens directly in the field.
4. **Microfluidic PCR:** Uses miniaturized devices for rapid analysis with small sample volumes.
5. **CRISPR-based Detection:** Combines CRISPR technology with molecular diagnostics for highly specific pathogen detection.
6. **Lab-on-a-Chip Technology:** Integrates sample preparation, amplification, and detection into a single portable device.
7. **AI-assisted Molecular Diagnostics:** Uses artificial intelligence to analyze molecular data, improving the speed and accuracy of disease diagnosis.

Conclusion

PCR-based techniques have transformed the detection and diagnosis of plant pathogenic bacteria by offering rapid, highly sensitive, and specific identification of pathogens. These methods enable early detection directly from infected or asymptomatic plant materials, thereby facilitating timely disease management, reducing crop losses, and preventing the spread of bacterial diseases. Advanced PCR approaches, including multiplex PCR, nested PCR, real-time PCR, and digital PCR, have further enhanced diagnostic accuracy, sensitivity, and quantitative analysis. Emerging technologies such as portable PCR, CRISPR-based diagnostics, microfluidic systems, and AI-assisted data analysis are expanding the scope of field-based and high-throughput pathogen detection. As molecular diagnostic technologies continue to evolve, PCR will remain a cornerstone of plant disease surveillance, quarantine, epidemiological research, and integrated disease management, contributing significantly to sustainable agriculture and global food security.

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India's GI-Registered Dairy Delicacies: Tradition, Uniqueness and Heritage

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Introduction

The notion of Geographical Indication (GI) originated in France, where the Appellations of Origin Certification (AOC) system was developed in the early 20th century. This strategy allowed for the marketing of specific wines and food products based on their geographical origin and historic production methods (O'Connor & Company, 2020). In India, GIs are recognised under the Geographical Indications of Goods (Registration and Protection) Act, 1999, which was enacted by parliament on December 30, 1999, and went into effect on September 15, 2003. A GI is a characteristic symbol used to identify commodities that come from a certain geographical location and have traits or reputations that are unique to that location (WIPO, 2004). According to the WIPO, GI serves the following primary purposes:

1. The purpose of the product differentiator.
2. Contribution to rural areas' development.
3. Ways to protect traditional cultural expression (TCE) and traditional knowledge (TK).
4. Legal protection against unauthorised use, the preservation of traditional knowledge, and increased farmer income are all advantages of GI registration (Kangabam, 2013).

GI Registered Dairy Product

National programs like "Aatmanirbhar Bharat" and "Vocal for Local" can increase demand for and awareness of GI goods, promoting rural economic growth and sustainable development (The Economic Times, 2020). The GI Registry, whose office is in Chennai, Tamil Nadu, has recorded over 85 food items thus far. Twenty-two of these foods are dairy-based (Table 1).

Table 1: GI registered dairy product, state, year of registration and its key dairy components:

S.No.	Name of the GI Registered Dairy product	State	Year of Registration	Key dairy components
1	Dharwad Pedha	Karnataka	2008	Dharwadi Buffalo Milk solids
2	Tirupati Laddu	Andhra Pradesh	2009	Pure Milk-derived Desi Ghee
3	Banglar Rasogolla	West Bengal	2017	Spongy Cow's Milk Chhena spheres
4	Bardhaman Sitabhog	West Bengal	2017	Ultra-fine Chhena pressed in Desi Ghee
5	Bardhaman Mihidana	West Bengal	2017	Pure desi ghee.
6	Odisha Rasogola	Odisha	2019	Cow/Buffalo Milk Chhana
7	Srivilliputtur Palkova	Tamil Nadu	2019	Concentrated Cow's Milk
8	Banaras lal peda	Uttar Pradesh	2023	Deep-roasted Danedar Khoa
9	Kunthalgiri Khawa	Maharashtra	2023	Thickened Buffalo Milk solids
10	Kendrapara Rasabali	Odisha	2023	Fried Chhana soaked in Rabri
11	Nayagarh Chhenapoda	Odisha	2023	leaf-baked sweet Chhana cake
12	Udhampur Kaladi	Jammu & Kashmir	2023	Sun-dried Raw Milk Cheese disc, Mozzarella of Kashmir
13	Arunachal Pradesh Yak Churpi	Arunachal Pradesh	2023	Fermented & Smoked Indigenous Yak Cheese
14	Dhenkanal Magji	Odisha	2024	Buffalo Milk Chhana
15	Tripura Matabari Peda	Tripura	2024	Milk Khoya
16	Jaunpur Imarti	Uttar Pradesh	2024	Desi Ghee
17	Nolen Gur-er Sandesh	West Bengal	2025	Cow's milk Chhana
18	Murshidabad Chhanabora	West Bengal	2025	Chhana
19	Kamarpukur Sada Bonde	West Bengal	2025	Fluffy flour-and-milk based droplets
20	Bishnupur Motichoor Laddu	West Bengal	2025	Pure ghee
21	Chandannagar-er Jalbhora Sandesh	West Bengal	2026	Chhana
22	Janai-er Manohara	West Bengal	2026	Chhana

Detail description and uniqueness of GI Dairy Products:

1. Dharwad Pedha: Originated solely in the late 18th century in Dharwad City by Mr. Ram Ratan Singh Thakur (Migrated from Unnao, Uttar Pradesh). The Thakur family has been creating Dharwad Pedha for well over 200 years, and anybody who wants to make it in the GI Registry-designated Dharwad domain can now do so.

Uniqueness: Crafted specifically using the milk of Dharwad's native Dharwadi buffaloes. Made by hand, using Buffalo milk and sugar, having no flavoring agents.The *Khoya* are slow-roasted in desi ghee for hours.

2. Tirupati Laddu: India's most famous temple sweet, the Tirupati Laddu is given as prasadam at the Venkateswara Temple in Tirumala. While its base includes gram flour and sugar, its core richness comes entirely from pure cow desi ghee. In 2009, it was granted a GI tag. This means only the Tirumala Tirupati Devasthanams (TTD) has the legal right to make and sell it.

Uniqueness: Made from pure cow ghee, besan boondi, cashews, raisins, edible camphor, cardamom and sugar candy (kalkando), its unique soft yet aromatic texture gives it an exceptional shelf life of up to 15 days without artificial preservatives.

3. Banglar Rasogolla: Mr. Nabin Chandra Das as the inventor of the Rasogolla in preface of the book. Apart from the above evidences there are other evidences that state that the Bengalis were producing various products using channa, which is the basic material for preparing Rasogolla.

Uniqueness: Famous for its bright white color, perfectly spherical shape and a distinct spongy springy texture. When squeezed, it expels syrup, and when released, it acts like a sponge, retaining its original round shape. Traditional method of curdling milk to create *chhana* that yields the signature soft, non-chewy texture.

4. Bardhaman Sitabhog: It is a famous heritage sweet from the Bardhaman district of West Bengal, India. The name translates literally to "the food of Sita" (referring to the goddess Sita from the Ramayana), reflecting its royal and mythological associations. Sitabhog is a flavourful dessert that looks like white rice or vermicelli mixed with small pieces of Gulab jamun. Made from chhana, rice flour and sugar, Sitabhog often gives the appearance of pulao, which is albeit sweet in taste.

Uniqueness: Sitabhog's distinct identity lies in its soft, non-sticky, rice-grain-like strands made from region-specific Kanakchur rice flour and chhana, uniquely paired with deep-fried Nikuti dumplings for a perfect contrast in flavor and texture.

5. Bardhhaman Mihidana: The name translates directly from Bengali to "fine" (mihi) and "grain" (dana). Bardhaman Mihidana is characterized by its exceptionally miniature, pearl-like micro-granules.

Uniqueness: Mihidana stands out by using indigenous aromatic rice flour (like Gobindobhog) instead of standard gram flour, creating ultra-fine micro-droplets with a high surface area that rapidly absorb warm, cardamom-infused sugar syrup.

6. Odisha Rasagola: The reference of Rasagola is found in Odia Ramayana written by Balaram Das. The sweet has been offered as part of bhog (sacred offering) at the Puri Jagannath Temple for centuries. In the Geographical Indication (GI) registration for "Odisha Rasagola".

Uniqueness: Made from local cow's milk chhana, suji or maida, and cardamom, these round, off-white Rasagolas are exceptionally soft, juicy, and so tender they can be swallowed without chewing. Their signature off-white hue comes naturally from caramelization while cooking in a 60:40 blend of fresh and stored sugar syrup at 100°C for 50 minutes.

7. Srivilliputtur Palkova: Making of palkova was the known skill of local residents of Srivilliputtur. The making of palkova was introduced to the locals by Singh family who were rajputs, brought as cavalrymen to Kingdom of Sokkampatti. In 1945, the Government established cooperative societies, which made the intense production of palkova in this region.

Uniqueness: The fodder intake of cows at Srivilliputtur and their rice grazing habit gives a very special, unique and a high quality flavor to the milk and this is reflected in the Palkova. The Palkova is very filling and satiates hunger by a lesser quantity. It has all the nutrient qualities of milk and is very nourishing for the body.

8. Banaras Lal Peda: A celebrated sweet from Varanasi (Banaras), Lal Peda (literally "Red Peda") gets its distinct reddish-brown color from an intense, extended roasting of Mawa.

Uniqueness: It is flavored with saffron, cardamom and ghee, and is often coated with broken cashew nuts. It has a significantly deeper, roasted dairy flavor compared to regular pedas.

9. Kunthalgiri Khawa: Originating from the Bhoom taluka in the Osmanabad district. Khawa is the crucial baseline dairy product obtained by continuously boiling milk in an open iron pan until it thickens into a solid mass.

Uniqueness: Prepared by tirelessly reducing rich buffalo milk over open fires in large iron pans. It serves as the baseline ingredient for high-grade regional pedas and burfis across western India due to its immaculate moisture-fat balance.

10. Kendrapara Rasabali: Deeply rooted in Odisha's temple food culture (offered at the Baladevjew Temple), Rasabali consists of deep-fried, flattened patties of Chhena (fresh, unripened curd cheese/cottage milk). **Uniqueness:** These

melt-in-your-mouth milk delicacies feature fresh chhena flattened into small round patties, deep-fried to a golden brown, and then fully submerged in a thick, sweetened, cardamom-scented rabri (condensed milk cream).

11. Nayagarh Chhenapoda: It is a legendary baked cheese dessert originating from the Nayagarh district of Odisha, India. Literally translating to "burnt cheese" in the Odia language, it holds the distinction of being India's first indigenous cheese confection, often likened to a rustic, crusty cheesecake. Invented accidentally in the mid-twentieth century by a local confectioner named Sudarsan Sahoo, securing a GI tag to protect its unique regional heritage and traditional preparation method.

Uniqueness: Wrapped in Sal tree leaves and slow-baked over charcoal heat for hours, this delicacy features a smoky, caramelized exterior paired with a soft, moist, and slightly tangy interior. The leaf wrapping imparts a subtle earthy aroma that perfectly balances its rich, smoky sweetness.

12. Udhampur Kaladi: It is a famous indigenous, ripened cheese originating from the Jammu province of Jammu and Kashmir. Often referred to as the "Mozzarella of Kashmir," It is made from full-fat raw milk (usually cow or buffalo) that is soured using cooked whey. It is kneaded and sun-dried into dense, round discs. Locally, it is shallow-fried in its own fat until the outside is golden-crisp while the inside becomes gooey and stringy. As of early 2026, the central government has officially upscaled its production under the One District One Product (ODOP) initiative.

Uniqueness: Kaladi, a traditional artisanal cheese from Jammu & Kashmir made by sun-drying curdled milk on small straw mats called *dunas*. When shallow-fried in its own fat, it develops a crispy golden crust with a molten, stretchy interior, traditionally served hot in a local *bun-kaladi*.

13. Arunachal Pradesh Yak Churpi: A deeply traditional, hardened cheese made from the milk of the indigenous *Arunachali Yak* breed reared by nomadic tribal herders in high-altitude regions like Tawang and West Kameng. Because raw yak milk spoils rapidly and fresh food is scarce during harsh Himalayan winters, Churpi was developed as a brilliant ancient preservation technique. It provided a long-lasting, concentrated source of protein and energy to survive the extreme cold.

Uniqueness: Made from nutrient-dense yak milk, Churpi is a unique Himalayan cheese renowned for its smoke-cured hard variant that can last for years without refrigeration. Extreme drying turns it stone-hard, delivering an intensely savory, smoky flavor packed with protein to help communities survive harsh winters.

14. Dhenkanal Magji: Originating in Mandar village to preserve fresh milk, Dhenkanal Magji is a rectangular sweet made from buffalo milk chhena, sugar, and cardamom, renowned for its distinct earthy flavor derived from local buffalo grazing habits. Traditionally served as prasad at the Kapilas Temple, this nutritious delicacy features a unique dry texture born from a historic local preservation technique.

Uniqueness: Magji stands out for its uniquely coarse, grainy texture created by working roasted buffalo-milk chhena into a dry powder rather than a smooth paste. Flavored with aromatic green cardamom and shaped into rustic laddus, this thorough drying process gives it a significantly longer shelf life than typical moisture-rich chhena sweets.

15. Tripura Matabari Peda: Prepared as a sacred offering at the Tripura Sundari Temple in Udaipur (Matabari), this peda is crafted using two core ingredients: pure milk Khoya and sugar. The milk solids are meticulously stirred and cooked until they turn a deep brown color. Unlike many commercial sweets, it does not use any flour or binders, retaining a heavy, rich milk profile. Tripura Sundari Temple is one of the 51 sacred Shakti Peethas of Hinduism, built by Maharaja Dhanya Manikya in 1501.

Uniqueness: Matabari Peda is uniquely distinguished by its hand-rolled, rustic round shape and deep caramel flavor achieved by slowly reducing pure cow's milk with sugar in heavy iron woks. Its dense, grainy texture and low moisture content give it an extended shelf life, making it ideal for pilgrims traveling long distances.

16. Jaunpur Imarti: Jaunpur Imarti is a legendary, artisanal sweet from the historic city of Jaunpur in Uttar Pradesh, India. While Imarti is primarily made from a batter of black gram flour (urad dal) that is piped in circular patterns into hot oil and soaked in sugar syrup.

Uniqueness: Frying exclusively in pure milk-derived Desi Ghee to achieve its signature rich aroma and crisp texture.

17. Nolen Gur-er Sandesh: It is one of the most celebrated seasonal delicacies from West Bengal, India. It is a premium variant of the traditional Bengali fudge (*sandesh*), prepared exclusively using winter-harvested date palm jaggery (*nolen gur*). The roots of this sweet trace back centuries to rural Bengal, particularly around the Bardhaman region. The local Siuli community mastered the highly specialized art of climbing date palm trees at night to tap and collect the fresh sap before sunrise.

Uniqueness: Nolen Gur Sandesh is a seasonal winter delicacy made by blending fresh chhena with date palm jaggery, which gives it a pale caramel color, a subtly smoky flavor, and press-molded motifs like conch shells or fish. Distinctive variations like Jalbhara elevate this treat by hiding a liquid, molten jaggery core at its center.

18. Murshidabad Chhanabora: Originating from West Bengal's historic towns of Berhampore and Cossimbazar, Murshidabad Chhanabora is a heritage sweet created in the 18th or 19th century to welcome local royalty. Resembling

a dark, oversized gulab jamun, this iconic delicacy is renowned for its unique dual-texture profile born from centuries-old confectionary craftsmanship.

Uniqueness: Chhanabora is unique for its dramatic textural contrast—featuring a hard, near-black caramelized shell from deep-frying chhena balls in ghee, which encases an extraordinarily soft, porous, and syrup-filled interior. This durable outer layer prevents sogginess and extends its shelf life well beyond typical fresh Bengali sweets.

19. Kamarpukur Sada Bonde (White Bonde): Originating over 200 years ago in Kamarpukur, West Bengal, Sada Bonde is a historic, white-hued variant of bonde crafted from fluffy flour and milk droplets fried without artificial coloring to achieve an airy texture and a clean, dairy-forward flavor. Deeply intertwined with the legacy of Sri Ramakrishna Paramahamsa, this unique sweet stands out for its delicate preparation and rich regional heritage.

Uniqueness: Kamarpukur Sada Bonde is unique for its signature pure white appearance, achieved by replacing standard chickpea flour with a natural batter of sun-dried rice and *Roma Kolai* bean seeds without any added coloring. This unique grain-and-bean blend yields a light, non-sticky boondi with a delicate sweetness and a distinctively nutty undertone.

20. Bishnupur Motichoor Laddu: Hailing from the historic royal town of Bishnupur, West Bengal, Bishnupur Motichoor Laddu is a centuries-old heritage sweet developed under the patronizing Malla Dynasty. Visually similar to standard motichoor, this royal delicacy stands out for its exceptional structural precision and a secret local twist in its ingredient profile.

Uniqueness: Bishnupur Laddu stands out for incorporating Piyal (chironji) seed flour into fine gram flour, giving it a rich, nutty depth uncharacteristic of standard motichoor laddus. Free of artificial dyes and heavy garnishes, it relies on ultra-fine, microscopic boondi spheres fried in pure ghee to create a lustrous sweet that crumbles effortlessly into a melt-in-the-mouth texture.

21. Chandannagar-er Jalbhora Sandesh: It is an iconic, heritage sweet originating from the city of Chandannagar in the Hooghly district of West Bengal, India. Famed for its clever engineering and hidden surprise, it is one of the most intellectually celebrated confections in Bengali sweet-making history. The creation of the Jalbhora Sandesh dates back to the mid-19th century (around 1843–1844) and is credited to the legendary confectioner Surya Kumar Modak.

Uniqueness: Jolbhora's signature charm lies in its ice-apple-shaped chhena casing that masterfully encapsulates a hidden liquid center—traditionally date palm jaggery or rose syrup—delivering a dramatic burst of flavor when bitten into.

22. Janai-er Manohara: Meaning "that which steals the heart," Manohara is a legendary, 200-year-old sweet from Janai, West Bengal, crafted by local confectioner Nyara Moira during the Zamindari era. Cleverly designed as an early masterpiece of food preservation, this historic treat keeps fresh long without modern refrigeration while boasting a rich cultural legacy.

Uniqueness: Manohara is defined by a striking contrast of textures—a hard, glass-like molten sugar coating on the outside that historically served as a natural preservative, enclosing a delicate, melt-in-the-mouth center of fresh chhena and mawa.

Conclusion

India's registered dairy Geographical Indications (GIs) highlight a remarkable blend of regional heritage, traditional wisdom, and culinary artistry. Originating from distinct geographical micro-climates—from the high Himalayas to Bengal's historic towns—these 22 distinct delicacies reflect clever historical preservation methods like leaf-baking, deep roasting, and sugar-encasing. By utilizing indigenous ingredients such as local buffalo milk, date palm jaggery, and native rice varieties, these sweets protect traditional cultural expressions while promoting sustainable rural economies. Ultimately, these protected dairy confections preserve centuries of royal and sacred recipes, standing as a proud testament to India's rich artisanal food culture under global intellectual property standards.

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Flower for Food

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Introduction

Flowers have long been valued for their ornamental, cultural, and religious significance, but many species are also edible and have been used in traditional cuisines for centuries. Growing demand for natural and functional foods has increased interest in edible flowers as nutritious food ingredients. They are used in salads, beverages, desserts, herbal teas, confectionery, and garnishes, enhancing the colour, flavour, aroma, texture, and visual appeal of foods. Edible flowers are rich in phenolic compounds, flavonoids, anthocyanins, carotenoids, vitamins, minerals, and essential oils. These bioactive compounds possess antioxidant, anti-inflammatory, and antimicrobial properties that promote health. Consequently, edible flowers are gaining importance as functional foods with significant nutritional, therapeutic, and commercial value, offering opportunities for innovation and value addition in the modern food industry.



Rose

Rose is a queen of flowers. We can extract essential oil from roses and also roses we can used in cooking. Remove the white, bitter base and the remaining petals have a strongly perfumed flavor perfect for floating in drinks or scattering across desserts, and for a variety of jams. All roses are edible, with a flavor more pronounced in darker varieties.

Roses can be used in many ways in cooking and baking, including: Garnish: Rose petals can be used as a garnish for salads, soups, cakes, and pastries. We can prepare soup from rose hips also, Stir-fry: Small rose buds can be added to stir-fry dishes, Roasted: Rose buds can be roasted with vegetables to add fragrance, Candied: Rose petals can be crystallized with sugar to make candy, Jam: Rose petals can be made into a jam that goes well with cheese and crackers, Rose water: Rose water can be used to balance out savory spices, add flavor to frosting, ice cream, jams, and compotes, and more, Rose syrup: Rose petals can be made into a syrup for cooking, Pair with strawberries: Rose petals pair well with strawberries in ice cream or jam.



Rose petals soup



Rose petals salad



Rose Gulkhand



Flowchart of cake preparation by rose petals

Calendula

A great flower for eating, calendula blossoms are peppery, tangy, and spicy and their vibrant golden color adds dash to any dish. Calendula, a flowering plant also known as pot marigold, can be served as a tea or used as an ingredient in various herbal formulations. While the tea is made by steeping the flowers in boiling water, the extract is derived from both the flowers and the leaves.



Calendula flowers are edible and have many nutritional benefits, including:

1. Antioxidants: Calendula flowers contain carotenoids and flavonoids, which are antioxidants that can help boost immunity and prevent disease.

2. Vitamins: Calendula flowers contain vitamins A, C, D, and E. Vitamin A helps with vision, immunity, fertility, and growth, while vitamin C strengthens the immune system.

3. Fatty acids: Calendula flowers contain calendic and linoleic acids, which are two of their dominant fatty acids.

4. Oxygenated oils: The flower heads of calendula flowers are rich in oxygenated oils like monoterpenes and sesquiterpenes. Calendula flowers have been used for many purposes throughout history, including:

5. Cooking: In Germany, calendula flowers were used in soups and stews, and as a substitute for saffron in large pot dishes.

6. Medicine: Calendula flowers have been used medicinally since at least the 12th century. In Traditional Chinese Medicine, calendula petals were used to increase blood flow and detox wounds.

Dianthus

Petals are sweet, once trimmed away from the base. The blossoms taste like their sweet, perfumed aroma. Carnations have been used for medicinal purposes in various cultures for centuries. As with any herbal remedy, it's always best to consult with a healthcare professional before using carnations or any other botanical for medicinal purposes, especially if you have underlying health conditions or are taking medications.

1. Garnish: Sprinkle petals on top of desserts, cupcakes, salads, or pies
2. In salads: Toss petals into salads
3. In drinks: Add petals to cocktails, mocktails, sorbets, and syrups

4. In other dishes: Use petals in soups, aspics, pastries, and jellies
5. In tea: Some upscale tea rooms use crushed carnation petals to make custom tea blends
6. In Chartreuse: Carnation petals are used to make the French liqueur Chartreuse.

	
Carnation salad	**Carnation tea**

Gladiolus

Although gladioli are bland, they can be stuffed, or their petals removed for an interesting salad garnish. Gladiolus flowers are edible and can be used in cooking in a number of ways, including: Salads: The petals have a mild, lettuce-like flavor and can be tossed into salads, Garnish: The petals can be used as an elegant garnish, Stuffed: The flowers can be stuffed like squash blossoms, Sweet or savory spreads: The flowers can be used as receptacles for sweet or savory spreads or mousses.

Hibiscus

Famously used in hibiscus tea, the vibrant cranberry flavor is tart and can be used sparingly. Hibiscus can be used in a variety of food and beverage applications, such as teas, juices, smoothies, and even beer. It has a tart and slightly sweet taste that many consumers enjoy, so it can easily be incorporated into existing products. It helps in controlling blood pressure, Cholesterol, Weight loss etc,.

Jasmine

These super-fragrant blooms are used in tea; you can also use them in sweet dishes, but sparingly. Jasmine flowers can be used in many ways in cooking, including: Flavored drinks, Desserts, Baked goods: Jasmine flowers can be used to flavor baked goods and candy, Garnishes. Jasmine flowers can be used to flavor rice.

Conclusion

Edible flowers represent a unique combination of nutrition, flavor, aesthetics, and health benefits, making them a valuable addition to modern diets. Rich in bioactive compounds such as antioxidants, vitamins, and minerals, they contribute to both culinary diversity and human well-being. Their use also supports sustainable agriculture by promoting the cultivation and utilization of diverse flowering plants. However, only correctly identified, pesticide-free flowers should be consumed to ensure food safety. With increasing consumer awareness and scientific research, edible flowers have significant potential to become an important component of healthy and sustainable food systems.

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Advancing Indian Agriculture through Cloud Computing Innovations

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Introduction

Cloud computing refers to the delivery of IT infrastructure and services over the internet. It provides shared resources, software, and applications to users with minimal interaction required from the service provider. Although India is one of the largest producers of food grains and other agricultural products, the sector still operates using outdated and decentralized methods. These inefficiencies contribute to a significant gap between supply and demand, adversely affecting farmers' income and the national economy. Cloud computing can bridge this gap by centralizing data—such as soil conditions, weather updates, research findings, and farmer profiles—into a cloud-based system. This data becomes easily accessible to farmers, researchers, consultants, and other stakeholders, regardless of their location. The adoption of cloud computing in agriculture has significant potential for advancing India's overall development. Its effective implementation can revolutionize the agricultural sector by enhancing data accessibility, reducing costs, and promoting efficiency. Cloud computing is emerging as a robust commercial infrastructure that eliminates the need for maintaining expensive hardware, software, IT personnel, and other resources. It enables the sharing of computing resources—such as servers, storage, and applications—through a network-based environment. In the modern era, cloud computing allows for the centralization of agriculture-related databases (e.g., soil, weather, research, crops, farmer data, agricultural marketing, fertilizer, and pesticide information). This paper discusses the computing models, characteristics, deployment types, cloud service models, benefits, and challenges of using cloud technology in agriculture.

Computing Models

Desktop Computing: This type of computing used in single PC Computing. This types of computing facility applicable for personal, professional (Engineer, artist, authors, doctors, programmers) office and publishing house.

Client server computing: Client server computing is a system that performs both the functions of client and server to promote the sharing of information between them. A Client is any process that requests specific services from the server process. A Server is a process that provides requested services for the Client. it allows many users to have access to the same database at the same time, and the database will store much information. Various types of server used in Clint service computing such as mail server, file server, fax server, database server, web server. Example of client server System, File transfer: This is the transmission of files between the client and server. It also allows storing of files on the server. Files such as movies, images, music can be stored.

Cluster computing: In cluster computing, a group of similar computers is hooked up locally to operate as a single compute. This facility utilized for load balance of servers. Main advantages of this computer technology is distributed the load of server among the each servers of computer.

Grid Computing: Grid computing is the collection computers resources from multiple locations to reach a common goal. Benefits of grid computing are Increase access to data and collaboration, join data and distribute it globally, Support large multi-disciplinary collaboration, Workload balance, data security etc. Main characteristics of grid computing listed in the below:

a. Grid coordinates Resources that are not subjected to centralized control.
b. Grid use standard, open, general-purpose protocols and interfaces.
c. Grid deliver high quality of Service.

Cloud Computing: Cloud computing is the combination of cluster and grid computing. The IT environment evolved from mainframes to client servers, the Internet, virtualization and cloud computing. Cloud computing provides a shared pool of configurable IT resources (e.g. processing, network, software, information and storage) on demand, as a scalable and elastic service, through a networked infrastructure, on a measured (pay-per-use or subscription) basis, which needs minimal management effort, is based on service level agreements between the service provider and consumers, and often utilizes virtualization resources.

Characteristics of Cloud Computing

On-demand self-service: A consumer can unilaterally provision computing capabilities, such as server time and network storage, as needed automatically without requiring human interaction with each service provider.

Broad network access: Capabilities are available over the network & accessed through standard mechanisms that promote use by heterogeneous thin or thick client platforms (e.g., mobile phones, tablets, laptops, and workstations).

Rapid elasticity: Cloud services can be rapidly and elastically provisioned, in some cases automatically, to quickly scale out and rapidly released to quickly scale in. To the consumer, the capabilities available for provisioning often appear to be unlimited and can be purchased in any quantity at any time.

Measured service: Pay per use-capabilities is charged using a metered, fee-for-service, or advertising based billing model to promote optimization of resource use. Examples are measuring the storage, bandwidth, & computing resources consumed and charging for the number of active user accounts per month.

Resource pooling: The provider is computing resources are pooled to serve multiple consumers using a multi-tenant model, with different physical and virtual resources dynamically assigned and reassigned according to consumer demand. There is a sense of location independence in that the customer generally has no control or knowledge over the exact location of the provided resources but may be able to specify location at a higher level of virtuality (e.g., country, state, or data center). Examples of resources include storage, processing, memory, network bandwidth, and virtual machines.

Deployment Model of Cloud Computing

Public cloud: The cloud infrastructure applications, storage, and other resources are made available to the public for free or on pay-per-use model. It is owned by an organization selling cloud services. Example: Amazon, Google Apps, Windows Azure etc. Some Important point for Public Cloud

1. Entirely hosted by External Providers
2. Almost any customer can pay for resources on the cloud
3. Support is handling by the provider.

Community cloud: The cloud shares infrastructure for specific community with common concerns (security, compliance, jurisdiction etc), whether managed internally or by a third party and hosted internally or externally.

Hybrid cloud: The cloud infrastructure is a composition of two or more clouds (private, community, or public) that re-main unique entities but are bound together by standardized or proprietary technology that enables data and application portability.

Private cloud: The cloud infrastructure is operated solely for a single organization. It may be owned, managed and operated by the organization or a third party, and may exist on-premises or off-premises

Model of Cloud Computing

SaaS (Software as a service) model: Through this service delivery, model end users use the software application services directly over network according to on-demand basis. In this type, service only required administrator & cloud consultants. Example salesforce, drop box and Google applications such as Email, Google drive, talk etc.

PaaS (Platform as a service) model: In the PaaS model, cloud providers deliver a computing platform, typically including operating system, programming language execution environment, database, and web server. This type service only software developer required for deployment of software, Example Google application engine, window Azure, force.com etc.

Infrastructure as a service (IaaS): In an IaaS model, resources can easily be scaled up, depending upon the demand from the user, services being charged in a pay-per use model. Network administrator & programmer required for Iaas services, Example Amazon web service, IBM, HP etc.

Role of Cloud Computing in Agriculture Field (Rural & Hills)

Agriculture Information Data Bank: This refers to the creation of a centralized digital repository that stores critical agricultural data such as:

a. Crop types and growth stages
b. Weather forecasts and historical climate data
c. Soil health, fertility, and nutrient information
d. Farmer profiles and field history
e. Expert recommendations and research findings

Using cloud computing, this information is stored on remote servers and made accessible anytime, anywhere through internet-connected devices. This helps farmers, researchers, and policymakers make better decisions quickly.

Management of Land and Soil Data Through Centralized Decision Support Systems: Cloud platforms can support Decision Support Systems (DSS) that consolidate data related to:

a. Land ownership and boundaries
b. Geographical locations
c. Area under cultivation
d. Soil texture, moisture, pH, and fertility

With this data managed centrally on the cloud, land use planning, crop selection, irrigation scheduling, and fertilizer application become more scientific and efficient—especially in rural and hilly areas where data fragmentation is common.

High Integration & Sharing of Agricultural Information: Cloud computing allows multiple stakeholders—farmers, agronomists, researchers, government agencies, and cooperatives—to share data on a single unified platform.

a. It encourages real-time updates, joint problem-solving, and better coordination.
b. This integration boosts innovation and avoids duplication of efforts.

Elimination of Farmers' Limitations in Technical Knowledge & Resources: Most rural and hilly farmers lack access to modern agricultural techniques and information. Cloud-based applications can:

a. Deliver customized and easy-to-understand guidance in local languages
b. Offer remote consultations with experts
c. Provide access to educational resources and video tutorials Thus, cloud computing bridges the knowledge gap and empowers farmers to adopt modern practices.

Providing Agricultural Technology Services & Scientific Support: Cloud platforms can support:

a. Remote sensing data and satellite imagery for precision farming
b. AI-based pest and disease diagnosis tools
c. Weather prediction models and smart irrigation solutions. By integrating these technologies on cloud platforms, farmers in remote and hilly regions gain access to advanced scientific tools for better farm management.

Improvement of Agricultural Product Marketing: Cloud computing enables digital platforms and marketplaces where:

a. Farmers can list and sell their produce directly
b. Buyers can place orders online
c. Real-time price updates and market trends are available. This improves price transparency, reduces dependency on middlemen, and increases farmers' profits.

Efficient Use of Agricultural Resources: With real-time data on weather, soil, and crop conditions, farmers can optimize:

a. Water usage
b. Fertilizer and pesticide application
c. Harvest scheduling This not only saves input costs but also ensures sustainable and eco-friendly farming—especially critical in resource-scarce hill regions.

Promotion of Agricultural Product and Service Circulation on a Wider Scale: Cloud computing helps build stronger agricultural value chains by connecting:

a. Farmers with markets
b. Suppliers with input demand (e.g., seeds, fertilizers)
c. Government with service beneficiaries

This expands the reach of products and services to rural and inaccessible areas and facilitates better coordination across the agriculture ecosystem.

Benefits of Cloud Computing in Agriculture

Data Readiness Anytime & Anywhere: Cloud computing enables real-time access to agricultural data from any location with internet connectivity.

a. Farmers can instantly view crop status, weather updates, soil reports, and expert advice.
b. Researchers and officials can also access national-level agricultural statistics and field data without physical presence.
c. This ensures timely decision-making and better farm management.

Local and Global Communication: Cloud platforms connect local farmers with national and international experts, markets, and organizations.

a. Farmers can consult with agronomists remotely.
b. Agricultural producers can engage in export opportunities and global trade platforms. This expands their market reach and promotes knowledge exchange across borders.

Improvement of the Economic Condition of the Nation: By digitizing agriculture through cloud computing, farmers become more productive and profitable.

a. Increased yields and reduced waste lead to higher incomes.
b. Better planning ensures resource optimization. As agriculture contributes significantly to India's economy, these improvements positively impact overall economic development.

Enhanced the GDP of the Nation: Agriculture is a major contributor to India's GDP.

a. Cloud-based solutions streamline production, reduce losses, and enhance output.

b. Efficient marketing and reduced middlemen boost profits for producers. These improvements contribute to a higher Gross Domestic Product (GDP) through tech-driven agriculture.

Ensure Food Security Level: Cloud systems help monitor crop production, soil health, climate risk, and storage availability in real-time.

a. Governments can predict food shortages early and take corrective action.

b. Farmers can get alerts for pests, weather changes, and best sowing times. This ensures stable food supply, minimizes risk, and strengthens food security at the national level.

Motivation of Farmers and Researchers: Cloud technology:

a. Empowers farmers with digital tools and knowledge, encouraging them to adopt new techniques.

b. Supports researchers with easy access to field data, satellite imagery, and collaborative platforms. This promotes innovation and keeps both farmers and scientists engaged and motivated toward sustainable agriculture.

Reduction of Technical Issues: By centralizing information and services:

a. Farmers face fewer issues with outdated or unreliable technology.

b. Cloud platforms offer automated updates, troubleshooting, and technical support. This results in better service reliability and fewer disruptions in agricultural operations.

Rural-Urban Movement: Cloud computing reduces the need for physical movement of people by bringing services to their fingertips:

a. Farmers in rural or hilly areas no longer need to travel to cities for expert advice or market data.

b. Access to digital platforms also creates rural employment opportunities, reducing migration to urban areas.

Data Availability at Any Time and Any Location Without Delay: With cloud computing:

a. All data—crop health, irrigation status, input supply, market prices—is instantly accessible.

b. There is no dependency on office hours or physical infrastructure. This real-time data availability boosts productivity, transparency, and efficiency in farming operations.

Improved Market Price of Food, Seeds, and Other Products: Cloud platforms support digital marketplaces where:

a. Farmers can see real-time demand and supply trends.

b. Producers can bypass middlemen and sell directly to consumers or buyers. This creates price transparency, improves profit margins, and ensures fair pricing for seeds, grains, and other products.

Challenge of Cloud Computing in Agriculture

Maintenance & Supervision by Third Party, So Data Security is Less: Cloud services are often managed by external companies, meaning farmers and government agencies do not have full control over their data.

a. Sensitive agricultural data (like land records, farmer identities, or production reports) could be misused if not properly protected.

b. Data stored on third-party servers is vulnerable to breaches if strict security protocols are not in place.

Indirect Administrator Accountability: Since cloud services are managed remotely, users cannot directly monitor the actions of the administrators.

a. If data loss or misuse occurs, it becomes difficult **to** identify and hold the responsible party accountable.

b. This lack of transparency may discourage government and institutional adoption in critical sectors like agriculture.

Farmer is Unaware of Cloud Computing Technology: Most farmers, especially in rural and hilly regions, are not familiar with digital technologies.

a. They may find it difficult to understand how to access, interpret, or trust cloud-based data and services.

b. Without proper education or support, this technological gap limits widespread adoption.

Less Physical Control: Cloud computing takes data and infrastructure away from the user's local environment.

a. Farmers and agricultural officers cannot physically access the servers or infrastructure.

b. This reduces their control over storage, customization, and backups, which could lead to operational hesitation.

Attraction to Hackers: Cloud platforms, especially those containing massive centralized databases, **become** prime targets for cyberattacks.

a. Hackers may exploit weak points to steal or manipulate agricultural data, affecting markets or farmer decisions.

b. Cybersecurity becomes a major concern as digital agriculture grows.

Dependence on Network Connectivity: Cloud computing relies heavily on internet access.

a. In many rural and remote regions, internet coverage is poor or inconsistent.

b. Without strong connectivity, cloud services cannot be used effectively.

Requires a Constant Internet Connection: Real-time cloud features—like live weather updates, sensor data, or market prices—require continuous online access.

a. If the internet disconnects, farmers lose access to critical services, potentially leading to poor decisions or crop losses.

Platform Facility is Not Easily Available for Farmers: Many existing cloud platforms are designed for **tech-savvy users**, not small-scale or illiterate farmers.

a. Lack of user-friendly interfaces, language support, and agricultural-specific features limits usability.
b. Farmers may need intermediaries to help, which defeats the purpose of accessibility.

Farmers' Training Necessary for This Technology: To truly benefit from cloud computing, farmers must be trained in:

a. Using mobile apps or web portals
b. Understanding data insights
c. Accessing expert consultation services.
d. Without this training, the technology remains underutilized and the digital divide continues.

Does Not Work Well with Low-Speed Connections: Cloud platforms often involve data-intensive processes such as:

a. Uploading field reports
b. Accessing HD satellite imagery
c. Streaming instructional videos
d. In areas with slow internet speeds, these services lag, crash, or become inaccessible.

It Runs the Risk of Security: Even with encryption and firewalls, no system is entirely secure.

a. Agricultural data stored on the cloud could be stolen, deleted, or corrupted.
b. Data leaks can hurt farmers financially, especially if pricing, land ownership, or identity information is involved.

Cloud security risks are a serious concern, especially when applied in critical public sectors like agriculture.

Conclusion

This prominent technique may deliver the agriculture-based knowledge along with management of natural resources and knowledge directly to the consumers not only in a small region like in nonstop marketing or shops but also in a wider region. This will change the whole supply chain, which is mainly in the hand of large companies, now, but can change to a more direct, shorter chain between producers and consumers. Cloud computing technology, applicable for the improvement of agriculture growth, food, grain, product, economic condition, Ensure food safety, GDP of the nation & circulate information related to agriculture etc.

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El Niño and Indian Agriculture: Impacts on Crop Production, Alternate Crops and Climate-Resilient Cropping Systems in India and Telangana

Article ID: 74265

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Abstract

Climate variability has emerged as a major challenge for sustainable agricultural production worldwide. Among different climatic phenomena, El Niño plays a significant role in influencing rainfall patterns, temperature regimes, and agricultural productivity. In India, where a large proportion of cultivated land depends on monsoon rainfall, El Niño-induced changes often result in delayed monsoon onset, prolonged dry spells, heat stress, and reduced crop yields. Telangana, a predominantly semi-arid state with considerable rainfed agriculture, is highly vulnerable to these climatic fluctuations.

This article highlights the influence of El Niño on crop production in India and Telangana, discusses its effects on major crops, and presents alternate crops and climate-resilient cropping systems suitable for uncertain rainfall conditions. Adoption of drought-tolerant crops, crop diversification, efficient water management, and climate-smart agricultural practices can reduce production risks and improve farm resilience.

Keywords: El Niño, Climate Change, Crop Production, Telangana Agriculture, Alternate Crops, Climate Resilience, Cropping Systems.

Introduction

Agriculture is one of the most climate-sensitive sectors, directly influenced by variations in rainfall, temperature, and extreme weather events. In India, the southwest monsoon plays a crucial role in agricultural production, as nearly half of the cultivated area depends on seasonal rainfall. Any irregularity in monsoon behaviour affects sowing decisions, crop growth, productivity, and farmer income.

El Niño is one of the major climatic phenomena responsible for rainfall variability in India. It is associated with abnormal warming of sea surface temperatures in the central and eastern equatorial Pacific Ocean, which influences global atmospheric circulation. In many years, El Niño conditions lead to weak or uneven southwest monsoon rainfall over India.

Recent climate trends indicate increasing uncertainty in rainfall distribution, frequent heat waves, and prolonged dry spells. These changes have created new challenges for farmers, particularly in semi-arid regions such as Telangana. Developing climate-resilient agriculture through suitable crop choices and improved cropping systems has become essential for sustainable food production.

Understanding El Niño and Its Agricultural Significance

El Niño is a phase of the El Niño-Southern Oscillation (ENSO), a natural climate cycle involving changes in ocean temperature and atmospheric circulation. During El Niño events, warming of the Pacific Ocean influences monsoon circulation and may reduce rainfall over the Indian subcontinent.

The agricultural impacts of El Niño include:

a. Delayed onset of monsoon rainfall.
b. Reduced soil moisture availability.
c. Increased crop water requirements.
d. Higher frequency of drought conditions.
e. Increased temperature stress.
f. Decline in crop productivity.

The severity of impacts depends on the strength of El Niño, crop growth stage, soil conditions, irrigation availability, and farm management practices.

Impact of El Niño on Crop Production in India

Rice: Rice is one of the most affected crops because of its high water requirement. Delayed rainfall affects nursery preparation and transplanting schedules. Moisture stress during flowering and grain filling reduces grain number and yield.

Maize: Maize is highly sensitive to drought during tasseling and silking stages. Water stress during these critical stages results in poor pollination and reduced grain formation.

Cotton: Cotton can tolerate moderate drought conditions, but prolonged moisture stress during flowering and boll development reduces boll retention, fibre quality, and productivity.

Soybean and Oilseeds: Soybean, groundnut, and other oilseed crops require adequate moisture during flowering and pod formation. Extended dry periods reduce seed development and oil content.

Pulses: Pulses such as pigeonpea, greengram, blackgram, and chickpea are comparatively drought tolerant and can play an important role during rainfall-deficit years.

Impact of El Niño on Telangana Agriculture

Telangana experiences a semi-arid climate with rainfall mainly received from the southwest monsoon. The state has diverse cropping systems involving both irrigated and rainfed agriculture.

Major crops grown in Telangana include:

a. Paddy
b. Cotton
c. Maize
d. Red gram
e. Soybean
f. Groundnut
g. Bengal gram
h. Sorghum
i. Millets

During El Niño years, delayed rainfall affects sowing operations, seed germination, and crop establishment. Rainfed crops face severe moisture stress, while irrigated agriculture may suffer due to reduced reservoir storage and groundwater availability.

Cotton and maize are particularly affected when dry spells occur during reproductive stages. Paddy cultivation faces challenges due to increased irrigation demand. Livestock production is also affected because drought conditions reduce fodder availability.

Alternate Crops Suitable Under El Niño Conditions

Crop diversification is one of the most effective strategies to minimize climate risks.

Current Crop	Alternate Climate-Resilient Crops
Paddy	Foxtail millet, Finger millet, Sorghum
Maize	Pearl millet, Sorghum, Pigeonpea
Cotton	Red gram, Sesame, Castor
Soybean	Greengram, Blackgram, Cowpea
Groundnut	Sesame, Horse gram
Sugarcane	Pulses, Millets, Fodder crops

Millets and pulses require less water, perform better under moisture stress, and contribute to nutritional security.

Climate-Resilient Cropping Systems

Adoption of suitable cropping systems can improve productivity and reduce climate risks.

Intercropping Systems: Examples include:

a. Cotton + Red gram (6:1 ratio)
b. Maize + Cowpea
c. Groundnut + Pigeonpea
d. Sorghum + Red gram

Intercropping ensures better utilization of available resources and reduces the possibility of complete crop failure.

Millet-Based Systems: Millets such as sorghum, pearl millet, finger millet, and foxtail millet are excellent options for dryland agriculture due to their drought tolerance and lower water requirement.

Pulse-Based Systems: Integration of pulses improves soil fertility through biological nitrogen fixation and provides additional income opportunities.

Conservation Agriculture: Practices such as minimum tillage, crop residue management, mulching, and crop rotation improve soil moisture conservation and soil health.

Adaptation Strategies for Farmers

Farmers can reduce El Niño-related risks through the following measures:

a. Select drought-tolerant and short-duration varieties.
b. Follow weather-based crop advisories.
c. Diversify crops instead of depending on a single crop.
d. Adopt drip and sprinkler irrigation.
e. Develop farm ponds and rainwater harvesting structures.
f. Improve soil organic matter through compost and farmyard manure.
g. Use mulching to reduce evaporation losses.
h. Practice integrated pest and disease management.
i. Utilize crop insurance schemes.

Government Support and Future Outlook

Several programmes support climate-resilient agriculture in India, including:

1. National Mission for Sustainable Agriculture (NMSA)
2. Pradhan Mantri Krishi Sinchayee Yojana (PMKSY)
3. Pradhan Mantri Fasal Bima Yojana (PMFBY)
4. Climate-resilient agriculture programmes of ICAR
5. Millet promotion initiatives
6. Weather-based agricultural advisory services

Future agricultural sustainability depends on combining scientific knowledge with traditional farming wisdom. Crop diversification, efficient resource management, and climate-smart technologies will help farmers adapt to changing climatic conditions.

Conclusion

El Niño presents a significant challenge to Indian agriculture by influencing rainfall patterns, increasing temperature stress, and reducing water availability. Telangana, with its semi-arid climate and dependence on monsoon rainfall, requires special attention towards climate adaptation.

Promoting alternate crops such as millets, pulses, and oilseeds, along with resilient cropping systems and efficient water management, can reduce climate risks. Building climate-smart agricultural systems will improve productivity, strengthen farmer livelihoods, and ensure food and nutritional security under future climate uncertainties.

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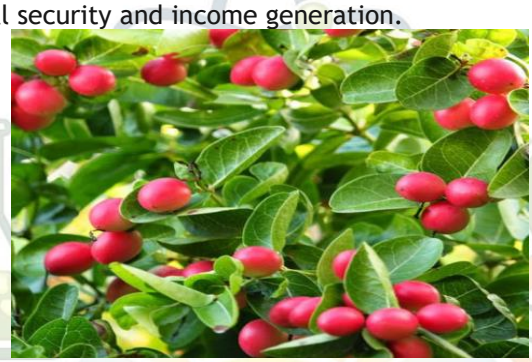
Karonda (*Carissa carandas* L.): A Hardy Indigenous Fruit Crop with High Nutritional and Economic Value

Article ID: 74266

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Introduction

Karonda (*Carissa carandas* L.), commonly known as Bengal currant, is a hardy fruit crop native to the Indian subcontinent. It is widely grown in tropical and subtropical regions of India and is valued for its adaptability to poor soils, drought tolerance, and multiple uses. The fruits are rich in vitamin C, antioxidants, and minerals, making Karonda an important underutilized fruit crop for nutritional security and income generation.



Karonda plants are thorny evergreen shrubs that can be used as live fencing while also providing edible fruits. The fruits are consumed fresh, but they are more commonly processed into pickles, jams, jellies, chutneys, squashes, and syrups because of their pleasant acidic flavor.

Botanical Information

Characteristic	Details
Scientific name	*Carissa carandas* L.
Family	Apocynaceae
Common names	Karonda, Bengal currant, Carandas plum
Plant habit	Thorny evergreen shrub
Fruit type	Berry
Propagation	Seed, stem cuttings, and air layering

Origin and Distribution

Karonda is believed to have originated in the Indian subcontinent, particularly in India and neighboring South Asian countries. It thrives well in warm climates and can tolerate drought conditions better than many other fruit crops. It is naturally distributed in dry and semi-arid regions and is commonly found in: **India:** Rajasthan, Uttar Pradesh, Madhya Pradesh, Maharashtra, Gujarat, and Karnataka.; **Nepal; Bangladesh; Sri Lanka; Myanmar.**

Types and Varieties of Karonda

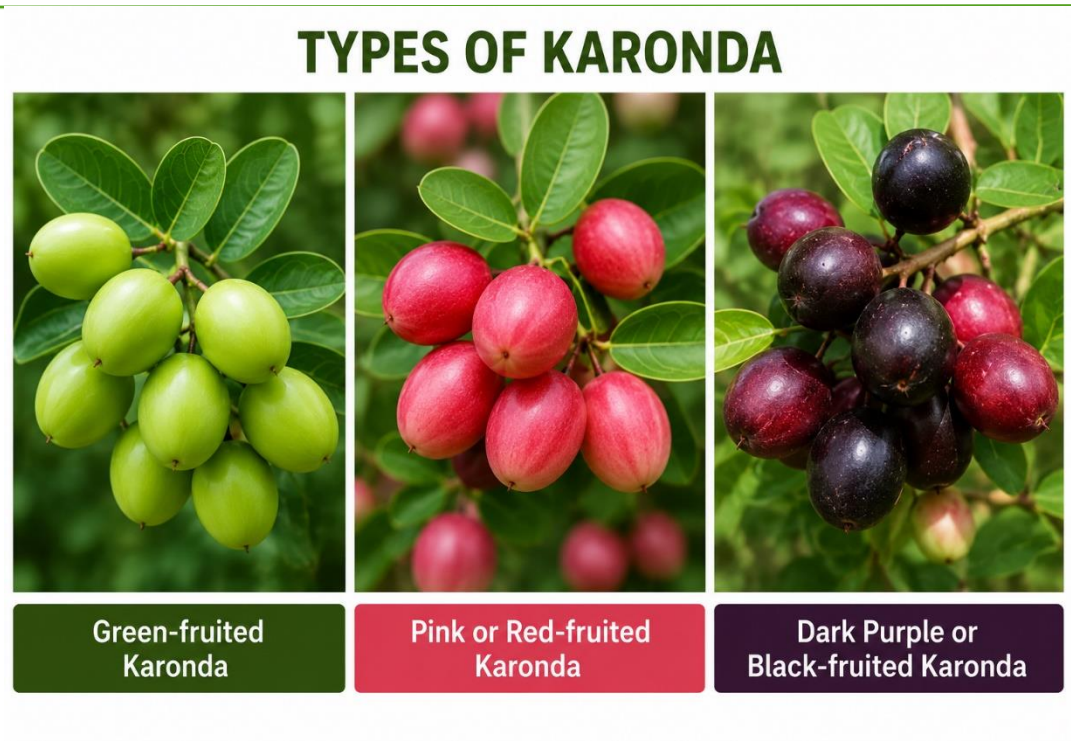
Karonda varieties are generally classified based on fruit color, fruit size, taste, and purpose of use.

Common Types:

a. Green-fruited Karonda
- i. Fruits are harvested in the immature green stage.
- ii. Highly acidic and suitable for pickles and chutneys.

b. Pink or Red-fruited Karonda
- i. Fruits develop a reddish or pinkish color during ripening.
- ii. Suitable for processing into jams, jellies, and squashes.

c. Dark Purple or Black-fruited Karonda
- i. Fully ripe fruits become dark purple or almost black.
- ii. Sweeter in taste and consumed fresh or used in desserts.



Popular Varieties

Variety	Important Features
Pant Karonda-1	Medium-sized fruits, suitable for pickling
Pant Karonda-2	Good yield and processing quality
Narendra Karonda	Large fruits with good pulp content
PKM-1	Suitable for cultivation in dry regions
Local cultivars	Differ in fruit color, acidity, and yield



Fruiting Time

Karonda generally starts bearing fruits **2-3 years after planting.** The main flowering and fruiting period is:

Stage	Time
Flowering	March–April
Fruit set	April–May
Harvesting	June–September

The fruits are harvested at different maturity stages depending on their intended use:

a. **Green immature fruits** for pickles.
b. **Partially ripe fruits** for chutneys and preserves.
c. **Fully ripe fruits** for fresh consumption and sweet products.

Nutritional Value of Karonda: Karonda is considered a nutrient-rich fruit because it contains vitamins, minerals, dietary fiber, and bioactive compounds. It is especially known for its high vitamin C content.

Nutrient	Approximate Value
Energy	42 kcal
Carbohydrates	2.6–2.9 g
Protein	1.1 g
Fat	2.9 g
Dietary fiber	1.6 g
Vitamin C	9–200 mg
Vitamin A	1619 IU

Note: Nutritional composition may vary depending on variety, maturity stage, and growing conditions.

Mineral	Amount
Calcium	21 mg
Phosphorus	28 mg
Iron	1.5–2.0 mg
Potassium	260 mg
Magnesium	15 mg
Sodium	13 mg
Copper	0.10 mg
Zinc	0.25 mg

Health Benefits of Karonda

Rich Source of Vitamin C: Karonda helps improve immunity and supports the body in fighting infections.

Antioxidant Properties: The fruit contains phenolic compounds and anthocyanins that help reduce oxidative stress.

Supports Digestive Health: Its fiber content aids digestion and helps maintain a healthy digestive system.

Good for Blood Health: The iron content contributes to the formation of hemoglobin and helps prevent anemia.

Supports Bone Health: Calcium and phosphorus present in the fruit contribute to healthy bones and teeth.

Uses and Economic Importance

1. Immature fruits are widely used for pickles and chutneys.
2. Ripe fruits are processed into jams, jellies, squashes, and syrups.
3. The crop is suitable for cultivation in dry and marginal lands.
4. Karonda plants are also used as live fencing due to their thorny nature.

Conclusion

Karonda is a valuable indigenous fruit crop with high nutritional, medicinal, and economic importance. Its adaptability to adverse climatic conditions and suitability for value-added products make it an ideal crop for sustainable horticulture and rural livelihood enhancement.

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Pathogenicity Genes in Plant Pathogenic Bacteria

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Abstract

Plant pathogenic bacteria cause significant crop losses by invading plant tissues, suppressing host immunity, acquiring nutrients, and inducing diseases such as blight, wilt, canker, rot, and tumors. Pathogenicity genes enable disease establishment, while virulence genes determine disease severity and host specificity. In Gram-negative bacteria, the type III secretion system (T3SS) is the primary virulence mechanism, delivering effectors that suppress plant defenses and promote infection. Additional pathogenicity factors include other secretion systems, phytotoxins, cell wall-degrading enzymes, exopolysaccharides, motility, adhesion, and iron-acquisition systems. Their expression is tightly regulated by quorum sensing, two-component systems, and environmental signals. Recent genomic studies reveal that these genes are highly dynamic and often spread through horizontal gene transfer. Modern disease management increasingly targets bacterial virulence using rapid diagnostics, resistant cultivars, microbiome-based approaches, and anti-virulence strategies.

Keywords: Pathogenicity genes; virulence factors; type III secretion system; quorum sensing; effectors; plant immunity; comparative genomics; sustainable disease management.

Introduction

Bacterial plant diseases cause severe crop losses, particularly under conditions favorable for bacterial growth, producing symptoms such as leaf spots, blights, cankers, wilts, soft rots, and tumors. Around 150 bacterial species are recognized as plant pathogens. Pathogenicity refers to the ability of a bacterium to cause disease, whereas virulence describes the degree of disease severity. Pathogenicity genes are essential for establishing infection, while virulence genes regulate and enhance disease development by promoting host damage and bacterial colonization.

Major Genera

The major model and high-impact genera repeatedly represented across the supplied literature are Pseudomonas, Xanthomonas, Ralstonia, Agrobacterium, Erwinia/Pectobacterium and Dickeya.

Sr. no.	Genus	Representative pathogenicity themes	Example disease relevance
1	Pseudomonas	Hrp/Hrc T3SS, large effector repertoires, coronatine, auxin-responsive regulation, methylome control	Leaf spots, cankers, halo bligh
2	Xanthomonas	Hrp2-type T3SS, TAL-like effector specialization, DSF quorum sensing, albicidin, IS-mediated avr disruption	Rice blight, citrus canker, leaf strea
4	Ralstonia	Large core effectomes, EPS-rich vascular colonization, multilayered QS, temperature-responsive regulation	Bacterial wilt across broad host range
5	Agrobacterium	VirB/D4 T4SS, T-DNA transfer, adhesion, AHL quorum sensing.	Crown gall disease
6	Pectobacterium / Dickeya	Strong T2SS/T1SS secretomes, pectinases, cellulases, Vfm or AHL signaling, soft-rot enzymes	Tissue maceration and soft rot

Conceptual Framework

Pathogenicity genes are often clustered on mobile genetic elements, such as transposons and integrative conjugative elements (ICEs), facilitating horizontal gene transfer and rapid evolution of bacterial virulence. These mobile elements commonly carry type III secretion system (T3SS) genes, hydrolytic enzymes, metal-resistance genes, and other fitness traits that enhance host adaptation. Host specificity is largely determined by the diversity of type III effector repertoires, with Pseudomonas syringae and Ralstonia solanacearum possessing highly variable effector sets, explaining differences in host range, disease severity, and symptom expression among closely related strains.

Secretion Systems

Type III secretion is the most consistently emphasized pathogenicity system in the supplied literature. It injects effector proteins directly into plant cells, is encoded by hrp/hrc-related genes, and is required both for disease in susceptible plants and hypersensitive response induction in resistant plants. T3SS effectors suppress PRR-triggered immunity, hijack immune signaling, and also modulate metabolism, hormones, organelles, and nutrient release.

Type II secretion exports many extracellular enzymes that act in the apoplast. In Xanthomonas and Ralstonia, T2SSs deliver pectinolytic and cellulolytic enzymes, while in soft-rot pathogens secreted pectinases, cellulases, proteases, and xylanases are major causes of tissue maceration. Type I secretion is simpler and includes export of proteases, lipases, and toxins in soft-rot bacteria.

Type IV secretion is exemplified by Agrobacterium VirB/D4, which transfers T-DNA and virulence proteins into host cells and underpins tumorigenesis. Type VI secretion is less represented in the supplied corpus, but comparative genomics in R. solanacearum identified candidate T6SS-associated effectors linked to cool-virulence phenotypes, indicating context-dependent roles in fitness and pathogenesis.

Major Pathogenicity Determinants

Pathogenicity genes are often clustered on mobile genetic elements such as transposons and integrative conjugative elements (ICEs), enabling horizontal gene transfer and rapid evolution of bacterial pathogens. These elements frequently carry type III secretion system (T3SS) genes and other virulence-related factors that enhance host adaptation. Variation in type III effector repertoires is a key determinant of host specificity, virulence, and symptom development, explaining differences in disease severity and host range among closely related bacterial strains.

Infection Process

Bacterial infection begins through natural openings (stomata, hydathodes) or wounds, followed by attachment using adhesins, pili, and extracellular polysaccharides. After colonization, bacteria form biofilms and secrete cell wall-degrading enzymes and exopolysaccharides (EPS) to spread within host tissues. The type III secretion system (T3SS) delivers effector proteins that suppress plant immunity (PTI) and promote bacterial multiplication. Nutrient acquisition and symptom development are mediated by effectors, toxins, enzymes, and EPS, resulting in chlorosis, necrosis, wilting, and tissue collapse.

Regulation

Quorum sensing is a major regulator of pathogenicity gene expression across phytopathogenic bacteria, using AHL, DSF, or Vfm-type systems to coordinate virulence with cell density. The supplied QS review specifically maps QS involvement in Pseudomonas, Ralstonia, Agrobacterium, Xanthomonas, Dickeya, Pectobacterium, Erwinia, and Xylella. In Dickeya, the Vfm cluster contains 26 genes, and polymorphism in vfmO/vfmP generates strain-specific signaling specificities that can restrict interstrain communication.

Two-component systems and higher-order regulatory hierarchies integrate QS with environmental sensing. In R. solanacearum EP1, the newly characterized RasI/R system regulates cellulase, motility, biofilm formation, oxidative-stress response, virulence.

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Artificial Intelligence (AI) and Multi-Omics in Plant Pathology

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Artificial intelligence (AI) together with multi-omics technologies is reshaping modern plant pathology by enabling researchers to study plant diseases at an unprecedented level of detail. Instead of examining a single biological process, scientists can integrate information from genes, RNA, proteins, metabolites, and observable plant characteristics to understand how plants respond to pathogens. AI can rapidly analyse these complex datasets, helping researchers identify resistance-associated genes, predict disease outbreaks, and accelerate the development of resilient crop varieties while reducing dependence on chemical pesticides.

Conventional disease management largely depends on field observations, laboratory diagnosis, and repeated pesticide applications after symptoms become visible. In contrast, the combination of AI and multi-omics supports a preventive strategy. By integrating biological information collected at different molecular levels, computational models reveal hidden interactions between plants and pathogens long before visible disease develops.

Multi-omics includes genomics, transcriptomics, proteomics, metabolomics, and phenomics. Each layer contributes unique biological information. Genomics identifies the genetic potential of a plant, transcriptomics measures which genes are active, proteomics reveals the proteins performing cellular functions, metabolomics reflects biochemical responses, and phenomics captures observable traits. Studying only one layer often provides an incomplete understanding because plant resistance depends on coordinated activity across all these biological systems.

AI combines these datasets using advanced computational approaches. Traditional machine-learning algorithms such as Random Forests and Support Vector Machines help identify the most informative genes, proteins, or metabolites associated with disease resistance. Deep-learning methods, including multimodal neural networks, can simultaneously analyse multiple omics datasets to detect complex patterns that would be difficult to recognize through conventional statistical methods. Such integrated models have demonstrated improved accuracy in predicting disease resistance using molecular profiles together with imaging data.

A systems-level perspective has become increasingly important for understanding plant defence. Rather than treating each omics layer separately, modern AI frameworks construct biological interaction networks in which genes, proteins, metabolites, and signalling pathways are connected. Graph neural networks and related approaches allow researchers to identify relationships among these components, providing insights into the dynamic processes that determine whether a plant successfully resists pathogen invasion.

AI is also transforming the study of pathogen effectors and plant immune receptors. Protein-structure prediction tools can estimate the three-dimensional structures of pathogen effectors directly from sequence information, allowing researchers to investigate how these molecules interact with host proteins. Likewise, machine-learning models can evaluate large collections of plant immune receptors and predict which variants are most likely to recognize specific pathogen effectors. These predictions provide valuable guidance for resistance breeding and future crop improvement.

Metabolomic information further strengthens disease research by revealing how plants redistribute their metabolic resources during infection. Advanced generative models can analyse changes in metabolic pathways together with gene-expression data to identify critical regulatory points that influence the production of defence-related compounds. These discoveries can support genome-editing strategies aimed at enhancing natural resistance.

The integration of AI and multi-omics offers several practical advantages. Early molecular biomarkers can enable disease detection before visible symptoms appear. Predictive breeding models shorten the time required to identify promising resistant lines, while microbiome-based analyses assist in discovering beneficial microorganisms that naturally suppress plant pathogens. Together, these advances contribute to more sustainable and climate-resilient agricultural systems.

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Pathobiome: A Holistic Perspective on Disease Development in Plant Systems

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A pathobiome is defined as the community or group of microorganisms which are having positive or negative interaction with each other in terms of their pathogenicity, mutualistic relationship, or opportunistic relationship, with a diseased host plant which influences disease development and progression.

The plant pathobiome comprises of multiple groups of microorganisms as they include,

Primary pathogens: Microbes that causes the disease to the host plant, and possess virulence factors which can be capable of overcoming plant defences. Example, most of plant pathogenic fungi, bacteria, virus, phytoplasmas, and nematodes etc.,

Opportunistic microorganisms: These microorganisms are harmless in nature but due to the advancement of infection by the plant pathogens they invade the plant by causing the secondary infections. These secondary colonizers may increase the disease severity, or modify pathogen behaviour. Example, sooty moulds infection in plants

Beneficial microorganisms: Includes Plant growth-promoting rhizobacteria, endophytic fungi, mycorrhizal fungi, antagonistic bacteria, and bacteriophages which supress the disease development, through the production of antimicrobial compounds, by competing for nutrients, and induces systemic resistance. Example, *Bacillus* species as endophyte in crops

Viral communities: The viruses that infecting fungi (mycoviruses), bacteria (bacteriophages), and even plants influence disease dynamics. Mycoviruses may reduce fungal virulence, whereas bacteriophages reshape bacterial populations through selective predation.

Environmental microbiota: Microorganisms that are present in the soil, irrigation water, crop residues, insects, aerosols, and surrounding vegetation continuously contribute to pathobiome assembly.

Factors Responsible for Formation of Pathobiome

Formation of the pathobiome is governed by the factors that are regulating the natural ecosystems. Microbial succession occurs as early colonizers modify host tissues, creating conditions suitable for the invasion of subsequent microorganisms. Ecological filtering determines which microorganisms successfully establish within host tissues based on nutrient availability, immune responses, moisture, temperature, and competition. Priority effects influence the disease because microorganisms arriving first often occupy ecological niches that exclude later colonizers. Functional redundancy enables many species of microbes to perform similar ecological functions, which increase the pathobiome resilience. Network interactions determine whether microorganisms cooperate, compete, or inhibit one another through chemical signalling and metabolite exchange.

Microbial Interactions Within the Pathobiome

Microorganisms communicate extensively through the chemical cues, nutrient exchange, volatile compounds, extracellular enzymes, quorum sensing molecules, and secondary metabolites.

Conclusion

The pathobiome concept represents a fundamental shift in plant pathology by recognizing the disease as an ecological phenomenon, rather than focusing exclusively on the infectious agent, the pathobiome framework highlights the importance of microbial diversity, ecological stability, interspecies communication, and functional networks in determining disease outcomes. As sequencing technologies, ecological modelling, and systems biology continue to advance, the pathobiome is likely to become a central paradigm for understanding plant health, disease emergence, and resilient agricultural ecosystems.

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Mycoviruses of Edible Mushroom

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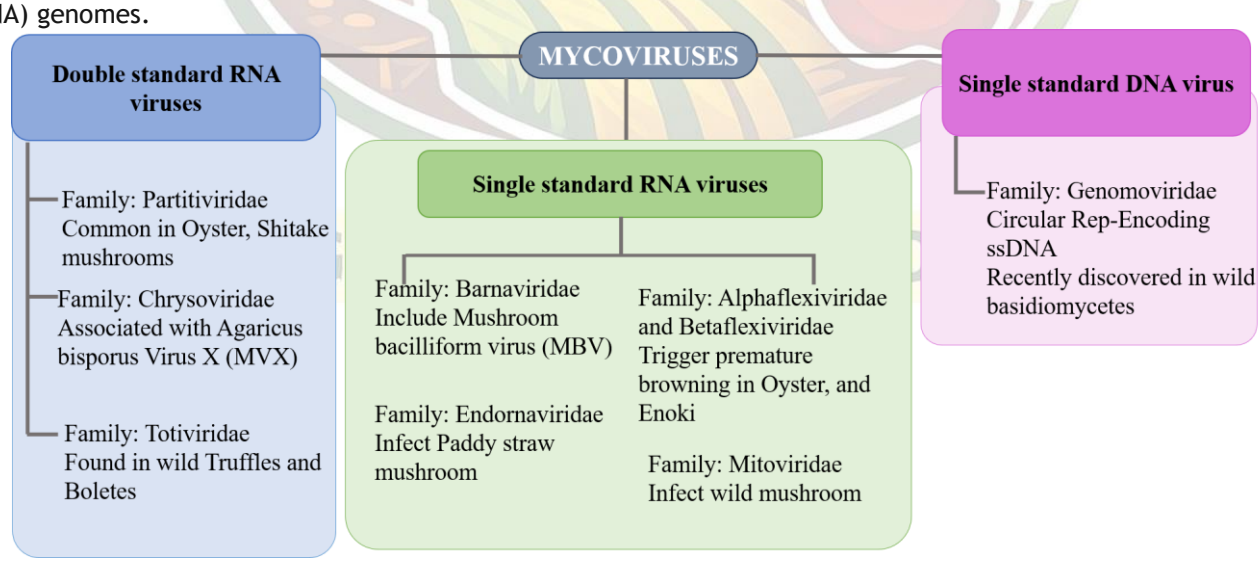
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Mycoviruses are also known as fungal viruses or macrophages, which infect the edible mushrooms and live inside them. In most of the cultivated mushrooms, these viruses may exist without producing visible symptoms and also do not cause much harm but few of them affect its commercial value by causing damage through interfering the normal physiological processes of the mushroom resulting in reduced growth of the mycelium delayed fruiting, deformed/malformed basidiocarp formation, discoloration of the basidiocarp, or significant yield losses. During 1948 La Francis brothers noticed mycovirus infection in their mushroom farm in Pennsylvania on cultivated white button mushrooms (*Agaricus bisporus*), the mushroom suddenly suffered catastrophic crop failures. And the basidiocarp exhibited weird, puny caps, severely elongated, crooked stems, and rapid browning. Plant pathologists J.W. Sinden and E. Hauser documented the crisis in 1950, and named the disease as "**La France disease**", the disease is also known as dieback or X-disease brown disease or watery stipe. Eventually the disease spread rapidly through mushroom farms and caused substantial economic losses. Initially, the disorder was suspected to result from unfavourable cultivation practices or unidentified microbial pathogens because no known fungal or bacterial organism could consistently explain the symptoms. A major breakthrough occurred in 1962 when Michael Hollings demonstrated the presence of virus-like particles in diseased mushroom tissues using electron microscopy. His work established that the disease was associated with viral infection, providing the first direct evidence that fungi could serve as hosts for viruses. This discovery marked the birth of the discipline now known as mycovirology (a branch of virology which mainly focuses on the study of mycoviruses which infecting the fungi), making edible mushrooms the first fungal organisms in which viruses were conclusively identified. In the 1990s, the primary driver of La France disease was formally characterized as La France Isometric Virus (LFIV), a double-stranded RNA (dsRNA) virus often assisted by a secondary hitchhiker, the Mushroom Bacilliform Virus (MBV).

List of the Mycoviruses Infecting Mushrooms

Researchers have identified approximately 60 distinct mycoviruses across these edible fungi species. The primary commercial and wild edible mushrooms affected by mycoviruses include White Button, Shiitake, Oyster, Enoki, and King Oyster mushrooms, along with prized wild varieties like Truffles, Porcini and milk caps.

Mycoviruses infecting mushrooms are classified by the type and structure of their genetic material (genome type), as established by the International Committee on Taxonomy of Viruses (ICTV). Unlike plant or animal viruses, the vast majority of mushroom-infecting viruses have double-stranded RNA (dsRNA) or positive-sense single-stranded RNA (+ssRNA) genomes.



Dispersal of Mycovirus

Mycoviruses spread within and between mushroom crops in two primary ways,

1. **Horizontal Transmission:** This is the spread of viruses between different fungal colonies or strains.
   - **a. Hyphal Anastomosis:** This is the most common method. When the threads (hyphae) of two separate mushroom colonies touch, they naturally fuse together, creating a shared cytoplasm. The virus particles "drift" or flow with the liquid cytoplasm from the infected colony into the healthy colony.

b. Vegetative Compatibility: Fungi only fuse with genetically similar strains (vegetative compatibility groups). This sets a genetic barrier, but some aggressive mycoviruses can actually suppress this recognition, allowing the virus to infect completely unrelated strains.

2. Vertical Transmission: This is the spread of the virus to future generations.

a. Spore Formation: Viruses are packaged inside the mushroom's spores (both sexual basidiospores and asexual conidiospores). When an infected mushroom releases its spores, the virus is inherited by the next generation of offspring. Transmission rates can range from partially to 100% depending on the specific virus and mushroom species.

b. Hyphal Tips & Fragmentation: Even simple division or breaking of the fungal mycelium allows the virus to persist in the separated segments.

Management of Mycoviruses

1. Production of virus-free spawn
2. Sanitation of the production farm and exclusion of infected mother spawn
3. Detection of the virus through RT-PCR for early diagnosis
4. Heat therapy
5. Chemical curing
6. RNAi- based management
7. Genome editing

Conclusion

The historical progression of mycovirus research illustrates a remarkable transition from the investigation of a single mushroom disease to the exploration of a diverse and dynamic virosphere associated with edible fungi. Modern genomic technologies continue to uncover previously unknown viral species and provide new insights into host–virus co-evolution, viral transmission, and fungal adaptation. Future research is expected to integrate virology with fungal genomics, microbiome studies, and precision cultivation to determine how mycoviruses influence mushroom productivity, nutritional quality, environmental resilience, and sustainable commercial production. Consequently, mycoviruses are no longer regarded merely as hidden pathogens but as important biological components that contribute to the complexity and functioning of edible fungal ecosystems.

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Two Enterprises, One Farm: The Magic of Fish and Poultry Integration

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Abstract
Integrated farming systems (IFS) have become an effective and sustainable farming approach that combines different agricultural enterprises to maximize resource utilization while minimizing waste. Among these, fish-cum-poultry is widely recognized for improving farm productivity, reducing production costs, and generating additional income for farmers. In these integrated systems, poultry droppings are directly used as organic manure in fish ponds, enriching the water with essential nutrients that stimulate the growth of phytoplankton and zooplankton, which serve as natural food for fish. This natural nutrient recycling significantly reduces the need for chemical fertilizers and supplementary fish feed, making fish production more economical and environmentally friendly. At the same time, farmers receive additional income from the sale of eggs, meat, and poultry ,thereby increasing the overall profitability of the farming system. Besides enhancing production, integrated fish farming contributes to better waste management, improved soil and water resource utilization, and sustainable agricultural development. Although proper management practices such as maintaining water quality, disease prevention, and suitable housing for birds are essential for successful implementation, the overall benefits outweigh the challenges. Therefore, fish-cum-poultry farming offer an efficient and eco-friendly farming model that supports food security, rural livelihoods, and sustainable aquaculture development (Kaur & Tanwar, 2023; Kumar *et al.*, 2012; Saikia *et al.*, 2020).

Keywords: Integrated Farming System (IFS), Fish-cum-Poultry Farming, Sustainable Aquaculture, Nutrient Recycling, Organic Manure, Polyculture, Pond Fertilization, Resource Utilization, Rural Livelihoods, Eco-friendly Farming, Fish Production.

Introduction
Integrated farming may be defined as a sequential linkage between two or more farming activities. When the fish becomes a major commodity of this system it is known as integrated fish farming (IFF). Integrated fish farming is based on the concept that 'there is no waste'.

Poultry Droppings as Manure
Poultry has now become a popular rural enterprise in different states of the country. Apart from eggs and chicken, poultry also yields manure, which has high fertilizer value. The poultry droppings comprise 2% nitrogen, 1.25% phosphoric acid and 0.75% potash. The low feeding cost per individual bird makes poultry farming along with fish, a common investment for poor farmers.

Species to be Cultured
1. Poultry manuring produces heavy plankton bloom so selection of planktophagous is more beneficial.
2. Additionally high production of detritus provides substrate for colonization of chironomid larvae, so insectivorous fish like common carp has to be added.
3. If macro vegetation is available on pond embackments then grass carp should need for that.
4. For exploiting all areas polyculture of IMC with exotic carps are more beneficial.
5. Stocking density – 5000 to 6000 fingerlings/ha
6. Species ratio –
   - Surface feeder: 40%
   - Column feeder: 20%
   - Bottom feeder: 30%
   - Weedy feeder: 10%

Polyculture with Prawns
In one hectare pond area, when stocked with 5000 giant freshwater prawns (*Macrobrachium rosenbergii*) and 1500 silver carp, and cultured for a period of four months, one can harvest 600 kg of prawns and an equal number of fish, along with 250 culled birds.

Housing of Birds

In integrated fish-cum-poultry farming the birds are kept under intensive system. The birds are confined to the house entirely.

The intensive system is further of two types –

1. Cage system
2. Deep litter system.



Deep Litter System

In these 250 numbers of birds are kept with floor is covered with litter. Dry organic material like chopped straw, dry leaves, hay, groundnut shells, broken maize stalk, saw dust etc is used to cover the floor up to a depth of about 6 inches. The birds are then kept over this litter and a space of about 0.3 - 0.4 m^2/bird is provided. The litter is regularly stirred for aeration and lime used to keep it dry and hygienic.



Bird Selection

1. The fowls which are able to produce more and large eggs as in the case of layers, or rapid b.w gains in case of broilers are selected along with fish.
2. 200 no of broilers in 4 batch and 250 no of layers are required for one hacter pond.
3. Floor space of 15-20 cm^2 are provided for each bird.

Feeding of Birds

1. Grower mash is provided to the birds during the age of 9-20 weeks at a rate of 50-70 gm/bird/day.
2. Layer mash is provided to the birds above 20 weeks at a rate of 80-120 gm/bird/day.

	
Grower mass	Layer mass

Egg Laying

1. Each pen of laying birds is provided with nest boxes for laying eggs.
2. Empty kerosene tins make excellent nest boxes.
3. One nest should be provided for 5-6 birds.
4. Egg production commences at the age of 18 weeks and then gradually decline.
5. The birds are sold after 18 months as the egg laying capacity of these birds decreases after that period.

Harvesting

1. Harvesting is done after 12 months of rearing.
2. Fish yield ranging from 3500-4000 kg/ha/yr with 6 species and 2000-2600 kg/ha/yr with 3 species stocking.
3. Each bird lays about 200 eggs/yr.

Advantages

1. Chicken manure is a very efficient fertiliser, so no chemical fertiliser is needed for fertilising the pond water.
2. This cuts down the expenditure of rearing fishes.
3. No supplementary fish feed is required.
4. The purchase and feeding cost per bird is low.
5. Chicks are readily available and their productivity can be improved with simple and cheap management.

Disadvantages

1. Chicks should be examined from time to time and diseased one should be isolated, otherwise they will destroy the entire stock.
2. Sufficient time should be given from one stocking of chicks to the next for renovation of the house and disinfection.

Economics

a)	**Expenditure**	**Rs.**
1	Construction of Pond,Water Supply Channel, Installation of Tube well/Renovation/Lease Amount	25000
2	Electricity & Water charges	60000
3	Construction of Poultry Shed (Rs.150000/- for 10 years)	15000
4	550 Chicks	8250
5	22500Kg Poultry Feed	230000
6	Medicines for Fish & Poultry	50000
7	Fishing, Sale of Poultry Birds & Labour	40000
	TOTAL EXPENDITURE	**428250**
b)	**Income**	
	Sale of 6000 KG Fish	300000
	Sale of 118750 Eggs	415625
	Sale of 500 KG Poultry Birds	50000
	Total Income	**765625**
c)	**Net Income(B-A)**	**337375**

Conclusion

Fish-cum-poultry farming are excellent example of sustainable integrated farming systems that effectively utilize farm resources while minimizing waste generation. By recycling poultry droppings as organic fertilizers in fish ponds, these systems naturally enhance pond productivity, promote the growth of beneficial aquatic organisms, and reduce dependence on costly commercial feeds and chemical fertilizers. As a result, farmers can achieve higher fish production while simultaneously generating additional income through poultry farming.

Beyond improving farm profitability, integrated farming also contributes to environmental sustainability by promoting efficient nutrient recycling, reducing pollution, and making better use of available land and water resources. The system is particularly suitable for small and marginal farmers because it requires relatively low investment while providing multiple sources of income and employment. However, successful adoption depends on proper management practices, including maintaining bird health, ensuring good water quality, selecting suitable fish species, and following appropriate stocking and feeding strategies.

Overall, fish-cum-poultry farming represent practical and climate-resilient farming models that support sustainable aquaculture, strengthen rural livelihoods, and contribute to long-term food and nutritional security. With increasing emphasis on environmentally friendly agricultural practices, these integrated farming systems are expected to play an important role in the future development of sustainable fisheries and agriculture (FAO, 2014; Kaur & Tanwar, 2023; Saikia et al., 2020).

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Synthesis of Nanoparticles from Starch: Mechanisms, Structure Property Correlations, and Emerging Applications

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Abstract

Starch nanoparticles (SNPs) are recognized for their environmentally friendly qualities, including biodegradability and biocompatibility. They are derived from natural starch using various methods such as acid hydrolysis and ultrasonication, which influence properties like size and stability. Factors affecting SNP characteristics include the starch's botanical source and processing techniques. Their versatile applications span food, pharmaceuticals, and packaging, particularly in controlled delivery systems and green packaging. Recent developments focus on sustainable production methods and machine learning for optimization. However, challenges remain in large-scale manufacturing and regulatory approval, necessitating further research into sustainable practices and safety assessments. SNPs offer significant potential for next-generation sustainable nanomaterials across various industries.

Keywords: Nanoparticles, Starch, Crystallinity, Gelatinization, Polysacchride.

Introduction

Starch is among the most abundant, renewable, biodegradable and non-toxic natural polysaccharides available today and thus represents a very attractive platform for nanoparticle engineering. Starch can be used in three different ways depending on the intended application, as the raw material from which starch nanoparticles (SNPs) are directly fabricated, as a mild reducing agent that drives the green synthesis of metallic nanoparticles or as a stabilizing and capping agent that limits particle aggregation in colloidal systems (Marta et al., 2023). This versatility, combined with excellent biocompatibility and biodegradability, has driven the expansion of starch-based nanomaterials in food, pharmaceutical, biomedical, packaging, agricultural and environmental sectors, where they are increasingly considered as sustainable alternatives to petroleum-derived and metal-based nanocarriers. The last decade has seen a steady rise in interest in this field by researchers in the search for low-cost, edible and scalable substitutes to synthetic nanocarriers. The following discussion tracks this development from the underlying fabrication chemistry through structure-property relationships to translational applications.

Mechanism of Starch Nanoparticle Formation

A schematic summary of the overall route of converting native starch granules to nanoscale particles is shown in Fig. 1. Fabrication usually begins with the dissolution or gelatinization of starch in a suitable solvent system, which causes the breakdown of the semi-crystalline granular structure and the exposure of single glucan chains. This dissolved starch is added drop-wise under constant stirring to a non-solvent such as ethanol or acetone in the widely used technique of nanoprecipitation (solvent-displacement); this abrupt change in polarity induces rapid self-assembly and precipitation of the polymer chains into discrete nanoparticles (Chen et al., 2024). At this stage, cross-linking agents are often added to improve particle integrity, while surfactants help control final particle size and colloidal stability. The formed nanoparticles are then recovered by centrifugation or filtration and dried, yielding a powder that can be redispersed for downstream use. This sequence dissolution, controlled precipitation or hydrolysis, stabilisation and recovery is the conceptual backbone of almost all SNP preparation strategies, irrespective of the exact energy input (chemical, enzymatic, mechanical or acoustic) used to achieve it.

Classification and Definitions: SNPs versus SNCs

Starch nanoparticles (SNPs) are generally defined as particles larger than a single macromolecule but with at least one dimension under 1000 nm, and many authors impose a stricter limit of 300 nm for at least one dimension (Campelo et al., 2020). Starch nanocrystals (SNCs), a mechanistically distinct subclass, specifically refers to the crystalline platelets liberated when acid hydrolysis selectively removes the amorphous regions of a starch granule, while leaving the crystalline lamellae intact (LeCorre et al., 2012). In practice, the SNPs made from fully gelatinised starch can be amorphous in character, whereas the SNCs are intrinsically more crystalline. This structural difference is at the heart of many of the functional differences reported between the two families of nanomaterials.

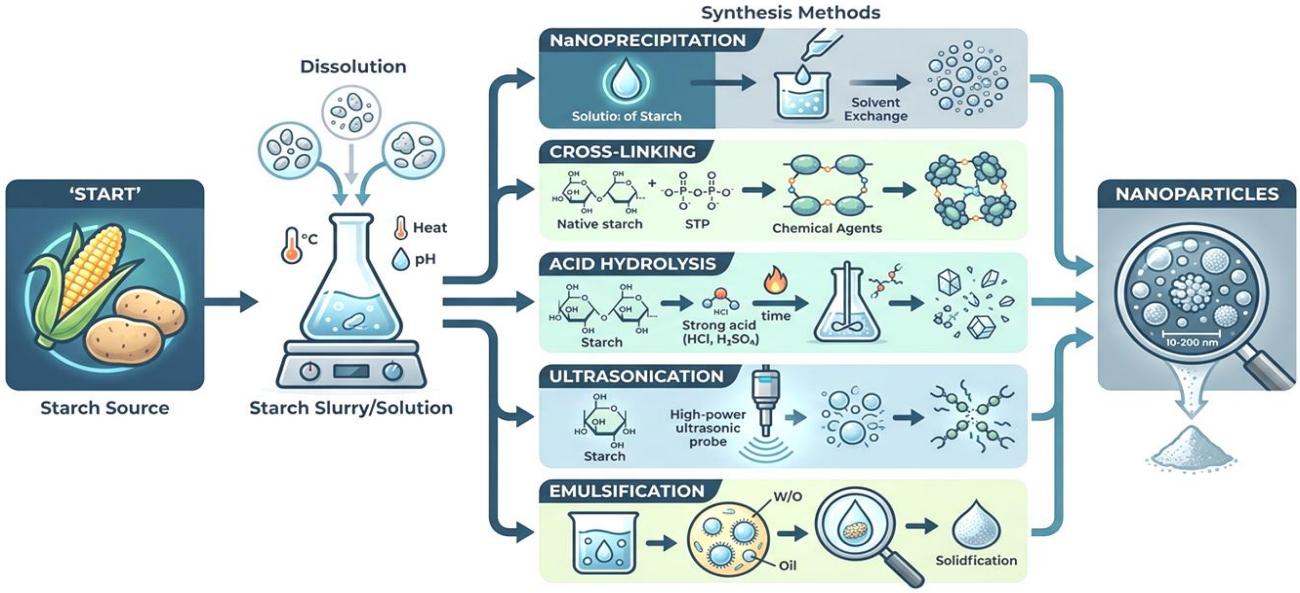


Fig. 1. Schematic representation of the processes involved in starch nanoparticle formation, from granule dissolution/gelatinisation to nanoprecipitation, stabilisation and recovery.

Case Study: Taro Starch Nanoparticles

Research on taro starch has shown that the botanical origin and subsequent modification play a major role in the final efficacy of SNPs. Das and Sit (2021) reported that the transformation of native taro starch into nanoparticles decreased both the particle size and the crystallinity as compared to the original starch, while significantly improving the freeze-thaw stability, a character of practical importance in frozen food development. Chemically modified SNPs from taro with octenyl succinic anhydride (OSA) led to amphiphilic nanoparticles that were efficient Pickering-emulsion stabilizers, able to effectively stabilize oil-in-water systems (Jiang et al., 2016). A similar study revealed that acid hydrolysis of taro starch nanoparticles decreased swelling power and gelatinization temperature but increased aqueous solubility, lending support to the notion that the selected modification method can be customized to attain functional results for a specific application.

Comparative Overview of Fabrication Methods

In general, the techniques can be categorized into "top-down" approaches like acid hydrolysis, ultrasonication, enzymatic hydrolysis, high-pressure homogenization, gamma irradiation, and ball milling that systematically break down native granules, and "bottom-up" methods such as nanoprecipitation, which reconstruct dissolved glucan chains into novel particles (Marta et al., 2023). Acid hydrolysis is valued for the high crystallinity and thermal stability of its output, but long reaction times and the generation of acidic waste pose challenges for its environmental sustainability (Marta et al., 2023). On the other hand, nanoprecipitation is relatively fast and scalable, with a narrow size distribution; however, it depends on the infrastructure of organic solvent recovery (Chen et al., 2024). Ultrasonication and enzymatic hydrolysis are recommended as more environmentally friendly and chemically efficient processes, but ultrasonication might lead to particle reaggregation, and enzymatic processes are typically more expensive and slow (Ullah et al., 2022; Li et al., 2023). Physical and solvent-free methods like high-pressure homogenization, gamma irradiation and ball milling are appealing for industrial consistency, but they are energy-demanding and often give broader, less uniform particle size distributions. Researchers are increasingly combining two treatment methods (e.g., acid pre-treatment followed by ultrasonication, or enzymatic pre-treatment followed by homogenization) to utilize synergistic mechanisms, resulting in smaller particles and higher crystallinity compared to using a single process (Li et al., 2023; Chen et al., 2024).

Factors Governing Starch Nanoparticle Properties

Because SNPs performance is affected by the particles fabrication, it is convenient to define the variables that determine their final physicochemical properties as shown in Fig. 2. The botanical origin determines the inherent ratio of amylose to amylopectin and granule structure, which sets the stage for any further processing. The main mechanism of size reduction is determined by the chosen preparation technique (acidic, enzymatic, mechanical, acoustic or precipitation) and the degree of reduction is fine-tuned by processing variables such as reaction time, temperature, acid or enzyme concentration and sonication intensity. Other treatment parameters like the cross-linking density, the presence of stabilizing surfactants, and the drying process for final recovery also influence particle size, surface charge, and extended colloidal stability. Researchers can rationally design SNPs with desired particle size, crystallinity or surface chemistry, instead of trial-and-error approach, by understanding the interplay of these factors.

Future Prospectus

The future of starch nanoparticles depends on a variety of priorities that will determine if they will evolve from experimental novelty into a common industrial component. There is first a great challenge in scaling-up. Most of the high-yield techniques (acid hydrolysis, enzymatic treatment) are slow while the faster physical techniques (homogenization, milling) require a lot of energy.

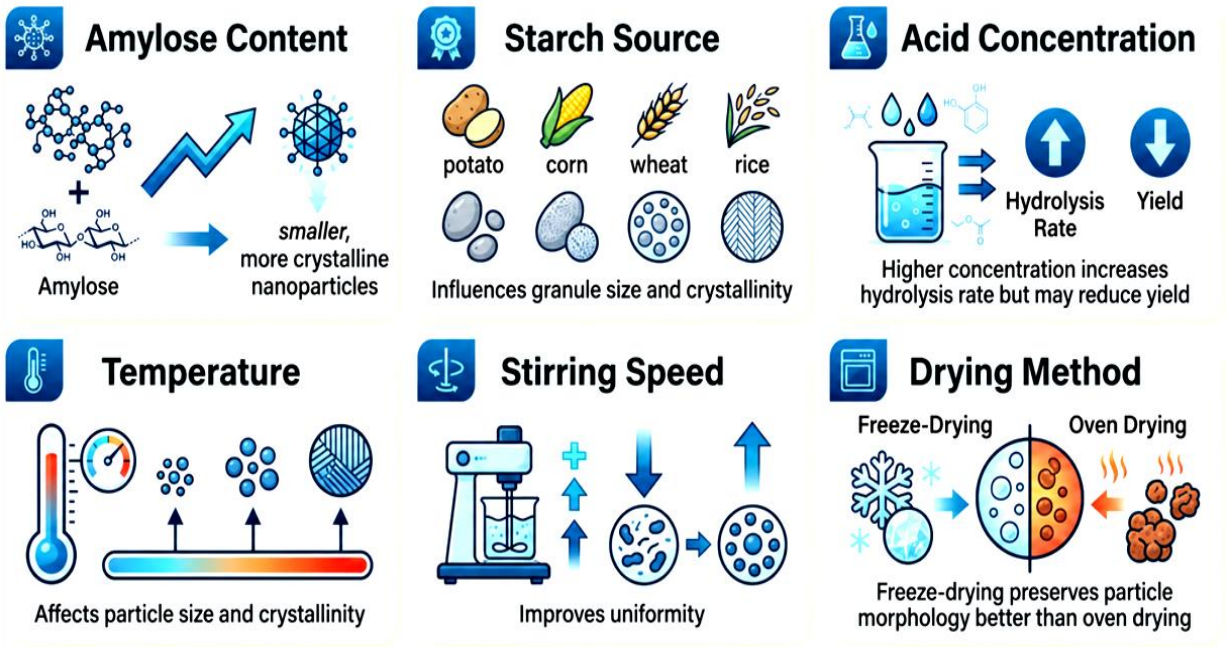


Fig. 2. Key factors - botanical source, preparation method, processing parameters, cross-linking, and drying technique - that govern the final size, crystallinity and stability of starch nanoparticles.

This leads to a search for continuous-flow and extrusion-based processes as a way to produce on an industrial scale at a reasonable cost. Secondly, toxicological and biodistribution data are still lacking, and with the global definition of regulations on nanoparticles, SNPs targeting food or biomedical applications will need standardized safety and migration assessments before being approved for use. Thirdly, there is growing interest in combining different therapies (e.g. enzymatic pre-treatment with high pressure homogenization) to benefit from each, while minimizing their individual limitations, and in substituting organic solvents with deep eutectic solvents or fully aqueous systems to improve environmental sustainability.Computational and data-driven tools are beginning to be applied to formulate nanostarch, such as machine-learning assisted optimization of processing parameters, which can greatly decrease development times for application-specific particles. For starch nanoparticles to realise their potential as a genuinely sustainable nanomaterial platform for food, pharmaceutical, packaging and agricultural applications, they will need to overcome the challenges of scale-up, safety, sustainability and optimisation in parallel. With the fast development of novel botanical sources, hybrid processing techniques and characterization methods, starch nanoparticles are expected to transition from a largely academic topic to a commercially viable class of sustainable nanomaterials within the next decade, if there continues to be interdisciplinary collaboration between food scientists, polymer chemists, toxicologists and process engineers to bridge the gap between laboratory synthesis and industrial application.

Conclusion

In summary, the synthesis of starch-based nanoparticles is an example of the transformation of a single renewable polysaccharide into a variety of nanomaterials with tunable dimensions, crystallinity and surface chemistry for specific purposes, through judiciously chosen physical, chemical or enzymatic routes. The interplay between the preparation technique, the influencing physicochemical parameters and the subsequent functionality provides a consistent design rationale that continues to guide ongoing investigations in this rapidly advancing field.

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Omics and Data Driven Approaches in Food Fraud Detection

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Summary of Article

Food fraud is an emerging nuisance worldwide, majorly with socio-economic motives are being the main causes of adulteration of the high-value commodities, including milk. The traditional detection methods are a setback in detecting complexes or low-level concentrations, such as the melamine, ethylene glycol and contaminated edible and are often time consuming. Omics based approaches, especially metabolomics, proteomics, lipidomics and genomics, are ideal in this regard as they allow the characterization of a complete biochemical finger print of food products and to detect subtle deviations from authentic reference food profile. These multi layered datasets, when used in conjunction with advanced analytical methods and artificial intelligence or machine learning algorithms, can be converted to powerful decision-making tools for the food authenticity assessment and fraud prevention. This article presents an overview on the integrated omics and data driven approaches and their impact on the food fraud detection and their potential for use in normal use in modern food supply chain.

Keywords: Food Fraud, Food Authenticity, Metabolomics, Spectroscopy, Machine Learning Algorithms.

Introduction

Food fraud is defined as any act of adulteration, substitution, tampering or mislabelling of food products, which is intentionally done to gain an economic advantage, typically to make low-grade food appear as a higher grade. It happens throughout the global food system and can have a profound impact on food safety authorities' trust, consumer health, and trust. To proactively identify and prevent such incidents, a risk management is established. Vulnerability Assessment and Critical Control Points (VACCP) is opted as a risk management which is broadly adopted to respond to economically motivated adulteration, systematically identifying and managing the points in the supply chain where adulteration is most likely to occur.

There are several categories of food fraud-related risks that serve to distinguish it from other food production problems (Spink et al., 2019) like the food quality risk refers to non-intentional deviations from product specifications which may not cause harm but are not in compliance with the requirements. Food safety risk is an unintentionally introduced contamination or failure in the process that can lead to the production of a product that could cause illness if consumed. Food defence risk is related to intentional contamination, which can be done with the aim of doing harm, including acts of bioterrorism. In fact, many actual food fraud incidents demonstrate the various types of food fraud reported around the world, such as dilution, substitution, mislabelling and adding of unlisted adulterants, as illustrated in figure 1 (Onyeaka et al., 2022). At times like these, it is clear that there is a demand for strong, up-to-date and sophisticated tools to identify clear and hidden fraud in increasingly complex food supply chains.

Omics Approaches in Food Fraud Detection

Omics approaches provide detailed molecular descriptions of the biochemical components present in food products. When combined with appropriate analytical technologies, they offer critical information on the composition and integrity of foods and can reveal whether a product has been adulterated or misrepresented. Different omics disciplines contribute complementary insights:

Proteomics - the study of peptides and proteins, including their structures, functions and behaviour in different food matrices.

Lipidomics - the investigation of lipid species and metabolic pathways in lipid networks.

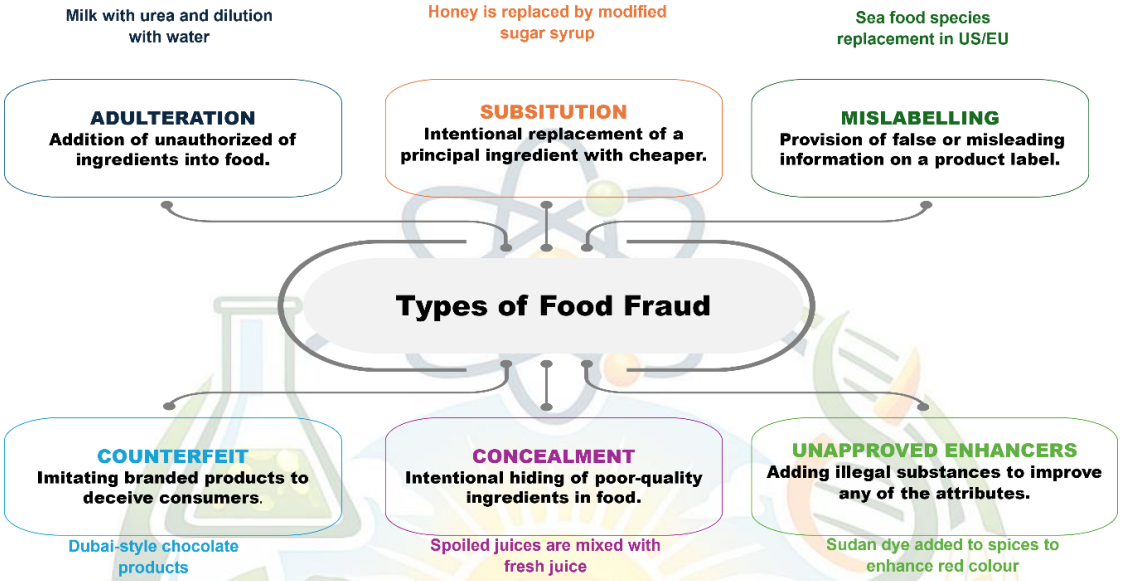
Metabolomics - the molecular interpretation of small molecules and metabolites that reflect the biochemical state of a food product.

Genomics - the analysis of DNA and genomic structures, often used to confirm species identity and origin.

Metabolomics Fingerprinting of Detection

Metabolomics can offer a 'chemical profile' of a food product which reflects the food's metabolic composition. Detection involves comparison of the metabolite profile of the sample with the profile of metabolites from the authentic products, and metabolites can be used to detect identity and integrity (Selamat et al., 2021). There are two approaches: Untargeted metabolomics - Search for as many metabolites as possible, including the ones that are unknown or

unexpected. Since there are not many known metabolites, an untargeted study often requires sophisticated chemometric analysis of the large number of data points to be able to interpret the complex signals into smaller groups of variables. It can be very effective for finding new markers for adulteration, but can be difficult for definite identification and interpretation. Targeted metabolomics targets a specific group of metabolites whose chemical properties, biological functions and pathway interactions have been well established. Targeted analysis is more precise, selective and reliable, as metabolites are quantified that are related to authenticity or adulteration. The metabolomics tests are generally carried out on NMR or MS platform, which is used to determine the concentrations and polarity of metabolites in tissues or food matrices. In practice, application of untargeted and targeted metabolomics can be combined, with untargeted metabolomics first identifying possible authenticity markers and then targeted metabolomics confirming and quantifying them, which enhances the authenticity detection accuracy of food fraud detection.



Integration with AI and Machine Learning of Advanced Omics Techniques

AI techniques, such as deep learning models and machine-learning algorithms, enable the extraction of hierarchical features that are able to discriminate between authentic and adulterated samples, identify biomarkers specific to adulterant, and detect subtle changes in datasets created by analytical techniques (Yetgin, 2025). The Multiple Co-Inertia Analysis (MCIA), DIABLO, JIVE and Sparse Generalized Canonical Correlation Analysis (SGCCA) are machine learning applications that combine different omics data with chemical and spectroscopic data to enhance the detection of adulterants. Algorithms such as Random Forest, Support Vector Machines and Gradient Boosting are used for the model validation on complex datasets derived from FT-IR, NIR, NMR, chromatographic and mass spectrometry techniques, which are suitable tools for routine authenticity testing (Becchi et al., 2025).

Conclusion

Occupational opportunities for economically motivated adulteration in the food supply are varied and the best way to combat food fraud is to take a proactive approach to control rather than relying on end product testing alone. Omics approaches and data-driven tools, coupled with advanced analytical methods like FT-IR, NMR and MS, can significantly diminish the potential for food authenticity fraud by delivering fast, non-destructive and highly informative food authenticity assessments. In particular, metabolomics can be used to analyse small chemical compounds in comparison to reference samples in detail, and even AI or machine-learning algorithms can transform the complex data into useful decision-making models. Both targeted and untargeted metabolomics approaches are indispensable; untargeted analyses can be used to identify new markers for the detection of adulteration, and targeted analysis can be used to accurately quantify and confirm markers already known. Integrated, non-destructive analytical techniques, combined with multi-omics approaches, represents a promising approach for effective food authentication without destroying the sample. These tools are more accessible and easier to use and can help in routine monitoring, consumer protection and building trust in modern food supply chains.

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Breaking into a Fig: Inside the Hidden World of Pollinating Fig Wasps

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Abstract
Hidden within every fig unfolds one of nature's most remarkable partnerships. The solitary pollinating fig wasp, though only a few millimetres long, embarks on an extraordinary journey into the enclosed flowers of a fig syconium, ensuring the survival of both its own species and the fig tree. This article explores the hidden life of these tiny wasps, their remarkable adaptations, and their long-standing association with figs. It also highlights how their role extends beyond pollination, supporting fig-dependent food webs and underscoring the importance of conserving the intricate ecological relationships that sustain India's growing fig industry.

Keywords: Pollinating fig wasp; *Ficus*; *Agaonidae*; Fig–wasp mutualism; Coevolution; Fig Syconium.

Introduction
Fig trees (*Ficus* L.) are keystone species in tropical ecosystems, relying on specialised pollinating fig wasps (Hymenoptera: Agaonidae) for reproduction through an obligate mutualistic partnership. At present, the family *Agaonidae* comprises approximately 380 described species classified under four subfamilies: *Agaoninae*, *Blastophaginae*, *Kradibiinae*, and *Tetrapusinae* (Rasplus *et al.*, 2025). India harbours nearly 18% of the world's known fig wasp species, recorded from only about 26% of its native *Ficus* species. With almost three-fourths of Indian fig species still unexplored, the country's fig wasp diversity remains a promising frontier for research (Pramanik and Dey, 2016). Pollinating fig wasps have been recorded for only about 28% of the 89 described *Ficus* species in India, leaving the remaining 72% yet to be documented (Satheesan and Santhosh, 2019).

Types of Fig Crops Based on Pollination
Based on their pollination requirements, figs also called "anjeer" or "dumur" are grouped into four categories.

1. Common figs bear only female flowers and produce fruits without pollination, making them the most widely cultivated commercial type because they eliminate the need for caprification.

2. Caprifigs are the wild male figs that contain both male and short-styled female flowers. They serve as the breeding site for pollinating fig wasps and provide the pollen needed for pollination.

3. Smyrna figs depend entirely on pollination from caprifigs to develop normal fruits.

4. San Pedro figs produce an early crop without pollination, while the later crop requires pollination to mature properly (Aradhya *et al.*, 2010).

Smyrna Figs in India: Imported Rather Than Cultivated
Although Smyrna figs are available in the Indian market, particularly as premium dried fruits imported from countries such as Türkiye, they are rarely cultivated commercially in India. The primary reason is their complete dependence on the specialised pollinating fig wasp *Blastophaga psenes* for fruit development. In the absence of this wasp and the associated caprification system, immature Smyrna fruits fail to develop and are shed before ripening (Aradhya *et al.*, 2010). Consequently, commercial fig cultivation in India is dominated by parthenocarpic common fig cultivars, including Poona, Brown Turkey, Conadria, and Dinkar, which produce fruits without pollination. These varieties are extensively grown in major fig-producing states such as Maharashtra, Gujarat, and Karnataka, where they offer dependable yields without the need to maintain the specialised fig–wasp mutualism.

From Ecology to Economy
India's dried fig market has shown consistent growth in recent years, recording a compound annual growth rate (CAGR) of 4.01% between 2020 and 2024, with growth accelerating to 4.61% from 2023 to 2024 (6Wresearch, 2026). While premium Smyrna figs continue to be imported, Indian farmers cultivate mainly parthenocarpic varieties that do not depend on pollination, ensuring reliable and economical fruit production. The Indian fig industry illustrates how a tiny pollinating wasp can influence an entire production system. The fig–wasp partnership is therefore more than a biological wonder; it directly influences crop choice and cultivation practices.

The Clockwork of the Fig

The fig syconium develops in perfect synchrony with the life cycle of its pollinating wasps. It first opens a brief window for pollination, then becomes a protected nursery where the wasps lay eggs and their offspring complete development. Only after the new females have mated, collected pollen, and departed does the fig begin to ripen. Rising ethylene levels trigger fruit softening, making the ripe figs attractive to birds and other fruit-eating animals that disperse the seeds. By postponing ripening until the wasps have safely left, the fig ensures both successful pollination and efficient seed dispersal, making this partnership a remarkable example of evolutionary coordination.

Built for Life Inside a Fig

Female fig wasps possess broad wings that help them glide with air currents over long distances in search of receptive fig trees. Their antennae are equipped with highly sensitive olfactory receptors that detect the unique chemical signals released by their host figs, enabling them to locate the right tree even in dense forests. To enter the fig, females rely on strong toothed mandibles, spines, and specialized leg structures that allow them to crawl through the narrow, bract-lined ostiole. In many species, female wasps also possess specialized pollen-carrying structures that enable efficient pollination (Kjellberg *et al.*, 2001). Once inside the syconium, the wingless males use their powerful legs to move through the tightly packed flowers and reach the galls containing the females. Together, these specialized adaptations highlight how millions of years of coevolution have perfectly equipped fig wasps for every stage of their extraordinary life cycle.

An Evolutionary Lock and Key

The length of the wasp's egg-laying organ has evolved to match the flower structure of its host fig, ensuring that eggs are placed in the right flowers for successful development. Fig trees have evolved two different reproductive strategies, each closely linked to the life cycle of their pollinating wasps. In monoecious fig species, both male and female flowers are found within the same syconium, allowing seeds and wasp offspring to develop together. In gynodioecious species, such as the common edible fig (*Ficus carica*), male and female flowers occur on separate trees. Male trees produce pollen and provide a breeding site for the wasps, while female trees produce seeds. Although female wasps enter both types of figs, they can lay eggs only in the male figs because their flowers have shorter styles. The longer styles of female figs prevent egg-laying, ensuring successful seed production. Over time, this difference has driven the evolution of longer ovipositors in wasps associated with monoecious figs than in those pollinating gynodioecious species (Weiblen, 2001).

Breaking into a Fig

Female fig wasps are specially adapted to squeeze through the ostiole, often losing their wings and parts of their antennae during the journey. Inside the syconium, they lay eggs in some flowers while pollinating others, either passively or by actively transferring pollen carried from the fig where they developed (Jansen-González *et al.*, 2012). Most females die after completing this task, making their entire adult life devoted to pollination and reproduction.

A Nursery Hidden Within the Fig

Once an egg is laid, each developing fig wasp larva occupies a single flower, which transforms into a protective gall that serves as both its home and food source (Jansen-González *et al.*, 2012). The growing larva feeds on the nutrient-rich tissues inside the gall, which form after pollination and may also be stimulated by chemicals associated with the wasp egg or the developing larva itself. Once development is complete, the wingless males emerge first, followed shortly by the winged females to mate before leaving the fig to begin the next generation.

The Final Mission Before Leaving

Emerging ahead of the females, the wingless males remain inside the fig until their sister females begin to emerge from their galls. They then mate with them using their specialized telescopic abdomen (gaster) (Rasplus *et al.*, 2025). In one final act of service, the wingless male chews an escape tunnel through the fig wall, before dying inside the syconium. The newly emerged, pollen-carrying females finally depart in search of another receptive fig.

The Journey to a New Fig

The female wasps emerge just as the fig's male flowers release pollen, allowing them to collect it before departure. Carrying mature eggs and living for only one or two days, they must quickly locate another receptive fig, where they pollinate its flowers while laying eggs, restarting the life cycle.

A Delicate Partnership Under Threat

Female fig wasps may travel several kilometres, often carried by wind, to find another receptive fig. However, their short lifespan makes them highly vulnerable to rising temperatures and drought, which can reduce survival and disrupt the fig–fig wasp partnership. Such disruptions could affect many animals that depend on figs as a year-round food source (Gigante *et al.*, 2020).

Conclusion- The Guardians of Forest Biodiversity

Though only a few millimetres long, pollinating fig wasps play an indispensable role in sustaining both fig trees and the countless forms of life that depend on them. By ensuring successful pollination, they support forests where figs provide a year-round food source for a remarkable diversity of wildlife. Their partnership with fig trees also underpins the production of economically important edible figs, highlighting how these tiny, often overlooked insects quietly contribute to biodiversity, healthy ecosystems, and economic viability of fig cultivation.

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Regenerative Agronomy: Cover Crops, Biochar, and Microbes for Soil Carbon Sequestration and Soil Health

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Abstract

The current state of the agricultural sector is becoming increasingly complicated due to the problems with soil degradation, changing climate, biodiversity loss, and growing food demands. Intensive tillage, excessive use of artificial fertilizers, and monocropping practices cause fast depletion of SOC and weaken the biological functions of the soil ecosystems. The approach of regenerative agronomy offers an innovative and holistic way to restore the health of the soil and maintain productive crop yields at the same time. Regenerative agriculture uses various methods such as the introduction of cover crops, biochar, and beneficial soil microorganisms. Cover crops prevent soil erosion, promote nutrient cycling, and provide soil with the new amounts of organic carbon from roots and residues. Biochar – a stable carbon-containing product of biomass pyrolysis – improves the soil structure, its nutrient content, provides a habitat for microorganisms, and helps to store the carbon in the soil for a long time. Beneficial soil microorganisms – plant growth promoting rhizobacteria, mycorrhizal fungi, and nitrogen-fixing bacteria – help to cycle nutrients, improve the aggregation, and stabilize organic matter. Combined, these practices help to improve the biological activity of the soil, efficiency of nutrients use, carbon sequestration, and resistance to drought and climate change. This paper is devoted to investigating how these practices contribute to improved soil health, carbon storage, and sustainable agricultural productivity.

Introduction

Agriculture faces multiple problems today which are related not only to food production but also to many other issues. Changing climate, decreasing soil fertility, biodiversity loss, and increasing pressure on natural resources make conventional farming systems unsustainable. Many decades of intensive tillage, monocropping, excessive use of fertilizers, and residue removal resulted in the depletion of soil organic carbon by 25-75% (Lal, 2004). Such soil degradation not only decreases soil fertility but also leads to the increase of carbon dioxide in the atmosphere, thus contributing to climate change. Soil represents one of the biggest terrestrial carbon reservoirs and stores more carbon than the atmosphere and vegetation together. Therefore, the increase in soil organic carbon may not only improve agricultural productivity but also decrease greenhouse gas emissions (Lal, 2020). Such approach has led to changing agricultural researches in a direction of regenerative approach.

The main idea of regenerative agronomy is to restore soil as a living ecosystem. Instead of using external chemical inputs, regenerative agronomy focuses on the biological processes which will naturally improve soil fertility, nutrient cycling, and soil ecosystem resilience. Such practices as continuous soil cover, diverse crop rotations, minimal soil disturbance, organic amendments, and improvement of microorganism communities allow restoring ecological balance and keeping profitable crop production. Among numerous regenerative practices, three show a great potential and consistently bring results: cover crops, biochar, and beneficial soil microorganisms. Each of the practices individually improves the quality of soil by different means. Cover crops provide new amounts of organic carbon and protect soil from erosion. Biochar provides a highly stable form of carbon and improves soil physical and chemical properties. Beneficial microorganisms increase the nutrient cycling, organic matter stabilization, and plant growth. Combining all these practices together, one can get a biologically active soil system that will be able to support productivity and increase carbon storage (Lehmann et al., 2015).

Concept and Principles of Regenerative Agronomy

Regenerative agronomy is focused not only on sustaining agricultural productivity but also on the restoration of ecological functions of degraded soils. Unlike conventional agriculture, which often focuses on short-term yields by means of external inputs, regenerative systems restore natural soil processes which support long-term productivity. The core principles of regenerative agronomy are as follows: minimize soil disturbance, keep continuous soil cover, diversify cropping systems, keep living roots throughout the year, recycle crop residues, and encourage beneficial soil organisms. These practices increase the amount of soil organic matter, improve nutrient cycling, increase biodiversity, and increase ecosystem resilience.

One of the major features of regenerative agriculture is its focus on biological processes. Beneficial microorganisms help with nutrient mobilization, suppression of soil-borne diseases, improvement of soil structure, and decomposition acceleration. Such processes allow increasing nutrient availability and creation of stable soil organic matter. Continuous recycling of crop residues, compost, manure, and biochar provides a circular nutrient economy and prevents nutrient

losses because of erosion or residue burning. This approach decreases dependence on external inputs, greenhouse gas emissions, and improves sustainability of agricultural systems.

Soil Carbon Sequestration and Soil Organic Carbon Dynamics

In the recent years, soil science had undergone significant changes in understanding of carbon stabilization. Earlier, the theory was that stable carbon mostly consisted of chemically resistant plant residues. Nowadays, the evidence shows that microbial processes play much bigger role in carbon stabilization. Microorganisms transform plant-derived carbon into microbial biomass and necromass that become attached to mineral particles or encapsulated in soil aggregates and, thus, become stabilized for decades (Lehmann et al., 2020). So carbon sequestration depends on maintenance of positive balance between carbon input and carbon loss. Carbon is constantly taken from the soil due to microbial respiration, erosion, intensive tillage, and crop harvest. Regenerative farming increases carbon inputs while minimizing losses and, thus, rebuilding soil organic carbon stocks.

Soil carbon sequestration increases almost all the parameters of soil quality. It increases aggregate stability, water infiltration and water-holding capacity, nutrient retention, erosion prevention, and biodiversity of microorganisms. In such a way, increasing soil carbon became one of the most efficient strategies to improve soil productivity, restore degraded land, and mitigate climate change (Lal et al., 2020).

Role of Cover Crops in Regenerative Agronomy

Cover crops are grown to improve soil quality rather than for economic purposes, so it is one of the most important components of regenerative agriculture. Their main advantage is growing of living roots for most of the year. Root exudates such as sugars and amino acids feed beneficial soil microorganisms, increase nutrient cycling, and help in soil organic carbon formation.

Cover crops prevent soil erosion by reducing the impact of rainfall and soil stabilization by root systems. Higher organic matter improves water infiltration, decreases evaporation, and increases moisture storage which allows crops withstand drought conditions. Cover crops help to conserve nutrients by decreasing leaching and improving nutrient availability. Deep-rooted species such as cereal rye can recover nitrate from deep soil layers while legumes like clover and hairy vetch can fix atmospheric nitrogen by symbiosis with Rhizobium bacteria. While the residues are decomposing, nutrients are released to subsequent crops while increasing soil organic matter.

Different cover crop species can have different influences on the soil, however, all of them combined contribute to the health of the soil ecosystem. Leguminous crops such as clover, hairy vetch, cowpea, sunn hemp, and field pea are rich in nitrogen and provide nitrogen-enriched biomass, whereas grasses such as cereal rye, oats, barley, sorghum-sudangrass, and annual ryegrass provide carbon-enriched mulch to the soil. Furthermore, brassicas such as mustard, forage radish, and turnip contribute to the improvement of the soil structure by breaking up the compacted soil, reducing soil-borne pest infestation. Multispecies cover crop mixtures that include legumes, grasses, and brassicas are becoming increasingly popular due to their potential to improve microbial diversity, balance the ratio between carbon and nitrogen, and improve soil carbon budget. In addition, cover crops constitute the key component of regenerative agriculture since they contribute to protecting the soil, increasing the soil's biodiversity, and creating optimal conditions for such practices as biochar application.

Types of Cover Crops and their Ecological Functions

Cover crops refer to a group of different plant species which can be grown in a certain region depending on the climatic characteristics, crop rotations, and agronomic practices. Legumes such as clover (*Trifolium* spp.), hairy vetch (*Vicia villosa*), cowpea (*Vigna unguiculata*), sunn hemp (*Crotalaria juncea*), and field pea (Pisum sativum) are used to fix nitrogen in the soil. Such crops enrich the soil with nitrogen using their roots as well as by adding it through biomass incorporation into the soil. On the other hand, grasses such as cereal rye (*Secale cereale*), oats (*Avena sativa*), barley (*Hordeum vulgare*), sorghum-sudangrass, and annual ryegrass (*Lolium multiflorum*) use their fibrous roots to improve soil structure. The carbon-rich residue left in the soil contributes to organic matter accumulation. Brassicas such as mustard (*Brassica juncea*), forage radish (*Raphanus sativus* var. *longipinnatus*), and turnip (*Brassica rapa*) are yet another group of cover crops that help to improve the soil structure by using their tap roots to break up the soil structure. Certain species of brassicas such as mustard have the capability to produce pesticides that help to destroy some soil-borne pests. Multispecies mixtures of legumes, grasses, and brassicas become increasingly popular as cover crops because of their capability to improve microbial diversity, create a balanced ratio between carbon and nitrogen, and build the soil carbon budget. In addition, such cover crop mixtures help to protect against frost, drought, and weeds.

Biochar: A Stable Carbon Amendment for Regenerative Agriculture

Biochar has become one of the most prospective amendments in the context of regenerative agriculture because it can help to improve the soil as well as to accumulate large amounts of carbon for very long periods. Biochar is produced from such sources as crop residues, wood chips, and manure under high temperatures without oxygen (pyrolysis). Biochar usually contains large amounts of carbon and thus helps to make the soil fertile while serving as carbon sinks. The fact

that carbon in the biochar is accumulated in the form of charred organic matter helps to make it a very appropriate material for carbon storage (Lehmann et al., 2015). The benefits from the biochar application are determined not only by the properties of the feedstock used to make it but also by the temperature of the pyrolysis process (Lehmann et al., 2015). Therefore, it is very important to know what kind of biochar is suitable for the specific soil taking into account its physiochemical characteristics. Biochar improves the physiochemical properties of the soil in a number of ways.

Physically biochar reduces soil density while improving its water-retention capacity and aeration. These aspects are particularly important in sandy and dry soils in which the capacity to retain water is low, and water is the main limiting factor for agricultural production. Application of biochar to such soils increases the water-retention capacity of the soil and the ability to retain nutrients while also improving soil aeration. Chemical properties of biochar help to increase the CEC and reduce soil erosion and nutrient leaching (Lehmann et al., 2015). For example, in the case of acid soil, biochar can help to increase soil pH making it less acid and thus making phosphorus and magnesium available in the soil. In addition, biochar's porous structure can create favourable conditions for beneficial microorganisms (bacteria, fungi, and actinomycetes) which play a key role in maintaining the health of the soil. Providing the proper environment for these microorganisms biochar helps to increase the rate of decomposition of organic materials in the soil and facilitates the nutrient cycle (Lehmann et al., 2015). Beside the ability to improve soil properties, biochar is also a valuable tool for mitigating the consequences of climate change due to its capacity to store large quantities of carbon.

Beneficial Soil Microorganisms in Regenerative Agronomy

Soil microorganisms play an essential role in maintaining soil health since they help to decompose organic matter, participate in nutrient cycle and facilitate biological processes in the soil. There are various kinds of soil microorganisms such as bacteria, fungi, actinomycetes, protozoa, and archaea with their respective roles in the soil ecosystem. Modern soil microbiology highlights the importance of these microorganisms for improving soil structure and fertility and increasing the ability of long-term carbon sequestration (Lehmann et al., 2020). There are many species of bacteria which are beneficial for agricultural production, among them are plant growth-promoting rhizobacteria (PGPR). Species of bacteria such as *Bacillus*, *Pseudomonas*, *Azospirillum*, and *Paenibacillus* play a key role in promoting the growth of plants by different mechanisms such as nitrogen fixation, production of plant growth hormones, synthesis of siderophores and suppressing the growth of soil-borne pathogens. This helps to increase the productivity of plants and thus their biomass which can be used to build fertile soil.

It is also important to note the importance of mycorrhizal fungi in the soil because they help most plant species absorb nutrients from the soil. Arbuscular mycorrhizal fungi (AMF) help in improving the phosphorus, zinc, and copper condition of plants while at the same time improving their tolerance to drought and salinity. Mycorrhizal fungi are also important in the carbon cycle as the glycoproteins produced by the hyphae of the fungi referred to as glomalin help to bind the organic matter and stabilize it to protect carbon in the soil from being lost to the atmosphere (Rillig et al., 2002). Other important soil microorganisms include nitrogen-fixing bacteria such as Rhizobium, *Bradyrhizobium*, *Azotobacter*, and *Azospirillum* spp. These bacteria help in fixing the atmospheric nitrogen to make it useful for plants. Nitrogen fixed by these bacteria is then used by the plants to produce other metabolites, thus improving crop yield. Decomposer fungi and actinomycetes are also important as they help break down plant material such as lignin, cellulose, and other organic matter to form rich humus.

Synergistic Interactions Among Cover Crops, Biochar, and Soil Microbes

Cover crops and biochar are two crucial components of regenerative agriculture, but they become even more valuable when used together with certain soil microbes. Although each of these components has its own role in making the soil fertile and healthy, their combined effect is much more powerful because of the synergistic interactions between them. Cover crops help to increase the supply of fresh organic matter to the soil as mulch and serve as a carbon source for microorganisms. Biochar is also an important component since it provides a stable environment for the proliferation of beneficial soil microbes and helps retain carbon in the form of char. Soil microbes help decompose mulch added to the soil through cover cropping and biochar application and make nutrients available to plants while producing stable carbon suitable for long-term sequestration in the soil. In addition, biochar is important in improving mycorrhizal colonization while also helping to improve the growth of nitrogen-fixing and phosphate-solubilizing bacteria.

Contribution to Soil Health

Ultimately, the success of regenerative agriculture is determined by improvements in soil health. Healthy soils work as living ecosystems able to support crop productivity and environmental quality. Through regenerative practices, soils experience changes in terms of their physical, chemical, and biological state at the same time. Physical changes include increased organic matter that enhances soil structure, aggregate stability, porosity, infiltration, water-holding capacity, and resistance to erosion. Soil structure improves as well allowing plants to penetrate roots deeper and get moisture and nutrients from the soil. Chemical changes include increased soil organic carbon that enhances nutrient retention, cation exchange capacity, and buffering capacity while at the same time decreasing nutrient losses as a result of runoff and leaching. Therefore, fertilizer-use efficiency is increased thus reducing production costs and environmental

pollution. Biological changes are characterized by increased microbial biomass, earthworm populations, enzyme activities, and diversity. All these changes lead to faster nutrient cycling, decreased number of soil-borne diseases, and healthier root systems.

Climate Change Mitigation and Carbon Sequestration

Agriculture is both susceptible to climate change effects and responsible for greenhouse gas emissions. Regenerative agronomy represents an opportunity to mitigate the greenhouse gas emissions while increasing agricultural productivity at the same time. Cover crops help to increase the input of carbon through continuous photosynthesis and root growth. Biochar provides a highly stable carbon pool remaining in the soil for centuries, while soil microorganisms help transform fresh organic residues into mineral-associated organic matter persisting for a long time. All these processes lead to an increase in soil carbon content and reduction in atmospheric CO_2 concentration. Environmental benefits also appear in decreased fertilizer usage, reduced fuel consumption as a result of reduced tillage, improved nutrient-use efficiency, and organic residues recycling. Therefore, regenerative agriculture not only mitigates climate change but also helps in sustainable food production and ecosystem restoration.

Challenges and Future Prospects

Regenerative agronomy has great potential but there are several practical challenges associated with it. First, it is expensive, people are not familiar with it, have inadequate knowledge and variable results in different soils and climates. Benefits of such practices as cover crops and biochar appear only after several growing seasons, therefore, it is difficult to adopt them in those areas where immediate economic benefits are expected. In addition, biochar varies in quality with feedstock and production method, while microbial inoculants are inconsistent in performance due to soil conditions and competition with indigenous microorganisms. Future research should focus on location-specific management, improved microbial formulations, standardized biochar production, and soil health assessment. Genomics, remote sensing, artificial intelligence, and precision agriculture will help to advance regenerative farming. Carbon credit programs, supportive government policies, farmer training, and extension services are also necessary for its widespread adoption and successful implementation.

Conclusion

Regenerative agronomy is an approach to restore degraded soils and maintain crop productivity. Cover crops, biochar, and beneficial soil microorganisms help to increase the amount of organic carbon in the soil, improve nutrient cycling, soil structure, and increase the resilience to climate variability. Cover crops provide organic matter and soil protection, biochar helps to increase carbon persistence while improving soil quality, and beneficial soil microorganisms help in nutrient transformations and organic matter stabilization. All these approaches create biologically active soils. As food security issues, land degradation and climate change become more intense, regenerative agronomy will become increasingly important. Research, innovations, supportive policies, and farmer extension services will be needed to realize its potential.

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Climate-Smart Agronomy: Conservation Agriculture and Digital Tools for Crop Resilience Under Climate Change

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Abstract
Climate change has emerged as one of the most significant threats to global agricultural productivity, food security, and environmental sustainability. Increasing temperatures, erratic rainfall patterns, prolonged droughts, floods, and frequent extreme weather events have adversely affected crop production across diverse agroecosystems. These climatic uncertainties demand innovative agricultural approaches capable of improving productivity while enhancing resilience and minimizing environmental degradation. Climate-smart agronomy has gained global recognition as a comprehensive strategy that integrates sustainable crop management practices with advanced digital technologies to improve agricultural resilience under changing climatic conditions. Conservation agriculture, characterized by minimum soil disturbance, permanent soil cover, and diversified crop rotations, contributes significantly to improving soil health, conserving water, increasing carbon sequestration, and stabilizing crop yields. Simultaneously, digital technologies including remote sensing, geographic information systems, artificial intelligence, Internet of Things, drones, satellite monitoring, precision agriculture, and decision support systems enable real-time crop monitoring, efficient resource utilization, and climate-informed farm management. The integration of conservation agriculture with digital tools offers a promising pathway for sustainable intensification by enhancing productivity while reducing greenhouse gas emissions and production risks. This review discusses the principles of climate-smart agronomy, the role of conservation agriculture in enhancing crop resilience, recent advances in digital agriculture, their synergistic integration, current challenges, and future prospects for achieving climate-resilient agricultural systems.

Introduction
Agriculture is among the sectors most vulnerable to climate change because crop growth and productivity are directly influenced by climatic variables such as temperature, rainfall, humidity, solar radiation, and atmospheric carbon dioxide concentration. During recent decades, increasing climatic variability has intensified the occurrence of droughts, heat waves, floods, cyclones, salinity intrusion, and irregular precipitation patterns, leading to considerable yield instability in both rainfed and irrigated farming systems. The Intergovernmental Panel on Climate Change has projected that global agricultural productivity may decline substantially during the twenty-first century unless effective adaptation and mitigation strategies are widely adopted (IPCC et al., 2022).

Developing countries are particularly susceptible because agriculture continues to support the livelihoods of millions of smallholder farmers who depend heavily on natural resources. In countries such as India, where agriculture contributes significantly to employment and rural income, climate-induced production risks threaten food security, nutritional security, and economic stability. Traditional production systems characterized by excessive tillage, intensive monocropping, indiscriminate fertilizer application, residue burning, and unsustainable water use have further aggravated soil degradation, declining organic carbon, biodiversity loss, and greenhouse gas emissions (Lal et al., 2020).

Climate-smart agriculture has emerged as an integrated framework that simultaneously addresses three interrelated objectives: increasing agricultural productivity, strengthening resilience to climate variability, and reducing greenhouse gas emissions wherever possible. Climate-smart agronomy represents the practical implementation of climate-smart agriculture through improved crop management, resource conservation, technological innovation, and sustainable farming practices. It seeks to optimize the interactions among soil, water, crops, climate, and technology to achieve resilient and environmentally sustainable production systems. Recent advances in digital agriculture have significantly transformed agronomic management by enabling precise monitoring of crop growth, soil moisture, nutrient status, pest incidence, and weather conditions. The integration of conservation agriculture with digital technologies creates opportunities for data-driven decision-making that improves productivity while reducing production risks under changing climatic conditions.

Climate Change and the Need for Climate-Smart Agronomy
Climate change affects every stage of crop growth, beginning with seed germination and continuing through vegetative growth, flowering, grain filling, and maturity. Rising temperatures accelerate crop phenology, shorten crop duration, reduce biomass accumulation, impair pollen viability, and decrease grain filling efficiency. Heat stress during flowering is particularly detrimental in cereals such as wheat, rice, and maize, often resulting in substantial yield losses. Altered

rainfall distribution increases both drought and flooding risks, while unpredictable weather complicates planting schedules and harvesting operations. Climate change also influences soil processes by accelerating organic matter decomposition, increasing erosion, reducing soil moisture availability, and altering nutrient cycling. Soil degradation decreases water infiltration, nutrient retention, and biological activity, thereby reducing crop resilience during climatic stress. Furthermore, changing climatic conditions modify pest and disease dynamics, allowing many insects, pathogens, and weeds to expand into new geographical regions and complete more life cycles annually.

These multidimensional impacts require agronomic strategies that enhance resource-use efficiency while improving adaptive capacity. Climate-smart agronomy emphasizes integrated soil management, efficient water utilization, climate-resilient crop varieties, diversified cropping systems, conservation agriculture, and digital decision-support technologies to sustain productivity despite increasing climatic uncertainty (FAO et al., 2013). Unlike conventional production systems that focus primarily on maximizing yield, climate-smart agronomy considers long-term ecosystem sustainability. It integrates scientific knowledge with technological innovations to improve productivity while maintaining soil fertility, conserving biodiversity, reducing environmental pollution, and enhancing farm profitability.

Conservation Agriculture as the Foundation of Climate-Smart Agronomy

Conservation agriculture has become one of the most effective agronomic approaches for enhancing agricultural sustainability under climate change. It is based on three interconnected principles: minimum mechanical soil disturbance, permanent soil cover, and diversified crop rotations. These principles function synergistically to improve soil quality, conserve natural resources, and strengthen resilience against climatic stresses. Unlike conventional intensive tillage systems, conservation agriculture minimizes soil disruption, thereby preserving soil structure, microbial diversity, organic carbon, and biological activity. Permanent retention of crop residues protects the soil surface against erosion, reduces evaporation losses, moderates soil temperature, and enhances water infiltration. Diversified crop rotations interrupt pest and disease cycles, improve nutrient cycling, and increase overall system productivity. Long-term experiments across diverse agroecological regions have demonstrated that conservation agriculture improves soil health while maintaining or increasing crop yields under water-limited conditions. Its benefits become particularly evident during drought years, when improved soil moisture retention enables crops to better withstand prolonged dry spells (Kassam et al., 2019).

Principles of Conservation Agriculture

The first principle involves minimizing soil disturbance by reducing or eliminating conventional ploughing operations. Excessive tillage disrupts soil aggregates, accelerates oxidation of soil organic matter, increases carbon dioxide emissions, and exposes soil to erosion by wind and water. Reduced tillage preserves soil structure, enhances microbial activity, and promotes earthworm populations that naturally improve soil aeration and nutrient cycling. Zero tillage has emerged as an important component of conservation agriculture in several countries, particularly for wheat cultivation following rice. Under zero tillage, seeds are directly placed into untilled soil using specialized seed drills. This practice reduces fuel consumption, labour requirements, machinery costs, and planting time while improving soil moisture conservation. Studies have reported that zero tillage can significantly reduce production costs while maintaining comparable or even higher yields under suitable management conditions (Hobbs et al., 2008).

The second principle involves maintaining permanent soil cover through crop residues, cover crops, or mulch. Crop residues reduce direct exposure of soil to solar radiation, decrease evaporation, suppress weed emergence, moderate soil temperature fluctuations, and protect against erosion caused by heavy rainfall. Residue retention also provides substrates for beneficial microorganisms, gradually increasing soil organic carbon and improving nutrient availability. Cover crops further enhance soil protection during fallow periods by reducing nutrient leaching, increasing biological nitrogen fixation in leguminous species, suppressing weeds, and improving soil aggregation. Their extensive root systems enhance soil porosity and water infiltration, thereby increasing drought resilience.

The third principle emphasizes crop diversification through systematic crop rotations and diversified cropping systems. Continuous monocropping often results in nutrient depletion, pest buildup, weed proliferation, and declining soil fertility. Crop rotations involving cereals, legumes, oilseeds, and vegetables improve nutrient balance, increase microbial diversity, reduce disease incidence, and enhance long-term productivity. Inclusion of legumes contributes biologically fixed nitrogen, reducing dependence on synthetic fertilizers while improving soil fertility.

Soil Health and Carbon Sequestration

Healthy soils represent the cornerstone of climate-resilient agriculture. Conservation agriculture contributes substantially to improving physical, chemical, and biological properties of soil. Reduced tillage minimizes soil compaction while preserving aggregate stability, resulting in improved root penetration and water infiltration. Retention of crop residues increases soil organic matter, which serves as a major reservoir of plant nutrients and enhances water-holding capacity. Higher organic matter also supports diverse microbial communities responsible for nutrient mineralization, organic matter decomposition, and disease suppression.

An important environmental benefit of conservation agriculture is its contribution to carbon sequestration. By reducing soil disturbance and increasing biomass inputs, conservation agriculture facilitates long-term storage of organic carbon in soils, thereby reducing atmospheric carbon dioxide concentrations. Soil carbon sequestration contributes simultaneously to climate change mitigation and improved soil fertility, creating a positive feedback between agricultural productivity and environmental sustainability (Lal et al., 2020). Enhanced soil organic carbon also improves cation exchange capacity, nutrient buffering, and moisture retention, enabling crops to tolerate drought stress more effectively. Consequently, conservation agriculture strengthens both productivity and resilience while supporting sustainable ecosystem functioning.

Water Conservation and Climate Resilience

Water scarcity has become one of the most significant constraints to agricultural production under climate change. Increasing temperatures, irregular rainfall patterns, declining groundwater resources, and greater evapotranspiration rates have intensified water stress in many agricultural regions, particularly in arid and semi-arid environments. Climate-smart agronomy seeks to improve water productivity by integrating conservation agriculture with efficient irrigation practices, precision water management, and climate-informed decision-making. Conservation agriculture substantially enhances the soil's capacity to capture, store, and utilize rainfall. Permanent soil cover reduces surface runoff, minimizes evaporation losses, and improves infiltration, allowing a greater proportion of rainfall to be retained within the root zone. The gradual accumulation of soil organic matter under conservation agriculture further increases water-holding capacity, enabling crops to withstand prolonged dry periods. During drought conditions, soils managed under conservation agriculture generally maintain higher moisture content than conventionally tilled soils, thereby supporting sustained crop growth and reducing yield losses (Kassam et al., 2019).

Climate-smart irrigation complements conservation agriculture by optimizing both the timing and quantity of irrigation water. Precision irrigation technologies use real-time information from soil moisture sensors, automated irrigation systems, and weather forecasts to deliver water according to crop requirements. Such approaches reduce unnecessary irrigation, improve water use efficiency, decrease energy consumption, and minimize nutrient leaching. Improved water management is particularly important in regions where groundwater depletion and increasing irrigation costs threaten agricultural sustainability.

Digital Agriculture and Precision Agronomy

Rapid advances in information and communication technologies have transformed modern agriculture into a knowledge-intensive and data-driven enterprise. Digital agriculture integrates advanced sensing technologies, satellite observations, artificial intelligence, geographic information systems, Internet of Things devices, cloud computing, and precision farming techniques to support informed agronomic decision-making. Precision agronomy represents a major component of digital agriculture by recognizing spatial and temporal variability within agricultural fields. Instead of applying uniform management practices across an entire farm, precision agriculture enables site-specific management based on field variability. This approach improves input-use efficiency while reducing production costs and environmental impacts.

Satellite imagery provides continuous monitoring of crop growth, vegetation health, soil moisture, and land-use dynamics over large geographical areas. Vegetation indices derived from satellite data allow early identification of crop stress before visible symptoms appear, enabling timely corrective interventions. Geographic Information Systems facilitate the integration of spatial datasets, including soil characteristics, topography, climate, irrigation infrastructure, and crop performance, thereby supporting informed land-use planning and resource management (Wolfert et al., 2017). The Internet of Things has further strengthened precision farming by connecting sensors, weather stations, irrigation systems, machinery, and mobile devices through wireless communication networks. Soil moisture sensors continuously monitor water availability, while nutrient sensors provide information regarding soil fertility status. Weather stations generate localized climatic information, including rainfall, temperature, humidity, wind speed, and solar radiation. The continuous collection and transmission of these data allow farmers to make timely management decisions that improve productivity and reduce climate-related risks.

Artificial intelligence and machine learning have emerged as transformative technologies for climate-smart agriculture. These technologies analyze large volumes of agronomic, climatic, and remote sensing data to identify complex patterns and generate predictive models. Artificial intelligence supports crop yield forecasting, disease diagnosis, weed identification, irrigation scheduling, fertilizer recommendations, and pest surveillance with increasing accuracy. Machine learning algorithms continuously improve their predictive capability as more field data become available, thereby enhancing the reliability of farm management decisions (Jha et al., 2019).

Drone technology has become another valuable component of digital agriculture. Unmanned aerial vehicles equipped with multispectral, hyperspectral, thermal, and high-resolution cameras provide rapid assessment of crop health, nutrient deficiencies, water stress, lodging, pest infestations, and disease outbreaks. Compared with conventional field scouting, drones enable rapid surveillance of large agricultural areas while reducing labour requirements and improving monitoring accuracy. Early detection allows farmers to implement corrective measures before significant yield losses occur. Decision Support Systems integrate weather forecasts, crop simulation models, soil information, pest surveillance,

and economic analyses into user-friendly platforms that assist farmers in selecting appropriate agronomic practices. These systems provide recommendations regarding sowing dates, irrigation scheduling, fertilizer application, crop protection measures, and harvesting time based on prevailing environmental conditions. Climate-informed decision support has become increasingly valuable for reducing production uncertainty under highly variable climatic conditions.

Integration of Conservation Agriculture with Digital Technologies

The integration of conservation agriculture with digital technologies represents one of the most promising developments in climate-smart agronomy. While conservation agriculture improves the resilience of agricultural ecosystems through sustainable soil management, digital technologies enhance the precision and efficiency of farm operations through continuous monitoring and data-driven decision-making. Remote sensing allows continuous evaluation of residue cover, crop establishment, soil moisture distribution, and vegetation performance under conservation agriculture. Artificial intelligence can analyze sensor data to identify nutrient deficiencies, water stress, and disease outbreaks in conservation-managed fields, allowing site-specific interventions. Variable-rate technologies further improve resource-use efficiency by applying fertilizers, irrigation water, and pesticides according to localized crop requirements instead of uniform application across entire fields.

Weather forecasting systems integrated with conservation agriculture enable farmers to adjust sowing dates, irrigation schedules, fertilizer application, and crop protection measures according to anticipated climatic conditions. Such climate-informed management reduces production risks associated with extreme weather events and improves overall farm resilience. The combined use of conservation agriculture and digital tools also contributes to climate change mitigation by reducing greenhouse gas emissions. Minimum tillage decreases fuel consumption during field operations, while optimized fertilizer management reduces nitrous oxide emissions associated with excessive nitrogen application. Improved irrigation scheduling decreases energy use for water pumping, and increased soil carbon sequestration further enhances environmental sustainability. Together, these technologies support sustainable intensification by increasing productivity while minimizing environmental impacts.

Challenges and Future Prospects

Despite the demonstrated benefits of climate-smart agronomy, widespread adoption remains constrained by several technical, economic, institutional, and social challenges. Conservation agriculture often requires specialized machinery, such as zero-till seed drills and residue management equipment, which may not be readily accessible to smallholder farmers. Initial yield variability during the transition period, limited technical knowledge, residue competition for livestock feed, and inadequate extension support also discourage adoption in many developing countries. Digital agriculture faces additional barriers related to high investment costs, inadequate internet connectivity, unreliable electricity supply, insufficient digital literacy, limited access to precision equipment, and fragmented landholdings. Small-scale farmers frequently lack the financial resources and technical expertise necessary to adopt advanced digital technologies. Furthermore, issues concerning data ownership, privacy, interoperability of digital platforms, and long-term maintenance of technological infrastructure remain important concerns.

Nevertheless, technological innovation continues to improve the accessibility and affordability of climate-smart solutions. Artificial intelligence models are becoming increasingly accurate and user-friendly, while low-cost sensors, smartphone applications, and cloud-based advisory platforms are expanding access to digital agricultural services. Government initiatives promoting digital agriculture, conservation agriculture, climate-resilient crop varieties, carbon farming, and precision irrigation are expected to accelerate adoption over the coming decades. Future research should emphasize integrated farming systems that combine conservation agriculture, precision nutrient management, renewable energy, carbon sequestration, climate-resilient crop breeding, artificial intelligence, and ecosystem-based adaptation. Greater collaboration among researchers, policymakers, extension agencies, technology developers, and farmers will be essential for translating scientific advances into practical field applications. Strengthening climate information services, improving digital infrastructure, expanding farmer training programmes, and developing supportive policies will further enhance the resilience and sustainability of agricultural production systems.

Conclusion

Climate change has fundamentally altered the operating environment of global agriculture, demanding innovative agronomic approaches capable of sustaining productivity under increasingly uncertain climatic conditions. Climate-smart agronomy provides an integrated framework that combines sustainable resource management with technological innovation to improve agricultural resilience while minimizing environmental degradation. Conservation agriculture serves as the cornerstone of this approach by enhancing soil health, improving water conservation, increasing biodiversity, and promoting carbon sequestration. Simultaneously, digital technologies such as remote sensing, artificial intelligence, Internet of Things, geographic information systems, drones, precision agriculture, and decision support systems provide farmers with accurate, real-time information for efficient crop management. The synergistic integration of conservation agriculture and digital technologies offers substantial opportunities for improving resource-use efficiency, reducing greenhouse gas emissions, strengthening climate adaptation, and enhancing long-term agricultural

sustainability. Although significant challenges related to technology adoption, infrastructure, institutional support, and farmer capacity remain, continued technological advancement and supportive policy interventions are expected to accelerate the transition toward resilient agricultural systems. Climate-smart agronomy therefore represents a critical pathway for ensuring global food security while simultaneously addressing the environmental challenges associated with climate change.

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Tilapia Breeding: The Secret Behind Successful Fish Farming

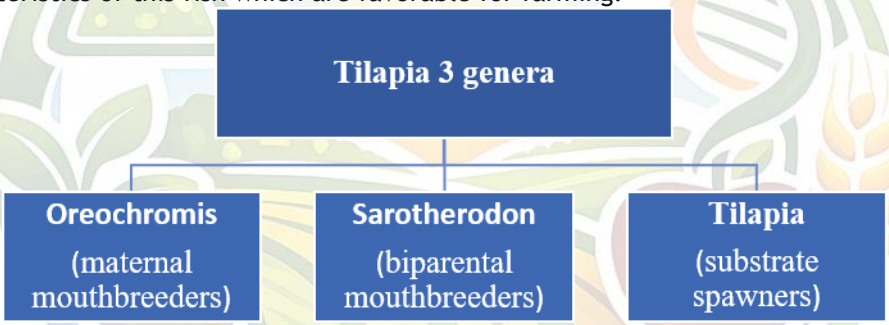
Article ID: 74277

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Abstract
Tilapia is one of the most widely cultured freshwater fish species due to its rapid growth, adaptability and high reproductive capacity. Successful seed production depends on efficient breeding technologies and hatchery management. Modern techniques such as broodstock conditioning, artificial egg incubation, hormonal sex reversal and hybridization have improved fry quality and monosex production. These advancements enhance growth performance, feed efficiency and farm profitability while reducing problems associated with uncontrolled reproduction. Continued genetic improvement and sustainable breeding practices will play a vital role in supporting global tilapia aquaculture and food security (El-Sayed, 2020; FAO, 2024).

Keywords: Tilapia breeding, Hatchery technology, Broodstock management, Mouthbrooding, Artificial incubation, Monosex tilapia, Hormonal sex reversal, Hybridization, Sustainable aquaculture.

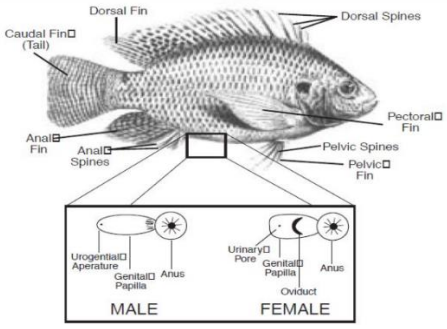
Introduction
Among the farmed species of fishes in inland waters, contribution of tilapia, a cichild fish, is perhaps next only to that of carps and other cyprinids. About 80 species of tilapia have been described out of which about 10 species are reported to be used for culture. Though originally a native of Africa, it is distributed all over the world at present because of certain distinct characteristics of this fish which are favorable for farming.

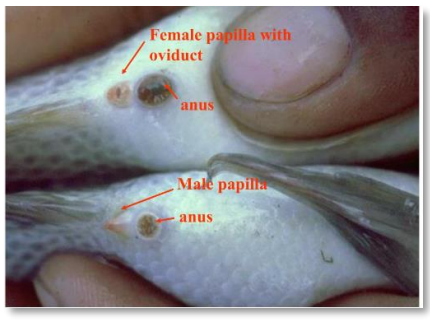


Importance of Species
It is an easy growing fish. Capacity to adapt to different climatic conditions, salinities, food and ecosystems, sexual maturation under certain adverse conditions. Highly resistant to diseases. Reproduces prolifically under natural conditions. Exhibits good growth rate and feed conversion efficiency.

Breeding of Nile tilapia (*Oreochromis niloticus*)
Species Biology: It an omnivorous fish feeding mainly on phytoplankton such as green algae, blue green algae and diatoms and also on detritus. Temperature below 12°C is found lethal. It can tolerate salinity up to 29 ppt. The males exhibit a growth rate 2.5 times more than female. It grows more than 600 g within 6 months.

Sexual Dimorphism

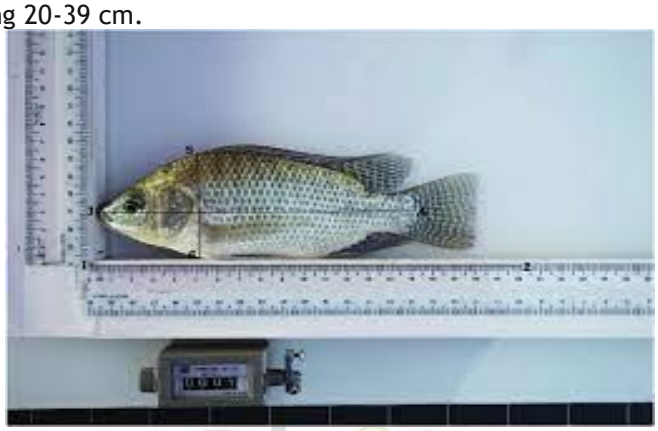




Male have pointed urinogenital papilla whereas female have thick genital papilla with oviduct.

Sexual Maturity

1. It attains 1st sexual maturity on reaching 10-17 cm length i.e. 4-5 months old in farm condition.
2. In wild, it matures on attaining 20-39 cm.



Courtship and Mating

The males engage themselves in active display in a breeding territory which is referred to as "lek" (Macintosh and Little, 1995) where nests are prepared by males by scooping out depressions at pond bottom.
The mature female visits a "lek" when there shall be immediate courtship and mating resulting in spawning, spermiation and fertilization.



Spawning and Fecundity

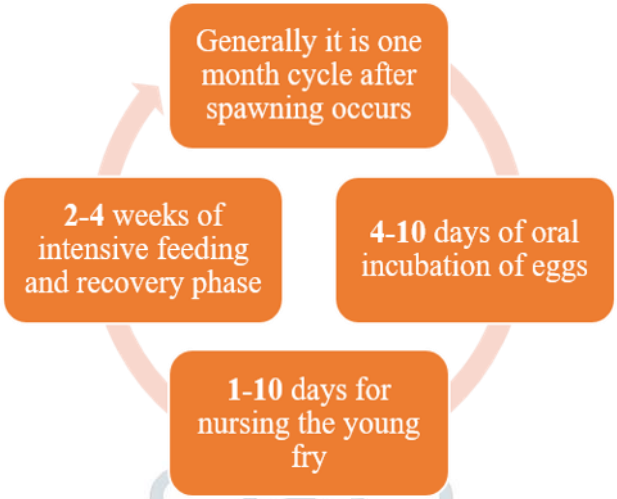
A mature fish spawn 6-12 times in a year. The no. of eggs / batch is reported to vary from a few hundreds to 2000.Larger females – more eggs per batch – larger in size. Smaller females – less no. of eggs – smaller in size. Though the number of eggs in a batch is less, the smaller fishes (less aged) spawn more frequently as a result, smaller brood fish yields more eggs/fry collectively.

Parental Care

Soon after the eggs are laid and fertilized the same are picked up by the female in its mouth for incubation. Soon after taking the eggs in its mouth the female leaves the breeding territory, "lek" or nesting area. Incubation period – 4 to 10 days depending on temperature. Yolk sac absorption – 4 to 6 days. After they are called swimup fry and they start feeding. The mother continues to shelter the larvae for another 1 to 4 days. Larvae take 10 to 12 days to become fully independent.



Reproductive Cycle



Environmental Factors Affecting Reproduction

Three major factors are found to affect the reproduction of tilapia- Temperature, Light & Salinity. Optimum temperature required is 27 ºC, but generally it breed in temperature between 20-23 ºC. Some scientists have reported that bright sunlight stimulates the breeding in tilapia. Salinity above 20 ppt shown to decreased fecundity. For optimum fecundity isotonic concentration reported to be ideal.

Constraints in Natural Condition

Tilapia breeds prolifically in confined waters, and fry are released by the mother into the pond continuously, collection of the naturally produced fry was not sustainable because of the following reasons. Cannibalism among the fry. Asynchronous spawning habit, Overcrowding, stunted growth and decline in the reproductive efficiency. Because of these limitations, for large scale production of fry under controlled conditions, advanced techniques for brood stock management became necessary.

These techniques included
1. Conditioning brood fish before spawning and
2. Replacement of spawned females with conditioned brood fish.

Broodfish Conditioning

Two major aspects of conditioning:
1. Stocking the fish at optimum stocking density.
2. Feeding the fish on good quality feed to meet actual nutritional requirements.

For green water system, 25 – 30 % CP, whereas 30 – 40 % required for clear waters.

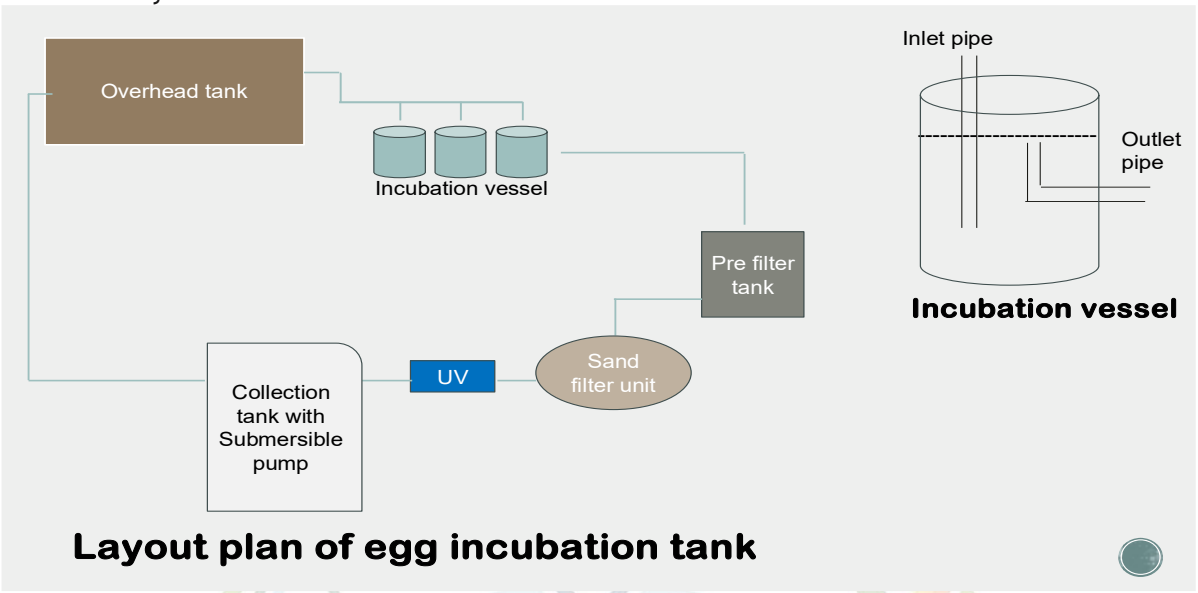
Collection of Eggs from Mouth

Water level lowered by draining out the water to a depth of 20-30 cm. So, we can easily collect and examine the mouth of females. Females are forces to spit out eggs and it collected into basin. Eggs are put under artificial incubation. Spawned females are replaced with ready to spawn (mature) females once in every 5-10 days.



Incubation of Eggs

Round bottom incubator of 20 ltr which can hold 80000 eggs for incubation are good as this avoid damage to egg chorion. Incubation period varies on temperature, 6 days at 20 °C2-3 days at 34.5°C Optimum incubation temperature is 28-29 °C at which period is 4 days.



Layout plan of egg incubation tank

Larval Care

Larvae are reared in trays for 20 days after hatching. Aluminium or plastic tray of size (40 x 30 x 10) cm with holes on lateral sides are used. Holes are drilled in a way that 3 cm water depth are maintained. Swim up fry start feeding 4-8 times a day for another 10 days. With 64 such trays, 0.5 million fries can be produced with stocking of 10000 fry per tray (80% survival). Maintain good quality water and optimum flow rate of water are necessary.

Production of *Monosex tilapia*

There are two techniques used for production of monosex tilapia

1. Hormonal sex reversal
2. Hybridization

Hormonal Sex Reversal

Androgens – genotypic female into functional males. Hormones administered orally mixed with feed. Oral administration done between 10th - 20th day of hatching when gonad is in undifferentiated stage.17 α methyl testosterone [17α MT] is used mostly with dose not standardized. Generally, 1.5 mg/gm body weight is necessary to achieve 100% sex reversal, but it can't be more than 8 mg/gm body weight.

Hybridization

Hickling was the first to produce all male offsprings by crossing *O. mossambicus* with *O. urolepis hornorum*. In hybridization if both parents are homogametic, all male offspring shall be obtained. Strong chromosomal sex determination mechanism does not exist in tilapia. Autosomal genes play major role in sex determination.

Red tilapia – Hybridization

Red tilapia is produced using hybridization by Taiwan fisheries research institute. Produced by crossing a mutant variety of *O. mossambicus* (having red body colour and red eyes) with *O. niloticus*, red stain exhibits fast growth rate i.e. 500-600 g in 5 months and 1200 gm in 18 months.

Conclusion

Tilapia breeding technology has greatly improved the production of healthy, high-quality seed for sustainable aquaculture. Modern hatchery practices, including broodstock management, artificial egg incubation, hormonal sex reversal, and hybridization, have enhanced fry survival and monosex production. These technologies improve growth performance, feed efficiency, and farm profitability while reducing uncontrolled reproduction. Continued genetic improvement and sustainable breeding strategies will further enhance productivity, disease resistance, and environmental adaptability. Overall, modern breeding technologies are essential for the long-term growth and global sustainability of tilapia aquaculture (El-Sayed, 2020; FAO, 2024; Thomas, 2003).

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Seed Mucilage: Nature's Hidden Shield for Seed Survival

Article ID: 74278

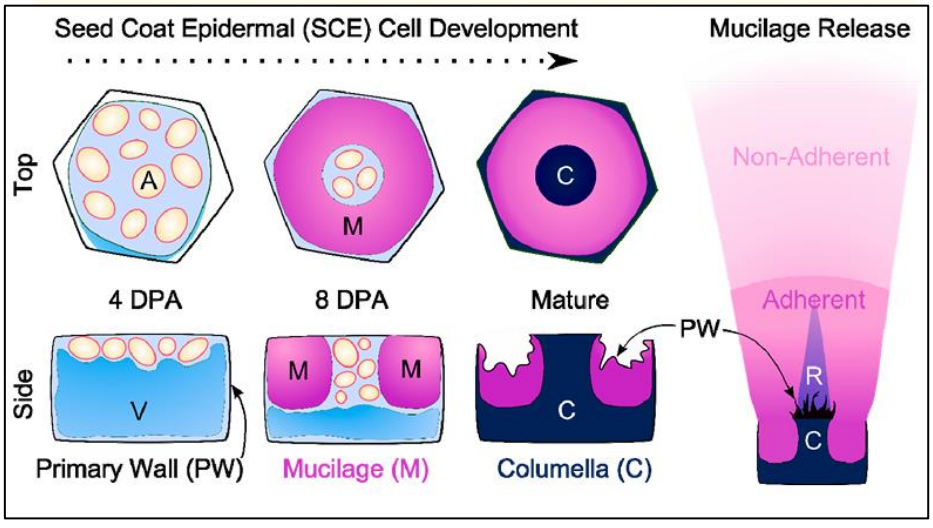
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Abstract
Seed mucilage is a gelatinous, polysaccharide-rich substance released by the seed coat or fruit wall when seeds come into contact with water. It forms a protective hydrogel around the seed and performs several important biological functions. Besides maintaining moisture, seed mucilage supports seed germination, seedling establishment, DNA protection and repair, seed dispersal, and interactions with soil organisms. These diverse functions enhance seed survival under different environmental conditions and contribute to successful plant establishment. Understanding the biological significance of seed mucilage provides valuable insights into plant adaptation and may contribute to the development of climate-resilient agricultural systems.

Introduction
Seeds are equipped with several natural adaptations that help them survive until favourable conditions are available for germination. One of these remarkable adaptations is seed mucilage, a jelly-like substance produced by the outer layer of the seed in many flowering plants. Depending on its origin, seed mucilage is classified as myxospermy, when produced by the seed coat, or myxocarpy, when produced by the fruit wall. During seed development, mucilage accumulates beneath the outer cell wall of specialised seed coat cells. When mature seeds absorb water, the mucilage rapidly hydrates and expands, forming a transparent capsule around the seed. This hydrated layer not only protects the seed but also supports several biological processes that improve seed survival and establishment in diverse environments.

Composition of Seed Mucilage
Seed mucilage is mainly composed of complex plant carbohydrates known as polysaccharides. The major components include pectins and hemicelluloses, such as galacturonans, rhamnogalacturonans, xylans, mannans, and glucans. Although present in smaller amounts, cellulose plays an important structural role by anchoring the mucilage to the seed surface. The proportion of these components differs among plant species, resulting in variations in mucilage structure and properties. Together, these polysaccharides form a highly hydrated network that determines the swelling, adhesion, and protective functions of seed mucilage. The interaction between cellulose, pectins, and xylans maintains the architecture of the mucilage and enables its rapid expansion when the seed comes into contact with water.

Mucilage Secretory Cells (MSC) Development and Mucilage Extrusion
Seed mucilage is produced by specialized mucilage secretory cells present in the outer layer of the seed coat. During seed development, these cells synthesise and store mucilage beneath the primary cell wall while gradually forming a central structure known as the columella.



Mucilage Secretory cells (MSCs) development | Figure 1. Development of seed coat epidermal cells and mucilage extrusion during seed maturation.

When mature seeds are exposed to water, the stored mucilage rapidly absorbs moisture, causing the outer cell wall to rupture. The hydrated mucilage then expands and surrounds the seed as a two-layered capsule. The inner layer remains firmly attached to the seed surface, whereas the outer layer spreads into the surrounding environment. This rapid extrusion forms a protective interface between the seed and its surroundings during the early stages of germination (Voiniciuc *et al.,* 2015).

Biological Functions of Seed Mucilage

1. Supporting Seed Germination and Seedling Establishment: Seed mucilage plays an important role in seed germination by maintaining moisture around the seed and creating a favourable environment for growth. In several plant species, intact mucilage improves germination and promotes healthy seedling development (Geneve *et al.,* 2017). However, its effects vary among species. For example, in *Leptocereus scopulophilus*, removal of mucilage from seed results in faster germination (Barrios *et al.,* 2015).

Mucilage also anchors seeds firmly to the soil surface, reducing movement caused by wind or rain. It facilitates radicle penetration into the soil and contributes to seedling growth through the release of sugars and other compounds during germination. In addition, degradation of mucilage by soil microorganisms improves microbial activity and enhances seedling establishment, particularly in nutrient-poor habitats.

2. Role in DNA Protection and Repair: An interesting function of seed mucilage is its ability to support DNA repair under stressful conditions. Studies on irradiated *Artemisia sphaerocephala* achenes have shown that intact mucilage significantly enhances DNA repair during exposure to dew compared with seeds from which the mucilage has been removed. This protective function helps maintain seed viability and improves the chances of successful germination under harsh environmental conditions (Yang *et al.,* 2011).

3. Role in Seed Dispersal: Seed mucilage plays a multifunctional role in seed dispersal by enabling seeds to spread through different ecological strategies. Through mechanisms such as topochory (local seed retention) and antitelechory (prevention of long-distance dispersal), hydrated mucilage firmly anchors seeds to the soil surface, preventing their displacement by wind or water and ensuring establishment in favourable microsites. Its adhesive nature also promotes epizoochory, allowing seeds to attach to the fur or feathers of animals for long-distance dispersal. In endozoochory, mucilaginous seeds can survive passage through the digestive tract of animals, where the mucilage provides lubrication, often resulting in successful dispersal and improved germination after excretion. Additionally, in hydrochory, hydrated mucilage reduces the specific weight of seeds, enabling them to float and disperse through water. By facilitating these diverse dispersal mechanisms, seed mucilage enhances seed persistence, colonisation, and plant establishment across a wide range of environments.

4. Interactions with Other Organisms: Seed mucilage serves as the first hydrated interface between the seed and its surrounding environment, influencing interactions with a wide range of organisms. It acts as a physical and chemical barrier against pathogens and seed predators. For example, the mucilage of basil contains phenolic compounds that help protect seeds from microbial pathogens, while intact seeds of *Anabasis sphaerocephala* are less likely to be harvested by ants than demucilaged seeds, indicating a protective role against granivores (Lee *et al.,* 2020). Seed mucilage also serves as a nutrient source for beneficial soil microorganisms, enhancing arbuscular mycorrhizal fungi colonisation, mineral uptake, and stress tolerance in seedlings, although it can also be utilised by pathogens such as the fungus *Colletotrichum graminicola* (Yang *et al.,* 2012; Geneve *et al.,* 2017). In addition, mucilage attracts certain nematodes, such as the root-knot nematode *Meloidogyne incognita,* which uses mucilage as a chemical cue to locate host plants. In *Capsella bursa-pastoris*, mucilage attracts *Steinernema feltiae*, and the seedlings can absorb nutrients released from dead nematodes, suggesting a form of protocarnivory (Tsai *et al.,* 2019; Roberts *et al.,* 2018). These diverse interactions demonstrate that seed mucilage is a multifunctional interface that contributes to seed protection, beneficial microbial associations, and ecological adaptation.

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Conclusion

Seed mucilage is far more than a sticky coating surrounding seeds. It is a multifunctional natural hydrogel that supports seed germination, promotes seedling establishment, protects DNA, aids seed dispersal, and mediates interactions with various soil organisms. Its unique composition and remarkable biological functions enable plants to survive and establish successfully under a wide range of environmental conditions. As agriculture faces increasing challenges from climate change and environmental stress, understanding the biology of seed mucilage may provide new opportunities for improving crop establishment and developing climate-resilient agricultural systems.

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Sea to Soil: The Rise of Algae-Based Bio stimulants in Agriculture

Article ID: 74279

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Summary of the Article

Seaweeds and microscopic algae are emerging as promising sources of natural agricultural inputs. Rich in bioactive compounds, nutrients, polysaccharides and other growth-promoting substances. Today's algae-based bio-stimulants improve nutrient uptake, stress tolerance and improves yield across a wide range of crops and the global market for these products now exceeds five billion dollars a year. More interestingly, microalgae can potentially recover nutrients from wastewater and carbon dioxide while producing useful biomass. Using seaweed farms to capture carbon and building seaweed-derived nanoparticles for plant and soil health remain only lightly explored. Researchers are also exploring algae in green nanotechnology and advanced nutrient-delivery systems. This article surveys these developments and argues that algae deserve far more systematic research attention as agriculture searches for lower-input, climate-resilient alternatives.

Introduction

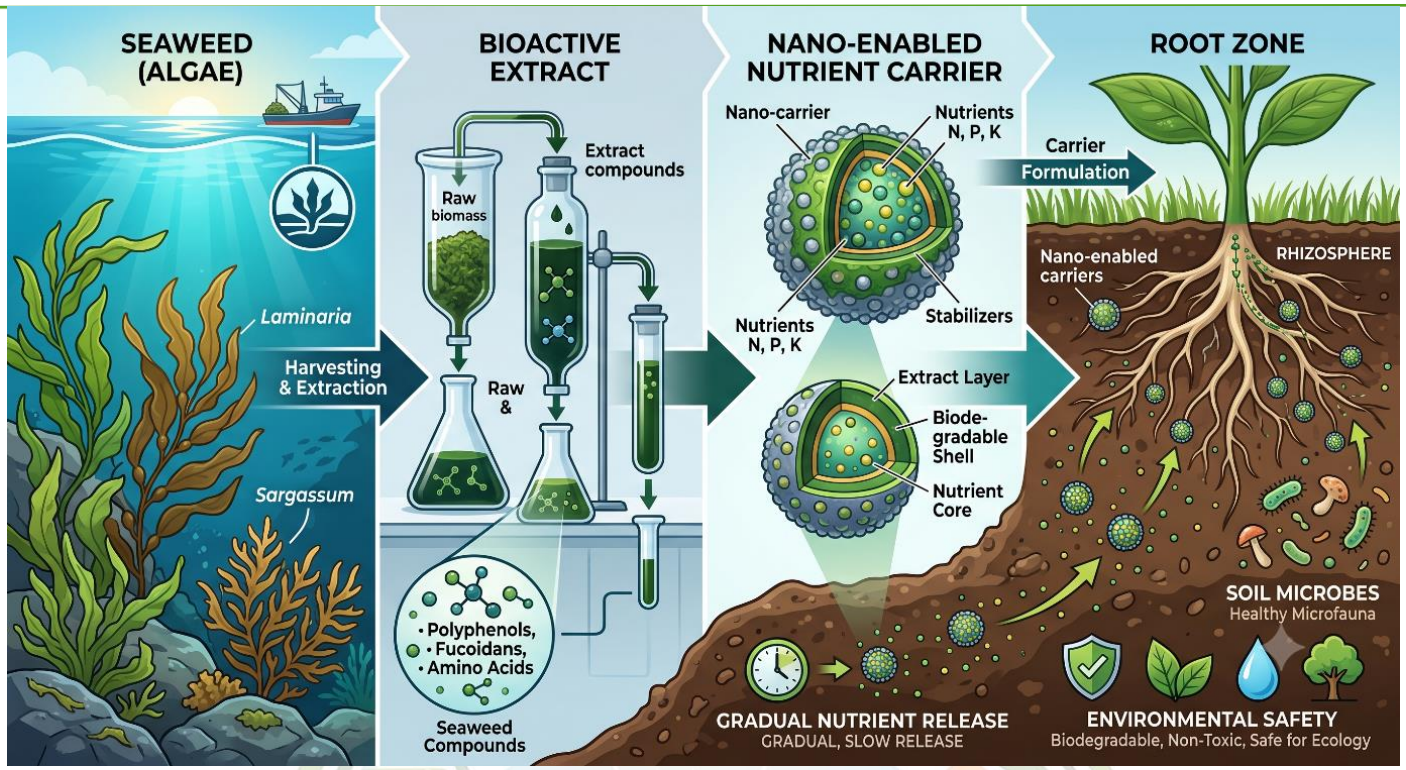
Seaweeds contain biologically active substances such as **polysaccharides, amino acids, phenolic compounds and other plant-active molecules**. Seaweed polysaccharides such as alginate, carrageenan, agar and ulvan, for example, are being investigated for their potential contribution to plant growth, stress resilience and soil health (Tariq et al., 2025).

Modern research recognizes two broad categories of algal bio-stimulant: **Macroalgae** (seaweeds) and **Microalgae** (single-celled species grown in ponds or bioreactors). Both are valued for phytohormones, amino acids and polysaccharides that help crops to cope-up with drought, salinity and disease pressure without acting as conventional fertilizers. However, macroalgae bio-stimulants have been extensively studied while microalgae remain comparatively underexplored and direct comparative work between the two groups are still limited.

One of the more promising and underexplored directions involves growing microalgae directly in wastewater. Microalgae grown in urban wastewater can simultaneously recover nitrogen and phosphorus while producing phytohormone-rich biomass usable as a bio-stimulant (Álvarez-González et al., 2023). (Álvarez-González et al., 2023) found that strains such as Scenedesmus achieved nitrogen and phosphorus removal rates above 70 percent while yielding measurable concentrations of natural plant hormones. This approach effectively converts a pollution problem into a resource stream, though most supporting research remains at laboratory or pilot scale, and questions about processing cost and consistency at commercial volume are still open.

Nanotechnology Derived from Seaweed Compounds

Algal and seaweed-derived compounds are being explored in greener approaches to nanoparticle synthesis and functional materials. Seaweed-derived nanoparticles can improve nutrient delivery to plant roots, stimulate natural disease resistance and support a healthier soil microbiome, all within a "**One Health**" framework that links plant, animal and environmental health together (Chanthini, 2026). (Chanthini, 2026) found that these nanoparticles, built from seaweed polysaccharides and polyphenols, reduce reliance on conventional agrochemicals while supporting food safety and ecosystem quality more broadly. Seen this way, a fertilizer input becomes part of a much larger, interconnected health system rather than an isolated agronomic tool.



From Soil Health to One Health

Healthy soil supports healthy microbial communities. Healthy soil and microbes support plants. Plants become food and feed, connecting agricultural practices with animals and people. Meanwhile, whatever escapes from farms can eventually reach water bodies and the wider environment.

Thus, algae-based agricultural inputs could be evaluated through a connected pathway:

Algae → Soil → Microbiome → Plant → Animal/Human → Environment

This means that the ideal algal product of the future should not merely increase yield. It should also be safe for soil organisms, minimize nutrient losses, protect water resources and contribute to producing healthy crops.

Laboratory to Farmer's Field

Despite their promise, algae are not ready to replace conventional fertilizers.

One major problem is **consistency**. The composition of seaweed can change with species, location, season and processing technique. Microalgal production also involves costs associated with cultivation, harvesting and extraction. Standardization, economic feasibility, safety and regulatory classification remain important barriers to wider commercialization. Recent assessments continue to identify these issues despite rapid progress in algae-based bio-stimulants.

Farmers ultimately need more than a product labelled *natural* or *green*. They need to know **what it contains, how much to apply, when to apply it, whether it works under field conditions and whether it is economically worthwhile**.

Conclusion

Seaweeds and microalgae could contribute not only as bio-stimulants but also as tools for nutrient recovery, wastewater valorization, soil-health improvement and potentially carbon management. Combining algae with emerging technologies may create even more sophisticated agricultural inputs. Seaweed and algae occupy a rare position in agricultural science: a centuries-old practice now being explained, refined and extended by cutting-edge biotechnology. Wastewater-grown bio-stimulants, carbon-conscious seaweed farming and One Health-aligned nanotechnology all point toward a future where a single marine resource supports cleaner water, healthier soil and more resilient crops at once. Realizing that potential will require more comparative research, clearer regulation.

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Melatonin Mediated Seed Germination During Abiotic Stress Condition

Article ID: 74280

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Article

Seed germination is highly sensitive to abiotic stresses, including drought, salinity, temperature extremes, and oxidative stress, which reduce seedling establishment and crop productivity. Melatonin (N-acetyl-5-methoxytryptamine) has emerged as an important regulator of seed germination under stress conditions. This review summarizes the biosynthesis, distribution, and functions of melatonin, highlighting its role in improving germination through the regulation of reactive oxygen and nitrogen species (ROS/RNS), activation of antioxidant defenses, enhancement of α-amylase activity, and modulation of gibberellin (GA) and abscisic acid (ABA) signaling. Melatonin also interacts with calcium-mediated signaling pathways to maintain cellular homeostasis during stress. Overall, melatonin enhances seed vigor, promotes successful germination, and improves abiotic stress tolerance, making it a promising approach for improving crop establishment under adverse environmental conditions.

Keywords: Melatonin, abiotic stress, seed germination, ROS.

Introduction

Seed germination is a crucial stage in the life cycle of seed plants. Seed germination is defined as the initiation of the seed from water absorption and completion when the radicle protrudes from the seed coat. This process triggered by favourable conditions like water, oxygen, and appropriate temperature. Both external factors like moisture content, temperature and abiotic stress and internal factors are endogenous phytohormones, and ROS can affect seed germination.

Abiotic stresses such as drought, salinity, temperature extremes, and oxidative stress significantly impact seed development and germination by disrupting physiological and biochemical processes. During germination, abiotic stresses affect water imbibition, enzyme activation, and metabolic processes essential for seedling establishment.

In response to stress, plants upregulate various genes involved in synthesis of biological molecules such as secondary metabolites, phytohormones, osmolytes, and melatonin, which can mitigate the effects of stress and maintain cellular homeostasis. These molecules can act independently or interact with each other to alleviate stress responses.

Melatonin is a ubiquitous molecule that is present in plants, animals, and microorganisms. It is (N-acetyl-5-methoxytryptamine) is an indoleamine first isolated from the pineal gland of cattle in 1958 by Aaron Lerner and co-workers. Its discovery in plants in 1995 in Japanese morning glory (Dubbels et al., 1995). Endogenous presence of melatonin in plants, the term “Phyto-melatonin” was coined in 2004.

Biosynthesis of Polyamines

The biosynthesis of melatonin primarily takes place in the mitochondria and chloroplasts, and its levels can be significantly elevated under abiotic stresses such as drought, salinity, or extreme temperatures.

1. Major biosynthesis pathway: This is dominant in optimal growth condition. Tryptophan is precussor of melatonin biosynthesis. During major biosynthesis pathway, tryptophan undergoes decarboxylation via the action of tryptophan decarboxylase (TDC) enzyme and converts into tryptamine, which later converts into 5-hydroxytryptamine (serotonin) via the action of tryptamine 5-hydroxylase (T5H). Serotonin then undergoes N-acetylation via the action of serotonin N-acetyltransferase (SNAT) and produces N-acetyl serotonin, which later converts into MEL by acetyl serotonin methyl transferase (ASMT) and/or caffeic acid O-methyltransferase (COMT).

2. Alternate biosynthesis pathway: During alternate MEL biosynthesis pathway, tryptophan initially undergoes hydroxylation and converts into 5-hydroxytryptophan by the action of tryptophan-5-hydroxylase (TPH), which later undergoes decarboxylation to produce serotonin. Later, serotonin can be catalyzed to form 5-methoxytryptamine by COMT or ASMT, which then converts into MEL by SNAT.

During MEL metabolism, MEL metabolizes into different MEL derivatives, including cyclic N1-acetyl-N2-formyl-5-methoxykynuramine (AFMK), N1-acetyl-5-methoxykynuramine (AMK), 2 hydroxy melatonin (2-OHM), and 3-hydroxymelatonin (3-OHM) via the action of different enzymes.

Distribution of Melatonin

The presence of melatonin has been reported in over 140 plant species and its endogenous concentrations range from per gram to mg per gram of tissues with the highest concentrations in flowers and seeds. In seeds, melatonin plays a particularly crucial role. It is found in different seed parts such as the seed coat, endosperm, and embryo. The concentration of melatonin in each tissue varies depending on the plant species, the developmental stage of the tissue, and the environmental conditions.

Melatonin effect depends on concentration of melatonin, type of stress and genotype specific. Seed priming, soaking, foliar spraying, seed root dipping, supplement with irrigation water and rhizospere application Melatonin can be applied to plants through several methods, depending on the developmental stage of the plant, the specific goal of the treatment, and the type of abiotic stress being addressed.

Role of Melatonin

Melatonin plays a crucial role in plant growth, development, stress responses, defence mechanism and storage. These are involved in various physiological processes such as cell division, differentiation, flowering, fruit development, and senescence. They help stabilize membranes, regulate ion channels, and modulate gene expression. Melatonin also acts as antioxidants, protecting plants from oxidative stress caused by environmental factors like drought, salinity, and extreme temperatures. Additionally, they contribute to plant defence mechanisms by enhancing resistance against pathogens. Their role in signalling pathways further highlights their importance in plant adaptation and survival under stress conditions.

Effect of Melatonin on Seed Germination Under Abiotic Stress

Plant encounters any abiotic stress like heat, drought, and salinity stress there will be changes in cellular metabolism that led to accumulation of melatonin. Under such stress conditions, melatonin not only acts as an antioxidant but also increases the levels of reactive oxygen species (ROS) like hydrogen peroxide (H_2O_2), and reactive nitrogen species (RNS) such as nitric oxide (NO) (Fig 1). Interestingly, both ROS and NO are not always harmful—in moderate, controlled levels, they act as signaling molecules that play important roles in regulating seed germination. The increase in ROS and NO, in turn, further stimulates melatonin biosynthesis, forming a feedback loop referred to as the MEL–ROS–RNS network. This network regulates SG in a highly orchestrated manner, for instance MEL activates plasma membrane located respiratory burst oxidase homologs (RBOHs) and NO synthase-like (NOS-like) and nitrate reductase (NR) and increases H_2O_2 and NO production respectively with concomitant improvement in SG. This response also regulates several other physiological processes in germinating seeds including activation of amylase enzyme, starch mobilization, energy production, hormonal regulation, and protein carbonylation to supply energy for SG.

Melatonin and ROS

1. Reactive nitrogen species (RNS) scavenging: Melatonin upregulates NO biosynthesis and increases NO during seed germination, which later converts into peroxy nitrite ($ONOO^-$) by the action of superoxide radical ($O2^-$). The $ONOO^-$ later either changes into hydroxyl radical (•OH) or converts into NO_2, later both reactive radicals undergo MEL-mediated enzymatic degradation, thus increasing NO levels to regulate SG (fig 2). Moreover $ONOO^-$ synthesis is also associated with higher accumulation of NO and O_2^-, thus the interplay of MEL and $ONOO^-$ may act as complementary mechanism of protein protection against nitration particularly during seed germination.

2. Reactive oxygen species (ROS) scavenging: Melatonin either acts as OH scavenger itself or activates antioxidant defense system to keep ROS at basal levels (fig 2). Having said that, NO scavenging could also advance the denitrosylation of RBOH to enhance RBOH-dependent ROS production,which is indicating a novel mechanism including RBOH mediated ROS signaling as an integral component of the melatonin driven seed germination and abiotic stress adaptation.

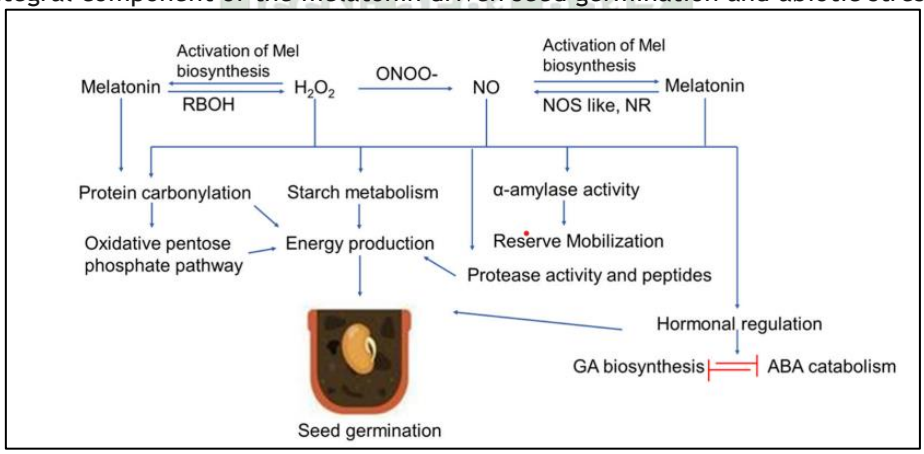


Fig 1: Effect of melatonin on seed germination under abiotic stress

Melatonin and GA_3

The interactive role of melatonin (MEL) with ROS & RNS in mediating GA-ABA network to regulate seed germination in plants. Upon abiotic stress exposure, MEL induces ROS (H2O2) production and enzymatic degradation of starch via α-amylase enzyme. Moreover, MEL also upregulates GA biosynthesis, which concomitantly improves SG. However, MEL may regulate Ca2+ transport (Ca2+ influx and Ca2+ efflux) as a component of Ca2+ signalling to regulate GA biosynthesis. Thus, future studies are required to study these points. Moreover, MEL application activates RBOH and increases H_2O_2 production with concomitant improvement in seed germination (fig 3).

Melatonin and ABA

Though seed dormancy (SD) is important from the ecological point of view, dormant seeds show reduced SG, thus MEL crosstalk with ROS to regulate SD as a part of regulating SG. Abiotic stresses increase MEL biosynthesis, which inhibits ABA catabolism, thereby regulating SD. Endogenous MEL also increases endogenous H2O2 production and Ca2+-efflux by upregulating the activities of RBOH and cation/H+ exchanger (CHX_3), respectively. As a part of regulatory mechanism, both H2O2 and Ca2+-efflux negatively regulate ABI4 and ABI5 activity, thereby regulating SG under stress conditions (fig 3).

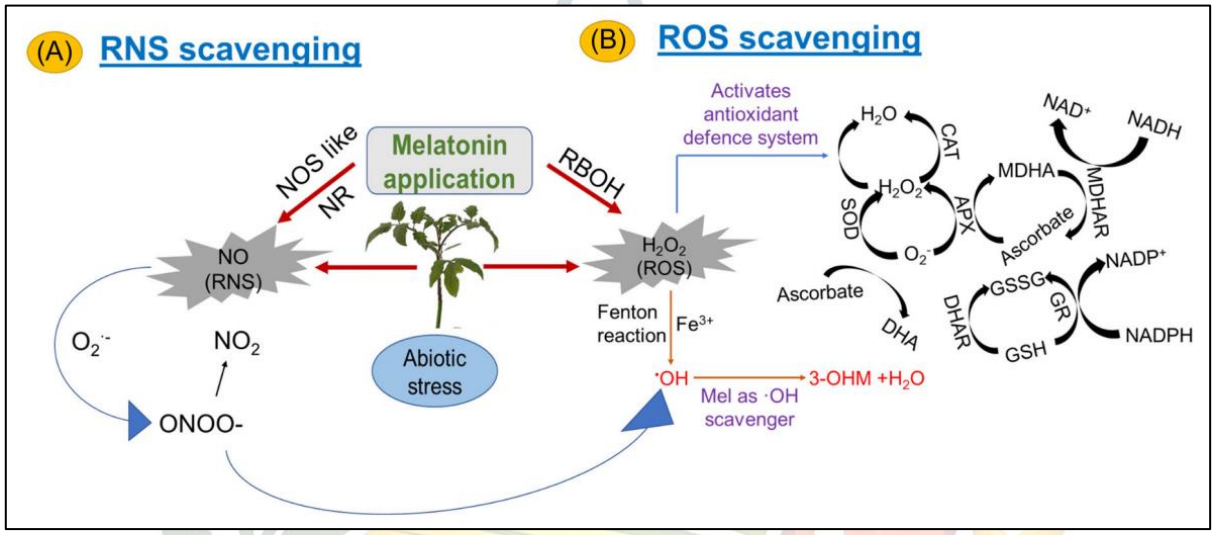


Fig 2: ROS and RNS scavenging during abiotic stress condition

Melatonin and Ca^{+2} Signaling

NO (RNS) increases endogenous MEL levels via triggering its biosynthesis, which in return increases endogenous NO level by triggering the activity of NOS like and NR for NO biosynthesis, thus making MEL-NO loop. This loop increases GA biosynthesis and ethylene biosynthesis, while inhibits ABA biosynthesis, thus indicating the involvement of RNS in MEL mediated SG under abiotic stresses. ABA, abscisic acid; RBOH, respiratory burst oxidase homologs; RNS, reactive nitrogen species; ROS, reactive oxygen species.

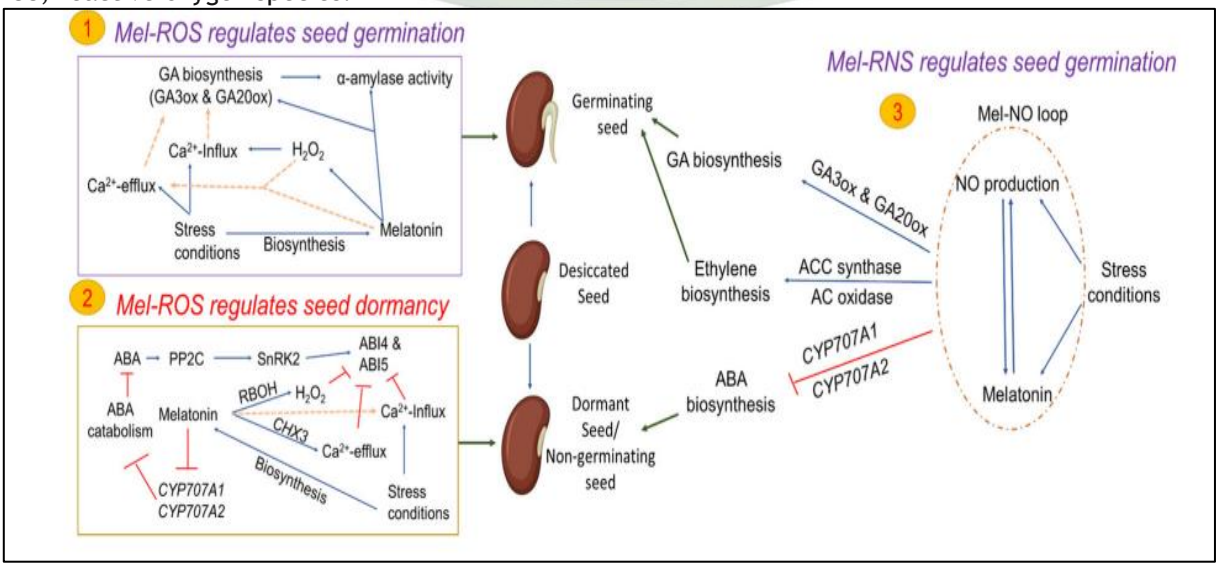


Fig 2: ROS and RNS scavenging during abiotic stress condition

Conclusion

Melatonin acts as a central signaling molecule in seeds, activating various biomolecules and hormonal pathways that regulate seed germination, especially under abiotic stress conditions. It interacts with reactive oxygen species (ROS) to modulate the endogenous levels of gibberellins (GAs), which are crucial for germination. By maintaining ROS homeostasis, melatonin ensures proper seed development either through its direct scavenging ability or by enhancing the activity of antioxidant enzymes.

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Post-Harvest Technology & Cold Chain Logistics Management of Crops

Article ID: 74281

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Summary
Post-harvest losses continue to be one of the biggest yet least visible problems in Indian agriculture. Every year, large quantities of fruits, vegetables, milk, fish, and other perishable products spoil before they reach consumers because of delayed transportation, high temperatures, and weak cold chain facilities, especially at the farm level. Although India has modern cold storage systems and refrigerated transport, these facilities are often beyond the reach of small and marginal farmers due to high costs and inadequate rural infrastructure. In recent years, government support through schemes such as the Pradhan Mantri Kisan SAMPADA Yojana (PMKSY), along with affordable technologies like Zero Energy Cooling Chambers (ZECC), solar-powered cold rooms, CoolBot-based refrigeration, Modified Atmosphere Packaging (MAP), and IoT-enabled temperature monitoring, has started to improve the situation. Expanding these practical, low-cost solutions according to local needs can significantly reduce food losses, increase farmers' incomes, strengthen food security, and create a more resilient and sustainable agricultural supply chain for India.

Introduction
Every single day, vast truckloads of fresh vegetables, fruits, dairy, and fish rot long before they ever see a dining table. For millions of Indian farmers, this isn't just an abstract statistic—it's a painful reality. After months of backbreaking labor, they are forced to watch their hard work decay simply because there's no refrigerator to store it in or a chilled truck to move it. What makes this crisis even harder to swallow is the hidden toll: along with the ruined produce, the millions of liters of water, endless farm energy, and fertile soil used to grow it evaporate into thin air. Fixing this leaky pipeline is no longer optional; it is central to India's agricultural survival. Building an unbroken cold chain—from the moment a crop is harvested to the minute it hits the retail shelf—is the only way to shield farmers from market crashes, keep food prices stable for city consumers, and cut down unnecessary carbon emissions. While government initiatives and modern post-harvest tech are finally making inroads, a glaring gap remains between what our farms produce and what actually arrives fresh in our kitchens.

Background
Harvesting doesn't kill fresh produce. A picked tomato or spinach leaf is still a living plant tissue—it respires, loses water, and slowly deteriorates. Every hour spent in the heat and every rough toss during loading cuts directly into its shelf life and nutritional content. This post-harvest decay explains why up to half the food grown globally never makes it to a dinner plate. Fruits and vegetables suffer the worst because they are mostly water (65% to 95%). In India, where farmers produce over 326 million tonnes of horticulture crops every year, losing this volume isn't just waste—it's a massive economic hit in a country struggling with nutritional gaps. The response to this problem was the "cold chain" -a temperature-controlled supply route from harvest to consumer. Developed in Western nations around the mid-20th century, the system changed agricultural trade. India adopted this model in 2008 with its Integrated Cold Chain and Value Addition Infrastructure Scheme, aiming to link farm gates with markets using pack houses, cold storage, reefer trucks, and better logistics. Yet, decades later, the system breaks down where it is needed most. Across rural India and much of the developing world, the "first mile"—the initial stage where farmers actually handle the crop—remains largely untouched by cold infrastructure.

Current Scenario
India's post-harvest management system has improved significantly in recent years, yet post-harvest losses continue to affect farmers and the food supply chain. Today, traditional storage practices and modern cold chain facilities exist side by side. In many villages, farmers still dry grains under the sun, store vegetables in earthen pots or simple underground pits, and sell fresh produce immediately after harvest because cooling facilities are either unavailable or located far from their farms. These methods are affordable and have been used for generations, but they provide only limited protection against heat, moisture, and spoilage. At the same time, modern cold chain technologies are becoming more common in the organized agricultural sector. Food processing companies, exporters, and large agribusiness firms use pack houses, pre-cooling units, refrigerated trucks, ripening chambers, and controlled-atmosphere cold storage to preserve the quality of fruits, vegetables, dairy products, meat, and fish. These technologies help maintain freshness, extend shelf life, and reduce losses during storage and transportation.

However, the benefits of these facilities are not equally shared. Most Indian farmers are small and marginal landholders with limited financial resources. Their production is often too small to make refrigerated transport or cold storage economically feasible. In many cases, the nearest cold storage facility is several kilometres away, making transportation costly and time-consuming. As a result, farmers are often compelled to sell their produce immediately after harvest, even when market prices are low, simply to avoid spoilage. The Government of India has taken several initiatives to strengthen cold chain infrastructure. Under the Pradhan Mantri Kisan Sampada Yojana (PMKSY), 404 Integrated Cold Chain Projects had been approved, and 300 of these projects were completed by December 2025. These investments have expanded cold storage capacity and improved the movement of perishable commodities across many regions. Even with these improvements, post-harvest losses remain a serious concern.

According to recent government estimates, losses range from 6.02% to 15.05% for fruits and 4.87% to 11.61% for vegetables. Marine fisheries and poultry record losses of 8.76% and 5.63%, respectively, while milk has a comparatively lower loss of 0.87%. These figures clearly indicate that infrastructure alone cannot solve the problem. Proper harvesting, grading, packaging, scientific handling, efficient transportation, and timely access to cold storage are equally important for reducing losses. The experiences of other countries also offer useful lessons. China has reduced losses of fruits and vegetables by continuously expanding refrigerated transport and cold storage infrastructure. Similarly, solar-powered cold rooms introduced in countries such as Nigeria and Kenya have shown that reliable cold storage is possible even in areas with limited electricity supply. Such solutions could be adapted to meet the needs of remote farming communities in India.

Overall, India has made encouraging progress in strengthening its post-harvest management system, but much work remains to be done. Improving access to affordable cold storage, strengthening rural roads, promoting Farmer Producer Organizations (FPOs), and encouraging private investment will help make the cold chain more inclusive. A stronger cold chain network will not only reduce post-harvest losses but also improve farmers' incomes, enhance food security, and support sustainable agricultural development.

Major Challenges in Post-Harvest Management and Cold Chain

Although India has expanded its post-harvest infrastructure over the years, several challenges continue to reduce the efficiency of the cold chain system. One of the biggest problems occurs immediately after harvesting. Fresh fruits and vegetables start losing moisture and quality as soon as they are picked. If they remain in the field for several hours under high temperatures, their shelf life is shortened. Even when they are later placed in cold storage, the quality lost during this initial stage cannot be fully recovered. Therefore, timely harvesting, careful handling, and rapid pre-cooling are essential. Another major challenge is inadequate rural infrastructure. Many agricultural areas still have poor road connectivity, an unreliable electricity supply, and limited access to nearby cold storage facilities. In addition, refrigerated vehicles are not available in sufficient numbers. Because of these limitations, farmers often transport produce under unsuitable conditions or sell it immediately after harvest at lower prices to avoid spoilage.

The high cost of cold chain facilities is another barrier. Establishing cold storage units, purchasing refrigerated trucks, and maintaining cooling equipment require substantial investment. For most small and marginal farmers, these costs are difficult to bear. Regular expenses such as electricity, fuel, and equipment maintenance further increase the financial burden, limiting the use of modern cold chain technologies. A shortage of skilled manpower also affects the performance of the cold chain sector. Refrigeration equipment requires trained technicians for installation, operation, and maintenance. In many rural areas, a lack of technical expertise leads to equipment breakdowns, poor maintenance, and inefficient use of existing facilities. Selecting the right technology is equally important. Different crops require different storage temperatures and humidity levels. In some situations, simple and low-cost solutions such as evaporative cooling systems are more suitable than expensive cold storage units. Using inappropriate technologies can increase operating costs and may even reduce the quality of certain agricultural products.

Another concern is the underutilization of government-supported infrastructure. In some locations, cold storage facilities have been established without adequate planning for market linkages, regular supply of produce, trained staff, or efficient management. As a result, some facilities operate below their capacity despite significant public investment. The adoption of digital technologies also remains limited. Modern tools such as the Internet of Things (IoT), artificial intelligence (AI), remote sensors, GPS-based monitoring, and digital supply chain management systems can help monitor storage conditions, improve traceability, and reduce post-harvest losses. However, their adoption is still slow because of high initial costs, limited technical awareness, and inadequate digital infrastructure in many rural regions. Addressing these challenges requires a balanced approach that combines infrastructure development with farmer training, affordable technologies, reliable electricity, improved transportation, and stronger coordination among farmers, government agencies, and private companies. Strengthening these areas will help reduce post-harvest losses, improve farmers' incomes, and build a more efficient and sustainable agricultural supply chain.

Emerging Technologies and Practical Solutions for Post-Harvest Management

Reducing post-harvest losses does not always require costly infrastructure. In many situations, simple and affordable technologies can effectively preserve fresh produce, particularly for small and marginal farmers. One of the best

examples is the Zero Energy Cooling Chamber (ZECC), which cools fruits and vegetables through natural evaporation. Built with two brick walls filled with wet sand, it operates without electricity and is suitable for rural areas. Similarly, clay pot coolers and charcoal-based cooling systems provide low-cost storage options, especially in hot and dry regions. Affordable cold storage technologies are also making modern cooling more accessible. The CoolBot system converts a standard air conditioner into an efficient cold room at a much lower cost than conventional refrigeration. In several developing countries, including Nepal, Bangladesh, and Nigeria, farmers are also using walk-in solar-powered cold rooms and modified shipping containers to store perishable produce where electricity is unreliable. These innovations show that effective cold storage does not always depend on expensive infrastructure.

Advances in packaging are further improving the shelf life of fresh produce. Modified Atmosphere Packaging (MAP) regulates oxygen and carbon dioxide levels around fruits and vegetables, helping them remain fresh for longer. Researchers are also developing edible and nano-based coatings that reduce microbial growth and delay spoilage. In addition, smart packaging with freshness sensors can detect quality deterioration before visible signs of spoilage appear. Digital technologies are transforming cold chain management. Internet of Things (IoT) sensors continuously monitor temperature and humidity in cold stores and refrigerated vehicles, while GPS-based tracking improves the movement of perishable goods. Artificial intelligence (AI) is increasingly used to optimize delivery routes, estimate storage requirements, and predict product shelf life. Some companies are also adopting blockchain technology to improve traceability and ensure transparency throughout the food supply chain. Combining affordable traditional methods with modern technologies offers the most practical path toward reducing post-harvest losses. Wider adoption of these innovations can improve farmers' incomes, reduce food waste, strengthen food security, and build a more efficient and sustainable cold chain system.

Government Initiatives and Real-World Examples

The Government of India has introduced several initiatives to strengthen post-harvest management and expand cold chain infrastructure across the country. Under the Pradhan Mantri Kisan Sampada Yojana (PMKSY), 404 Integrated Cold Chain Projects had been approved, creating better facilities for the storage and transportation of perishable commodities. The scheme encourages broad participation by allowing Farmer Producer Organizations (FPOs), Self-Help Groups (SHGs), cooperatives, companies, NGOs, partnership firms, and government agencies to establish cold chain projects. In November 2025, the Ministry of Food Processing Industries (MoFPI) invited a Request for Proposal (RFP) to conduct a nationwide study on post-harvest losses, highlighting the government's focus on evidence-based planning. In addition, the National Horticulture Board (NHB) provides financial assistance for developing cold storage facilities, while subsidy schemes help reduce investment costs for farmer groups and small entrepreneurs. Experiences from other countries also demonstrate the value of targeted investment. Uzbekistan expanded its cold storage capacity dramatically through a dedicated financing programme over a decade. In Nepal, subsidized CoolBot cold rooms enabled kiwi farmers to store their produce for longer and sell it in higher-value markets.

Several practical examples further illustrate the impact of appropriate cold chain solutions. ColdHubs in Nigeria established solar-powered walk-in cold rooms in local markets, allowing farmers and vendors to rent storage space without depending on the electricity grid. In Guntur, Andhra Pradesh, chilli farmers used cold storage to avoid distress sales and wait for more favourable market prices. Similarly, mango growers in East Africa adopted simple evaporative cooling rooms made from bricks, sand, and water, helping them preserve fruit quality long enough to reach regional markets. These examples show that selecting technologies suited to local conditions can significantly reduce post-harvest losses and improve farmers' incomes.

Future Scope of Post-Harvest Management and Cold Chain

The future of post-harvest management in India will depend on adopting practical and affordable solutions rather than relying only on expensive technologies. Different crops and farming regions have different requirements, so selecting the right combination of storage, cooling, and transportation will be more important than using a single solution everywhere. Simple decision-support tools can help farmers, cooperatives, and planners choose technologies that match local conditions and available resources. Renewable energy is expected to play a major role in expanding cold chain facilities, particularly in rural areas where electricity supply is unreliable. Solar-powered cold storage systems and solar-battery hybrid technologies can provide reliable cooling while reducing operating costs. For mixed farming systems, integrating dry storage for grains and pulses with cold storage for fruits, vegetables, dairy products, and other perishables can improve overall farm efficiency. However, technology alone cannot solve the problem. Better rural roads, farmer training, affordable credit, and efficient transport networks are equally important to ensure that modern cold chain systems deliver lasting benefits across India's agricultural sector.

Conclusion

Post-harvest losses should not be viewed as an unavoidable part of agriculture. With timely harvesting, proper handling, efficient transportation, appropriate storage, and suitable packaging, a large share of these losses can be prevented. Experiences from India and several other countries clearly show that maintaining the cold chain from the farm to the

consumer helps preserve the quality, safety, and shelf life of agricultural produce. Depending on local conditions, both low-cost solutions such as Zero Energy Cooling Chambers and clay pot coolers, as well as modern technologies like solar-powered cold rooms, IoT-based monitoring, and digital cold chain management, can contribute to reducing food losses. For India, strengthening post-harvest management is not only a technological challenge but also an opportunity to improve the livelihoods of millions of smallholder farmers. A reliable cold chain can reduce food waste, improve market access, increase farmers' incomes, and ensure that consumers receive better-quality food. Continued investment in cold chain infrastructure, rural roads, farmer training, affordable credit, and supportive government policies will be essential for achieving these goals. The focus should not be on adopting the most expensive technology, but on providing practical, affordable, and location-specific solutions that farmers can easily use. Building an efficient and inclusive cold chain system will play an important role in creating a more resilient, sustainable, and productive agricultural sector in India.

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Micronutrient Deficiencies in Indian Soils: Their Causes and Management

Article ID: 74282

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Abstract

Crops grown in most soils in India suffer from deficiencies of one or more micronutrients, even though the soils often contain apparently adequate total amounts of the respective elements. The nature and extent of deficiencies vary with soil type, crop genotype, management and agro-ecological situations. With the intensive cropping of high-yielding varieties of rice and wheat, deficiency of zinc (Zn) initially, and subsequently deficiencies of iron (Fe) in rice, and manganese (Mn) in wheat, emerged as threats to sustaining high levels of food crop production. Analysis of soil and plant samples has indicated that 49% of soils in India are potentially deficient in Zn, 12% in Fe, 5% in Mn, 3% in copper (Cu), 33% in boron (B) and 11% in molybdenum (Mo). Basal application to soil and/or foliar sprays of Zn, B and Mo, and foliar sprays of Fe and Mn have been recommended as the most suitable methods for correcting such deficiencies in crops. Deficiency of these nutrients in soil is also affecting crop productivity, quality of food, and human nutrition.

Keywords: Micronutrients, secondary nutrients, crop genotype, high-yielding varieties, agronomic fortification.

Introduction

Indian agriculture during the past 50 years has achieved a fourfold growth in food production by adopting modern agricultural practices. The availability of fertilizer-responsive, high-yielding varieties (HYV) of rice, wheat and maize has made it possible to produce 15–20 t ha^{-1} $year^{-1}$ of biomass dry matter. Initially, this became possible by using nitrogenous (N) fertilizers alone, as the soil could provide all other essential nutrients needed by plants. However, within a few years, the nutrient reserves in soil were gradually exhausted and it was no longer possible to sustain higher yields even by applying both N and phosphorus (P) Thus, in areas of high cropping intensity, deficiencies of secondary nutrients and micronutrients were frequently observed in cereal, oilseed, pulse and vegetable crops, which became critical in obtaining and sustaining higher crop production over the years.

India is endowed with a diverse climate. The rainfall ranges generally between 200 and 2,200 mm per annum. The country has 142 Mha of cultivable land out of a total area of 329 Mha. The cropping intensity is 145%. Cropping systems based on rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), sorghum (*Sorghum vulgare* L.), cotton (*Gossypium hirsutum* L.), soybean (*Glycine max* L.), sugarcane (*Saccarum officinarum* L.), potato (*Solanum tuberosum* L.), mustard (*Brassica juncea*), groundnut (*Arachis hypogaea* L.), green gram (*Vigna radiata* L.), black gram (*Phaseolus mungo* L.) and chick pea (*Cicer arietinum* L.) occupy most of the area. These crops show high responses to the application of both macro and micronutrients. Field-scale zinc (Zn) deficiency was first noticed in rice in tarai soils (Mollisols) of the foothills of the Himalayas, which caused the complete failure of the rice crop. The problem is more acute in alkali soils.

To address the emerging problem of micronutrient deficiencies in crops in the mid-1960s, the Indian Council of Agricultural Research (ICAR) established the All India Coordinated Scheme of Micronutrients in Soils and Plants during 1967 at Punjab Agricultural University, Hisar, with Late Dr. N.S. Randhawa as its first Project Coordinator. Basic objectives of the scheme were to delineate micronutrient deficiencies in various soils and crops and develop strategies to alleviate these deficiencies. Initially, the scheme had six cooperating centres, but the project was expanded with time both in terms of mandate and cooperating centres.

Currently, it is named as the ICAR-All India Coordinated Research Project on Micro- and Secondary Nutrients and Pollutant Elements in Soils and Plants (AICRP-MSPE) with headquarter at the ICAR-Indian Institute of Soil Science, Bhopal, having 21 cooperating centres spread over the entire length and breadth of the country.

Currently, the AICRP-MSPE has the following objectives.

1. To delineate and/or reassess and map micro- and secondary- nutrients deficient and toxic areas using GPS/GIS, and developing amelioration techniques for their correction

2. To forecast emerging micro- and secondary nutrients deficiencies and toxicities in crops and soils in different soils, crops and management systems

3. To establish the critical limits of micro- and secondary nutrients as well as phytotoxic limits of heavy metals in different soils and crops, including vegetables

4. To develop suitable techniques for increasing fertilizer-use-efficiency along with inclusion of nano-fertilizers, organic manures, and sewage sludge for ameliorating the micro- and secondary- nutrient deficiencies in crops and soils

5. To develop agronomic biofortification approaches for micronutrient enrichment and to identify mechanisms and processes of micronutrient enrichment and their role in reproductive physiology

6. To study micronutrients in soil-plant-animal and /or human continuum

7. To monitor health hazards from heavy metals or pollutant elements in soils, plants and animals 8. To disseminate technologies generated through frontline demonstrations and suitable publications for enhancing the nutrient use efficiencies and their impact on soil, animal and human health and crop productivity

Soil fertility and plant nutrition are both governed by criteria of essentiality (Arnon and Stout in 1939 and further modified by Arnon in 1954). Earlier, there were 16 essential elements and now there are 17. Researchers, policymakers and farmers are mostly concerned with the primary nutrients, i.e., NPK, to manage the crops, and it further aggravates the deficiency of micronutrients, which is now a major concern for all because it is affecting human and animal nutrition along with plants. This deficiency concerns not only plant nutrition but has far reaching implication in the form of nutritional insecurity among the livestock and marginal sections of the population.

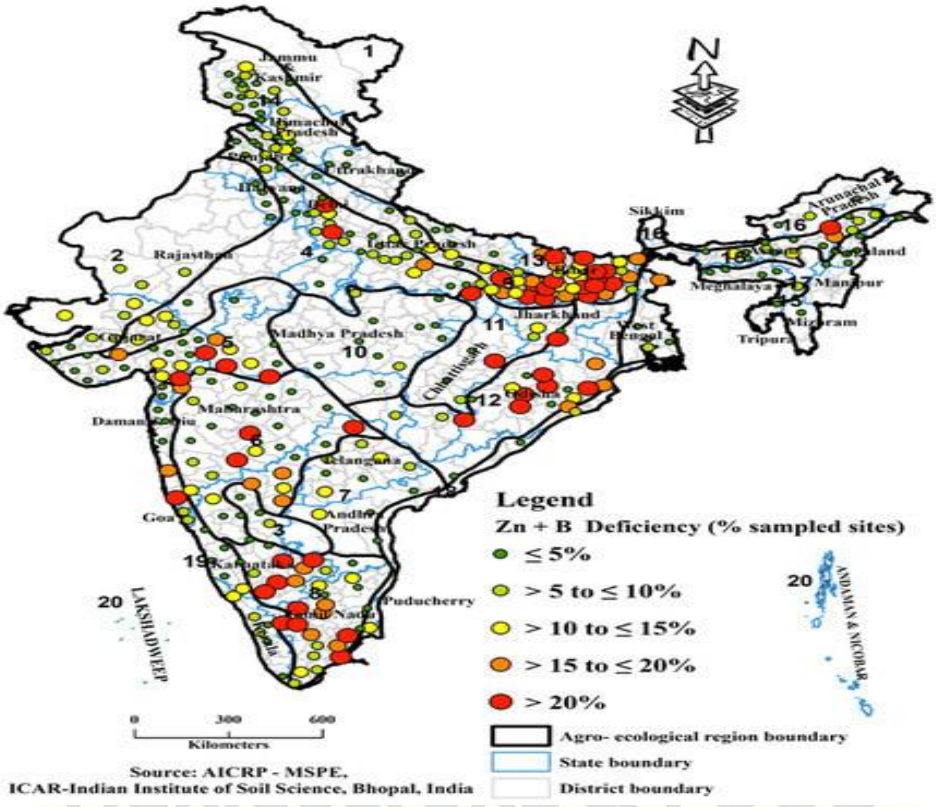


Figure 1. Distribution of Zn + B deficiency in soils (% of sampled sites) of different parts of India. Number denotes agro-ecological regions

Causes of Micronutrient Deficiencies

The introduction of high-yielding varieties, intensive cultivation systems, micronutrient-free fertilizer application, non-addition of organic manures and imbalanced plant nutrition has led to multi-micronutrient deficiencies in soils in many parts of the globe. The importance of micronutrients can be realised from their incredible functions in plants that result in quality produce, as each essential micronutrient plays some specific functions in plants. Availability of micronutrients to plants is regulated by various soil factors such as texture, soil reaction, organic matter, clay content, soil moisture, nutrient interactions in soil, microbial activity, redox potential and aeration, etc. Most Indian soils are alkaline in nature, which reduces the availability and plant uptake of essential micronutrients such as zinc (Zn), iron (Fe), and boron (B). In addition, the calcareous nature of many soils, characterized by high calcium carbonate ($CaCO_3$) content, further immobilizes iron and zinc, making them less accessible to plant roots. Furthermore, light-textured sandy soils are prone to leaching, allowing water to carry essential micronutrients beyond the root zone, thereby reducing their availability for crop uptake.

Management of Micronutrient Deficiency in Indian Soils

Micronutrient management varies with crops, soil types, severity of deficiency, method, time, rates and frequency of application. While planning for replenishment of the micronutrients removed by the crop and /or depleted from soil through micronutrient management, important aspects like micronutrient requirements of the crops and cropping systems, ranges between their deficiencies and toxicities, low use efficiency of micronutrients, and residual availability etc. Through proper management practices, liming and applying micronutrients directly in soil or as foliar application. Moreover, exploitation of soil microbes such as micronutrient solubilisers and AM fungi has proven as boon in micronutrient uptake and improving soil quality. Maintenance of optimum soil organic matter status and balanced fertilization or soil test-based fertilizer application also lead to biofortified farm produce, eliminate micronutrient deficiency and improve soil and plant health.

Future Research Requirements

1. Develop efficient soil testing methods and establish critical micronutrient limits for accurate diagnosis of deficiencies, improving nutrient use efficiency and site-specific nutrient management.

2. Identify and map micronutrient-deficient and toxic areas using georeferenced GIS-based databases to support sustainable crop production and soil health.

3. Develop predictive models for micronutrient availability and integrate them with GIS for field-level nutrient management.

4. Investigate micronutrient transformations, fixation, release, and soil-root interactions to optimize micronutrient management across different soils and cropping systems.

5. Promote integrated micronutrient management by combining organic amendments, microbial inoculants, and industrial by-products to enhance nutrient availability and use efficiency.

6. Advance genetic and agronomic biofortification to increase micronutrient concentrations in food grains and fodder, improving human and animal nutrition.

Conclusions

Micronutrient deficiency in plants is a notable challenge in crops. Following good farming practices can effectively manage these challenges. Regular field inspections, early detection of symptoms, and timely corrective actions are the key pillars of successful cultivation. Such measures help crops grow stronger, greener, and more productive. Overall, nutrient deficiencies followed the order: S > Zn > B > Fe > Mn > Cu. Severe S and B deficiencies were most common in Kerala, Odisha, and West Bengal, while acute Zn deficiency was prevalent in Rajasthan, Madhya Pradesh, Goa, Odisha, and Karnataka. Multiple nutrient deficiencies, particularly S + Zn, Zn + B, S + B, and Zn + Fe, were observed in specific regions. The need to overcome micronutrient deficiency site-specific nutrient management, customized fertilizers, and regular monitoring of soil nutrient status at 3–5-year intervals. The use of GIS- and geostatistics-based nutrient maps can further support precision nutrient management and sustainable crop production while improving soil health and crop quality.

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Current Perspectives on Insect Pests and Diseases of Gladiolus and their Integrated Management

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Gladiolus (*Gladiolus grandiflorus* L.) is one of the most important commercial cut flowers cultivated worldwide due to its attractive spikes, wide range of colors, and excellent vase life. It belongs to the family Iridaceae and is extensively grown for cut flower production, garden decoration, and landscape beautification. India has emerged as a major producer of gladiolus, with cultivation concentrated in states such as West Bengal, Karnataka, Himachal Pradesh, Uttarakhand, Maharashtra, and Rajasthan. Despite its economic importance, gladiolus production is often constrained by numerous insect pests and diseases that reduce flower quality, corm yield, and market value. Effective management of these biotic stresses requires proper identification of the causal organisms, understanding of their epidemiology, and adoption of integrated pest and disease management (IPDM) practices.



Major Insect Pests of Gladiolus

1. Thrips (*Thrips tabaci* Lindeman): Thrips are considered the most destructive insect pests of gladiolus. Both nymphs and adults feed by scraping the leaf and flower tissues and sucking cell sap. Their feeding results in silvery streaks, curling of leaves, deformation of flower buds, discoloration of petals, and reduced spike quality. Heavy infestations may prevent proper flower opening. Thrips also serve as vectors of viruses, particularly Iris yellow spot virus (IYSV) in some ornamental crops.

Management includes the use of healthy planting material, destruction of crop residues, installation of blue or yellow sticky traps, conservation of natural enemies such as predatory mites and lacewings, and need-based application of insecticides such as spinosad, imidacloprid, or fipronil following local recommendations.



2. Aphids (*Myzus persicae* and *Aphis gossypii*): Aphids attack young shoots, flower buds, and leaves by sucking plant sap. Infested plants exhibit leaf curling, yellowing, stunted growth, and reduced flower production. Aphids excrete honeydew, which encourages the development of sooty mold fungi. More importantly, they transmit several plant viruses that significantly reduce flower quality.



Management strategies include removal of weed hosts, monitoring populations regularly, encouraging predators such as ladybird beetles and hoverflies, and spraying systemic insecticides when infestations exceed economic thresholds.

3. Red Spider Mite (*Tetranychus urticae* Koch): Spider mites are important pests under warm and dry environmental conditions. Feeding causes tiny yellow specks on leaves, followed by bronzing, drying, and premature leaf fall. Severe infestations reduce photosynthetic activity and corm development.



Management includes maintaining adequate field humidity, avoiding moisture stress, conserving predatory mites, and applying recommended acaricides when necessary.

4. Cutworms (*Agrotis ipsilon*): Cutworm larvae remain hidden in the soil during the day and cut young gladiolus plants near the soil surface at night. This results in poor plant establishment and reduced plant population.

Deep summer ploughing, field sanitation, collection and destruction of larvae, light traps, poison bait, and recommended insecticides are effective management measures.

5. Root-Knot Nematodes (*Meloidogyne* spp.): Although nematodes are microscopic roundworms rather than insects, they are serious pests of gladiolus. They induce characteristic root galls, reduce nutrient uptake, weaken plants, and decrease spike and corm production.

Crop rotation, soil solarization, organic amendments, biological control agents such as *Purpureocillium lilacinum*, and certified nematode-free planting material help minimize nematode damage.

Major Diseases of Gladiolus

1. Fusarium Wilt and Corm Rot

Causal organism: *Fusarium oxysporum* f. sp. *gladioli*

Fusarium wilt is among the most destructive diseases of gladiolus worldwide. The pathogen survives in soil and infected corms for several years. Initial symptoms include yellowing of lower leaves, wilting, vascular discoloration, and eventual death of plants. Infected corms develop brown to dark brown sunken lesions and internal rotting.

The disease develops rapidly under warm soil temperatures (25–30°C), poor drainage, and continuous cultivation of gladiolus.



Management includes the use of disease-free corms, crop rotation for at least 3–4 years, destruction of infected plant debris, hot-water treatment of corms, seed treatment with fungicides such as carbendazim or thiophanate-methyl (where permitted), and application of biological control agents including *Trichoderma harzianum*.

2. Botrytis Blight (Grey Mold)

Causal organism: *Botrytis gladiolorum* or *Botrytis cinerea*

Botrytis blight affects leaves, flowers, stems, and corms under cool and humid weather conditions. Small brown lesions enlarge rapidly and become covered with characteristic grey fungal growth. Flower quality deteriorates significantly during storage and transportation.

Proper spacing, improved air circulation, removal of infected plant parts, and preventive fungicide applications help reduce disease incidence.

3. Curvularia Leaf Spot

Causal organism: *Curvularia lunata*

The disease produces small, oval to elongated brown lesions with dark margins on leaves. Severe infections reduce photosynthetic area and flower quality. Warm temperatures combined with high humidity favor disease development.



Field sanitation, balanced fertilizer application, and protective fungicide sprays are commonly recommended.

4. Penicillium Corm Rot

Causal organism: *Penicillium* spp.

This storage disease mainly affects harvested corms. Infected corms become soft and are covered with characteristic blue-green fungal growth, resulting in poor sprouting and reduced field establishment.

Proper curing, storage at recommended temperature and humidity, careful handling to avoid injuries, and fungicide treatment before storage effectively reduce losses.

5. Viral Diseases

Bean Yellow Mosaic Virus (BYMV): BYMV causes mosaic mottling, chlorotic streaking, leaf distortion, reduced plant vigor, and malformed flowers. The virus is primarily transmitted by aphids in a non-persistent manner.



Cucumber Mosaic Virus (CMV)

CMV induces mosaic patterns, chlorosis, stunting, and poor spike development. The virus has a wide host range and is transmitted mainly by aphids.

Management of viral diseases depends largely on preventing vector populations, removing infected plants promptly, eliminating weed reservoirs, and planting certified virus-free corms.

Integrated Pest and Disease Management (IPDM)

An integrated approach is essential for sustainable gladiolus production. Important components include:

1. Selection of certified healthy and disease-free corms.
2. Crop rotation with non-host crops for at least three years.
3. Well-drained soil and balanced nutrient management.
4. Proper irrigation to avoid prolonged leaf wetness.
5. Regular field scouting for early detection of pests and diseases.
6. Installation of sticky traps for monitoring flying insects.
7. Conservation of beneficial insects and natural enemies.
8. Timely removal and destruction of infected plants and crop residues.
9. Judicious use of insecticides, fungicides, and biological control agents according to integrated pest management principles.
10. Proper curing and storage of harvested corms under recommended environmental conditions.

Conclusion

Insect pests and diseases remain major constraints to profitable gladiolus cultivation. Thrips, aphids, spider mites, and cutworms are among the principal insect pests, while Fusarium wilt, Botrytis blight, Curvularia leaf spot, Penicillium corm rot, and viral diseases cause significant reductions in flower quality and corm production. Successful management relies on integrated pest and disease management strategies that combine cultural, biological, physical, and chemical methods. The use of certified planting material, regular crop monitoring, proper sanitation, biological control, and need-based pesticide application not only minimizes crop losses but also promotes environmentally sustainable gladiolus production.

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Rainy Season Floriculture in India: Cultivation Practices and Crop Management

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Introduction

Seasonal flowers are an important component of the Indian floriculture industry due to their aesthetic value, economic importance, and increasing demand in landscaping, religious ceremonies, and the cut flower market. India possesses diverse agro-climatic conditions that allow the cultivation of numerous annual flowering plants throughout the year. The rainy season (Kharif season), extending from June to September, provides favourable environmental conditions such as adequate soil moisture, moderate temperatures, and high relative humidity, which support the vigorous growth of many seasonal flowering species. However, excessive rainfall, waterlogging, high humidity, and disease incidence also present significant production challenges. Therefore, scientific crop management practices are essential to achieve optimum flower quality and yield.

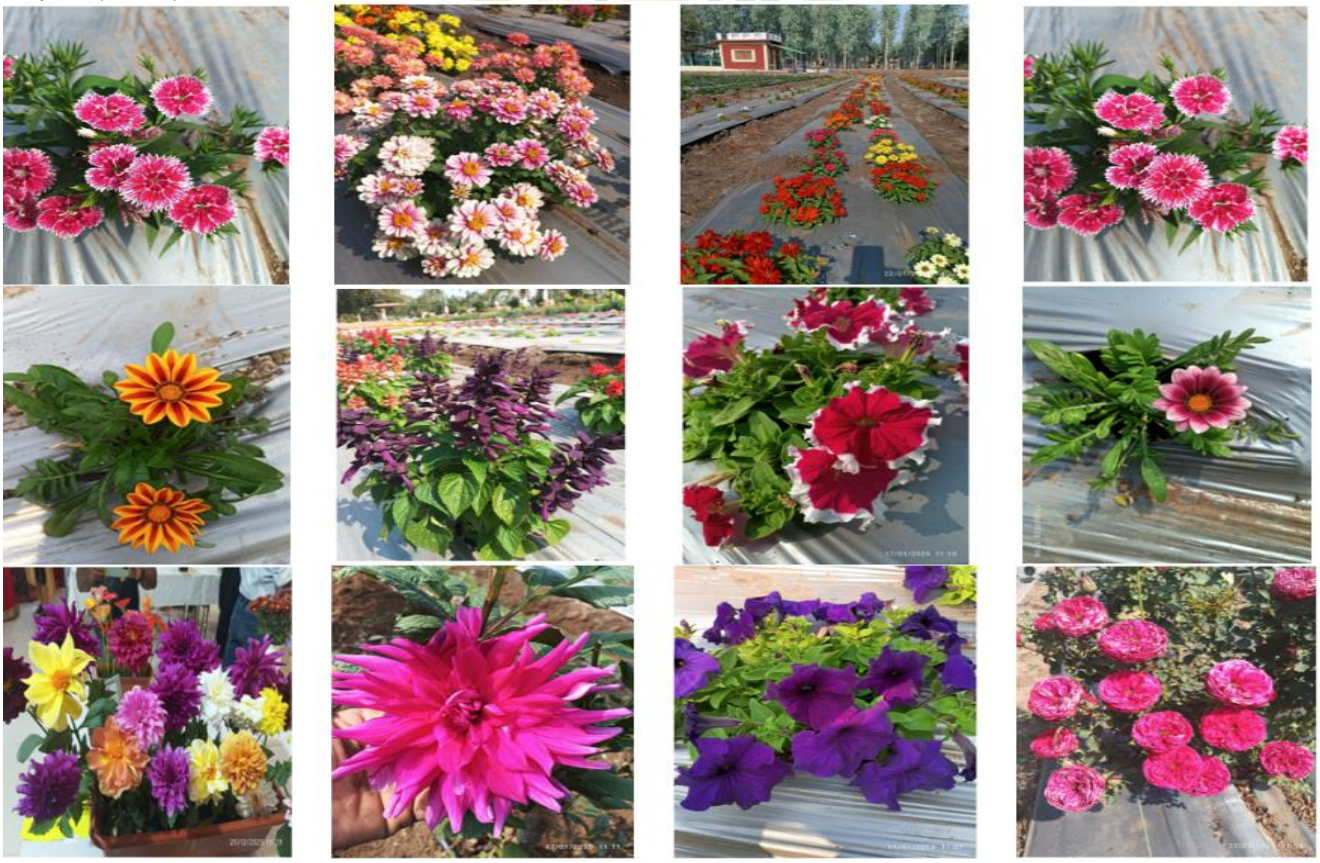


Fig. Annual Seasonal Flowers

Suitable Seasonal Flowers for Rainy Season

Several ornamental annuals perform well during the monsoon season in India. Common rainy-season flowering species include balsam (*Impatiens balsamina* L.), cockscomb (*Celosia argentea* L.), cosmos (*Cosmos sulphureus* Cav.), sunflower (*Helianthus annuus* L.), zinnia (*Zinnia elegans* Jacq.), gomphrena (*Gomphrena globosa* L.), marigold (*Tagetes erecta* L. and *T. patula* L.), portulaca (*Portulaca grandiflora* Hook.), and torenia (*Torenia fournieri* Linden ex E. Fourn.). These crops are widely cultivated for bedding, borders, landscaping, garland making, and cut flower production due to their adaptability and prolonged flowering period.

Climate and Soil Requirements

Rainy-season annual flowers thrive under warm and humid climatic conditions with temperatures ranging from 20 to 30°C. Adequate sunlight is necessary for proper flowering, although certain species tolerate partial shade. Well-drained

sandy loam or loam soils with good organic matter content and a soil pH of 6.0–7.5 are considered ideal. Proper drainage is critical because prolonged waterlogging reduces root aeration, encourages root rot pathogens, and negatively affects plant growth.

Land Preparation and Sowing

The field should be ploughed thoroughly to obtain a fine tilth. Well-decomposed farmyard manure (15–20 t ha^{-1}) should be incorporated during land preparation to improve soil fertility and structure. Raised beds of 15–20 cm height are recommended to facilitate drainage during heavy rainfall. Seeds are generally sown in nursery beds and healthy seedlings are transplanted after 20–30 days, whereas some species such as sunflower and cosmos are directly sown in the field. Appropriate spacing varies depending on the crop, generally ranging from 20 × 20 cm to 45 × 45 cm.

Nutrient Management

Balanced fertilization plays a vital role in maximizing flower yield and quality. In addition to organic manure, recommended doses of nitrogen, phosphorus, and potassium should be applied according to crop requirements. Nitrogen is usually applied in split doses to minimize nutrient loss through leaching during heavy rains. Micronutrients such as zinc, boron, and iron may be supplied through foliar sprays when deficiency symptoms appear. Integrated nutrient management combining organic manures, biofertilizers, and inorganic fertilizers enhances soil health and improves nutrient use efficiency.

Irrigation and Drainage Management

Although rainfall provides much of the crop water requirement, supplemental irrigation may be necessary during prolonged dry spells. Efficient drainage is more important than irrigation during the rainy season. Excess water should be removed promptly through drainage channels to prevent root diseases and oxygen deficiency. Mulching with organic materials can help reduce soil erosion, suppress weeds, and improve soil moisture conservation during intermittent dry periods.

Weed Management

Weeds compete with flowering plants for nutrients, water, sunlight, and space. Manual weeding at regular intervals remains the most effective method for small-scale cultivation. In commercial production, pre-emergence herbicides may be used judiciously following agricultural recommendations. Mulching also helps suppress weed emergence while maintaining favourable soil conditions.

Pest and Disease Management

High humidity during the rainy season favours the development of fungal diseases such as damping-off, powdery mildew, leaf spot, Alternaria blight, and root rot. Common insect pests include aphids, thrips, mites, whiteflies, and caterpillars. Integrated Pest Management (IPM) strategies involving disease-free planting material, crop rotation, proper spacing, field sanitation, biological control agents, and need-based application of recommended fungicides and insecticides are essential for sustainable flower production. Regular field monitoring enables early detection and timely management of pest outbreaks.

Harvesting and Post-Harvest Management

Flowers should be harvested during the cool hours of the morning when field temperatures are low. Harvesting at the proper developmental stage enhances vase life and market value. Immediately after harvest, flowers should be placed in clean water or appropriate preservative solutions and stored under cool conditions to maintain freshness. Careful grading, packaging, and transportation reduce post-harvest losses and improve market returns.

Economic Importance

Rainy-season flower cultivation generates substantial employment opportunities, particularly for small and marginal farmers. Seasonal flowers are extensively used in religious offerings, festivals, public gardens, landscaping, and the floral decoration industry. Increasing urbanization, tourism, and demand for ornamental plants have significantly expanded the commercial floriculture sector in India. Adoption of improved production technologies can enhance productivity, profitability, and sustainability.

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Nature's Blueprint for Next-Generation Engineering: Insect-Inspired Biomimetics

Article ID: 74285

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Abstract

Biomimetics is an emerging interdisciplinary field that uses biological structures, mechanisms and processes as an inspiration for developing innovative and sustainable technologies. Insects serve as exceptional models for biomimetic research because of their highly evolved adaptations for locomotion, sensing, protection, adhesion and structural design. Their lightweight exoskeletons, aerodynamic and highly efficient wings and specialized sensory systems have directly inspired advances in robotics, smart materials, micro-air vehicles and biomedical devices. Hymenopteran ovipositors, capable of flexible, precise and low-force penetration, offer especially valuable design principles for minimally invasive surgical instruments and bioinspired robotic manipulators. Insights into the functional mechanisms of insect adaptations provide a foundation for developing innovative, lightweight and adaptive technologies to address contemporary engineering challenges.

Keywords: Biomimetics, Bio-inspired engineering, Bio-inspired robotics, Biomedical devices, Insect-inspired technology, Insect biomechanics.

Introduction

Biomimetics involves studying biological structures, mechanisms and processes to develop innovative solutions for human challenges (Vincent *et al.*, 2006). The term was introduced by Otto H. Schmitt, while Jack E. Steele introduced the related concept of "*bionics*" for nature-inspired systems (Schmitt, 1969). Since the late 20th century, biomimetics has evolved into a multidisciplinary field, also referred to as biomimicry and bio-inspired design, integrating biology with engineering, materials science, medicine, robotics and architecture to develop sustainable and advanced technologies (Benyus, 1997). Insect biological systems serve as valuable design models due to their evolved properties, including adaptability, self-organization, lightweight structures and self-repair (Bar-Cohen, 2005; Vincent, 2001). Examples include bird-inspired aircraft, honeycomb-based lightweight structures and plant-inspired adaptive materials (Gordon, 1976; Stahlberg and Taya, 2006). With advances in nanotechnology and engineering, biomimetics continues to drive the development of sustainable, resilient and high-performance technologies (Bar-Cohen, 2005).

Insects as a Source for Biomimetics

Insects serve as important models in biomimetics due to their efficient solutions for movement, sensing, protection and adaptation. Their lightweight exoskeletons, specialized sensory systems and multifunctional structures inspire innovations in robotics, materials science and engineering (Vincent *et al.*, 2006). For example, the directional hearing mechanism of the parasitoid fly *Ormia ochracea* has inspired miniature sound sensors, while insect wing structures have contributed to the development of self-cleaning and water-repellent materials (Mason *et al.*, 2001; Wagner *et al.*, 1996). By applying the functional principles underlying insect adaptations, researchers are developing bio-inspired technologies, including smart materials and micro-scale devices.

Insects as Models for Biomimetics

Insects are highly successful organisms whose evolved structures provide valuable models for biomimetics. By studying insect morphology and biomechanics, researchers extract functional principles from natural systems to develop innovative technologies rather than simply copying biological forms (Vincent *et al.*, 2006). Insect-inspired designs, including lightweight exoskeletons, efficient wings, adhesion mechanisms, and sensory systems, have contributed to advances in robotics, materials science, micro-air vehicles, and medical devices (Bar-Cohen, 2006).

Insects as Models for Biomimetic Engineering

Insects provide valuable models for biomimetics due to their highly efficient structures and functions evolved through natural selection. Studying insect morphology and biomechanics allows researchers to apply biological principles to engineering rather than simply replicating natural forms (Vincent *et al.*, 2006). The lightweight chitin-protein exoskeleton inspires the development of advanced composite materials, while insect wing designs inform the development of micro-air vehicles and flapping-wing robots (Vincent, 2002; Ellington, 1999). Insect sensory systems, locomotion and adhesion mechanisms have further influenced miniature sensors, adaptive robots, reusable adhesives

and climbing technologies (Mason *et al*., 2001; Blickhan *et al*., 2007; Autumn *et al*., 2002). These bio-inspired approaches support the development of lightweight, efficient and adaptive technologies in robotics, materials science and engineering.

Hymenopteran Ovipositors as Models for Biomimetic Engineering

Hymenopteran ovipositors of bees, wasps and ants are specialized structures that demonstrate efficient natural engineering through their lightweight, flexible and segmented design. Originally evolved for egg-laying, these structures have adapted for drilling, piercing and venom injection, enabling low-energy penetration with minimal resistance. The ovipositor consists of three interacting valves that provide strength, flexibility and precise movement, making it a valuable model for biomimetic engineering (Quicke *et al*., 1999; Vincent and Mann, 2002). Their unique penetration mechanisms have inspired the development of bio-inspired medical needles, minimally invasive surgical tools, micro-robotic systems and advanced lightweight materials for biomedical, robotic and aerospace applications (Vincent *et al*., 2006; Lehnert *et al*., 2013; Vincent, 2012). These designs improve precision and reduce tissue or material damage compared with conventional rigid systems.

Biomimetic Technologies Inspired by Insects

Insect-inspired biological mechanisms have contributed to the development of innovative technologies in engineering, materials science, robotics and medicine. The flexible wing structures and efficient flight mechanisms of insects have guided the design of micro-air vehicles (MAVs) for applications such as environmental monitoring and surveillance (Ellington, 1999). Insect exoskeletons and wing structures have inspired lightweight, strong and flexible biomimetic materials, while ovipositor-based penetration mechanisms have influenced the development of minimally invasive medical needles and precision robotic devices (Vincent, 2002; Quicke *et al*., 1999). These approaches demonstrate how insect functional principles can be translated into advanced and efficient technological solutions.

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From Learning to Practice: Evaluating the Impact of Accrual Accounting Training in the ICAR System

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Abstract
The transition towards accrual accounting has emerged as a significant reform in public financial management, promoting greater transparency, accountability, and informed decision-making. To strengthen the financial management capabilities of administrative and finance professionals, the ICAR-National Rice Research Institute (NRRI), Cuttack, organized the fourth and fifth batches of a five-day Training Programme on Accrual Accounting through virtual mode during September and November 2021. The programme aimed to enhance participant's conceptual understanding and practical knowledge of accrual accounting, Goods and Services Tax (GST), General Financial Rules (GFR), Treasury Single Account (TSA), Income Tax, and related financial procedures. To objectively assess the effectiveness of the training, pre- and post-training assessments of participants from both batches were compiled and analysed after data curation. A total of 79 participants representing ICAR institutes across the country were included in the analysis. Statistical evaluation revealed a significant improvement in participant's knowledge after completion of the programme *(paired t-test, $p < 0.001$)*, with a medium-to-large practical effect size (Cohen's $d = 0.79$). The findings demonstrate that structured competency-based training substantially improves financial management knowledge and strengthens institutional capacity within the ICAR system.

Introduction
Financial management in research organizations has undergone substantial transformation with increasing emphasis on transparency, accountability, and efficient utilization of public resources. Traditional cash-based accounting systems, while useful for recording receipts and payments, often fail to provide a comprehensive picture of assets, liabilities, depreciation, and long-term financial obligations. Accrual accounting addresses these limitations by recognizing financial transactions when they occur rather than when cash is exchanged, thereby presenting a more realistic representation of an institution's financial position. Recognizing the importance of this paradigm shift, the ICAR-National Rice Research Institute (NRRI), Cuttack, organized the fourth and fifth batches of the five-day Training Programme on Accrual Accounting during 20-24 September 2021 and 22-26 November 2021, respectively. The programme was designed primarily for Finance & Accounts Officers, Administrative Officers and other officials working in ICAR institutes and Central Agricultural Universities. The training was delivered through virtual mode by eminent resource persons, including senior financial administrators from ICAR Headquarters and premier ICAR institutes. The sessions covered both conceptual and practical aspects of financial management, including Accrual Accounting, GST, General Financial Rules (GFR), Treasury Single Account (TSA), Income Tax, accounting procedures, financial reporting, and record management. Interactive lectures, assignments, daily quizzes, recapitulation sessions, and case-based discussions ensured active participation and improved learning outcomes.

Assessment Approach
The effectiveness of the training programme was evaluated using a pre- and post-training assessment design. Assessment scores from the fourth and fifth training batches were compiled and carefully curated to eliminate incomplete records and inconsistencies. The final dataset consisted of 79 participants, representing a broad cross-section of ICAR institutes across India. Each participant completed an objective assessment before commencement of the programme and an identical post-training assessment at the end of the course. The maximum obtainable score was 25 marks. Learning improvement was quantified by comparing individual pre-training and post-training scores and calculating percentage gain. To statistically validate the learning outcomes, descriptive statistics, gain analysis, histogram distributions, box plots, and paired *t*-tests were performed. Cohen's *d* effect size was also estimated to determine the practical significance of the observed improvement beyond statistical significance.

Results and Discussion
The combined analysis of the fourth and fifth training batches clearly demonstrated that the Accrual Accounting training programme significantly enhanced participant's knowledge and understanding of modern financial management practices. The distribution of assessment scores showed a noticeable shift towards higher scores following completion of the programme. Most participants recorded positive improvements, indicating that the structured training effectively strengthened their conceptual understanding of accrual accounting and associated financial regulations. Individual gain analysis revealed considerable learning improvement across participants. Although the magnitude of improvement varied

depending on participants' prior knowledge and professional experience, the majority achieved positive score gains, with several participants improving by $20 - 56\%$ over their baseline scores. A small number exhibited little or even negative change, which may reflect differences in initial competency, assessment performance, or learning pace. Nevertheless, the overall trend strongly favoured substantial knowledge enhancement.

Statistical analysis further confirmed these observations. The paired t-test indicated a highly significant improvement between pre- and post-training assessment scores ($t = -7.319, df = 78, p < 0.001$), providing strong evidence that the observed increase was not due to random variation. On average, participants improved by 3.32 marks on a 25-mark assessment (95% Confidence Interval: 2.41-4.22 marks). The practical importance of the programme was further supported by the estimated Cohen's effect size (d = 0.79), representing a medium to large educational effect. This suggests that the programme not only produced statistically significant improvements but also generated meaningful enhancement in participants' competency.

The effectiveness of the programme can largely be attributed to its carefully designed instructional strategy. Expert faculty members from ICAR Headquarters and leading ICAR institutes delivered practical sessions integrating accounting principles with real administrative situations. Regular quizzes, assignments, discussions, and daily recapitulation helped reinforce learning and encouraged active participation throughout the five-day programme. Overall, the findings indicate that structured competency-based financial training can substantially improve professional capabilities among finance and administrative personnel, thereby contributing to improved financial governance and accountability across ICAR institutions.

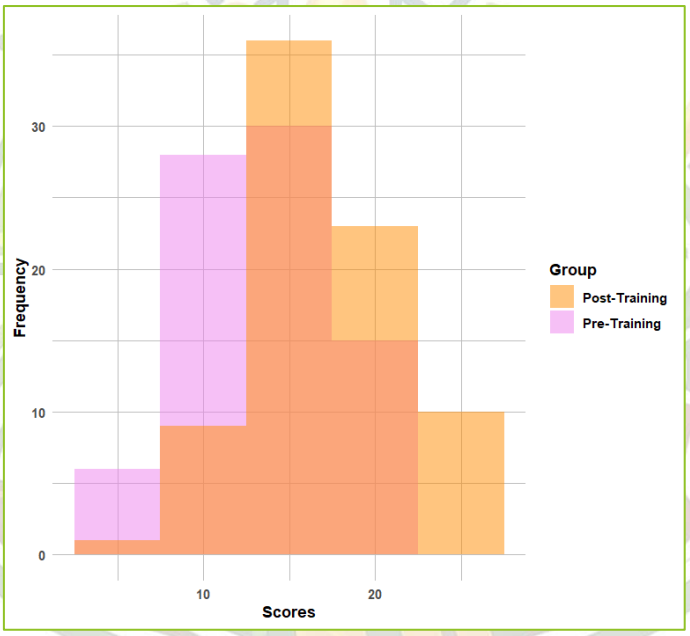


Figure 1: Histogram of Pre- and Post-training Scores



Figure 2: Box Plot Comparing Pre- and Post-training Scores.

Conclusion

The combined evaluation of the fourth and fifth batches of the Accrual Accounting training programme clearly demonstrates the effectiveness of structured capacity-building initiatives in strengthening financial management competencies within the ICAR system. Analysis of assessment scores from 79 participants revealed statistically significant and practically meaningful improvements in knowledge following the training. The medium-to-large effect size further indicates that the programme substantially enhanced participants' understanding of accrual accounting and related financial procedures. As ICAR institutions continue adopting modern financial management practices, such evidence-based training programmes will play a crucial role in improving financial transparency, accountability, and institutional efficiency. Regular assessment of learning outcomes, coupled with continuous refinement of training content, can further enhance the effectiveness of future capacity-building initiatives and support the development of a professionally competent administrative workforce.

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Quality Protein Maize (QPM): A Breeding Miracle for Combating Malnutrition and Poverty

Article ID: 74287

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Summary
Global malnutrition persists partly due to impoverished populations relying heavily on staple cereals like normal maize, which are severely deficient in essential amino acids such as lysine and tryptophan. Quality Protein Maize (QPM) addresses this deficiency by utilizing the naturally occurring, recessive *opaque-2* mutation, which significantly increases lysine and tryptophan content and doubles the biological value of the protein. Plant breeders can rapidly identify these improved kernels using a non-destructive light-box test, as the *o2* gene creates a porous, chalky endosperm that blocks light, unlike the hard, translucent starch of normal maize. Nutritional studies prove that QPM is immensely beneficial, offering 90% of the nutritional value of milk protein for young children, reducing stunting and illness, and providing cost-effective, growth-enhancing feed for livestock. To maximize its impact, future efforts must focus on breeding climate-resilient QPM varieties and establishing supportive policies, such as premium pricing and improved seed availability, to incentivize widespread farmer adoption.

Introduction
Despite advancements in agriculture and technology, malnutrition exits globally, with 88% of countries affected. Around 02 billion people suffer from micronutrient deficiencies, 815 million are undernourished, and malnutrition contributes to 45% of deaths in children under five. Key issues such as stunting, wasting, and underweight growth need to be addressed (Bouis and Saltzman, 2017). Excessive reliance on staple foods, poor-quality diets, and low intake of animal products, fish, and nutrient-rich fruits and vegetables are significant issues among impoverished populations in developing countries, resulting in inadequate essential nutrient intake (Hossain *et al.*, 2019). Therefore, a balanced nutritional supplement, including essential amino acids such as lysine and tryptophan, deficient in cereals, vitamins, and minerals, is necessary for healthy human growth and development (Bouis *et al.*, 2011).

Maize protein quality and nutritional value is low due to limited essential amino acids, particularly lysine and tryptophan. Lysine, the most critical limiting amino acid, is deficient in maize endosperm protein (2.7% vs. FAO's recommendation) due to the abundance of lysine-poor zeins. Similarly, zeins lack tryptophan, further lowering its content (Prasanna *et al.* 2001). Reducing zeins content and enhancing lysine- and tryptophan-rich proteins can improve maize protein quality, called *quality protein maize* (QPM). The improvements in lysine often correlated with tryptophan enhancement (Vivek *et al.* 2008). Thus, the term quality protein maize (QPM) now refers to maize having the *o2* gene in its homozygous recessive form (*o2o2*) results in high lysine and tryptophan content, which also makes maize endosperm firm enough to maintain acceptable ear characteristics.

Discovery of *Opaque* Mutants
n the 1960s and 1970s, several naturally occurring maize mutants with higher lysine and tryptophan content were discovered, including *opaque-2 (o2)*, *floury-2 (fl2)*, *opaque-7 (o7)*, *opaque-6 (o6)*, and *floury-3 (fl3)* (Table 1).

Table 1. Chronology of discovery of Opaque mutants for quality protein maize.

Mutant	Allele	Researchers	Year
opaque-2	*o2*	Mertz, Batesand Nelson	1964
floury-2	*fl2*	Nelson, Mertzand Bates	1965
opaque-6	*o6*	McWhirter	1971
opaque-7	*o7*	Maand Nelson	1975
floury-3	*fl3*	Maand Nelson	1975

Here, it should be made clear that *o2* is a natural mutant, not a genetically modified organism (GMO). The recessive *o2* mutation in the homozygous state increases the quality of maize protein (lysine and tryptophan) without affecting the total protein quantity. Maize homozygous for the *o2* mutation contains significantly higher lysine and tryptophan levels compared to heterozygous (*O2o2*) or homozygous dominant (*O2O2*) maize. Vivek *et al.* (2008) showed that these increased amino acid levels can double the biological value of maize protein. However, the protein content of such maize remains around 10%, similar to normal maize, meaning more than twice the amount of common maize is needed to achieve amino acid balance compared to *opaque-2* maize (FAO, 1992; Table 2).

Table 2. Comparison between normal (non-*opaque-2*) and *opaque-2* maize.

Amino acids	Normal	*opaque-2*
Lysine	2.6	4.2
Tryptophan	0.4	0.9

Note: The values indicate content in 'g/100 g protein'.

Normal Kernel vs. QPM Kernel

The light-box technique is a non-destructive visual screening method used primarily by plant breeders to distinguish between normal and QPM kernels. By placing kernels over a bright, upward-facing light source, researchers can easily observe the degree of light transmission through the endosperm. This test allows rapidly differentiation between hard, translucent normal maize (which lets light pass through) and soft, chalky Quality Protein Maize (which blocks the light). An elite normal maize inbred line 'CMI-145' carrying the dominant wild-type alleles (*O2O2*). When the kernels are placed on a light box, the light passes through the vitreous, crystalline starch easily, appear as yellow portion (Fig.1a). The QPM donor line 'MGU-QPM-18' (Fig.1b) carrying the recessive *opaque2* mutation (*o2o2*). The *opaque2* gene significantly increases the levels of essential amino acids (lysine and tryptophan) but fundamentally alters the starch structure. When placed on a light box, the porous, chalky endosperm blocks the light, appears dark. Though, early *o2* mutant kernels were soft, chalky kernels, reduced yields, and high susceptibility to pests but breeders successfully used genetic modifiers to create modern QPM with hard, vitreous endosperms that yield comparably or even higher than the normal maize hybrids. Consequently, the recessive gene is associated with the highest lysine and tryptophan content compared to normal maize (Hossain *et al.* 2019; Table 2).

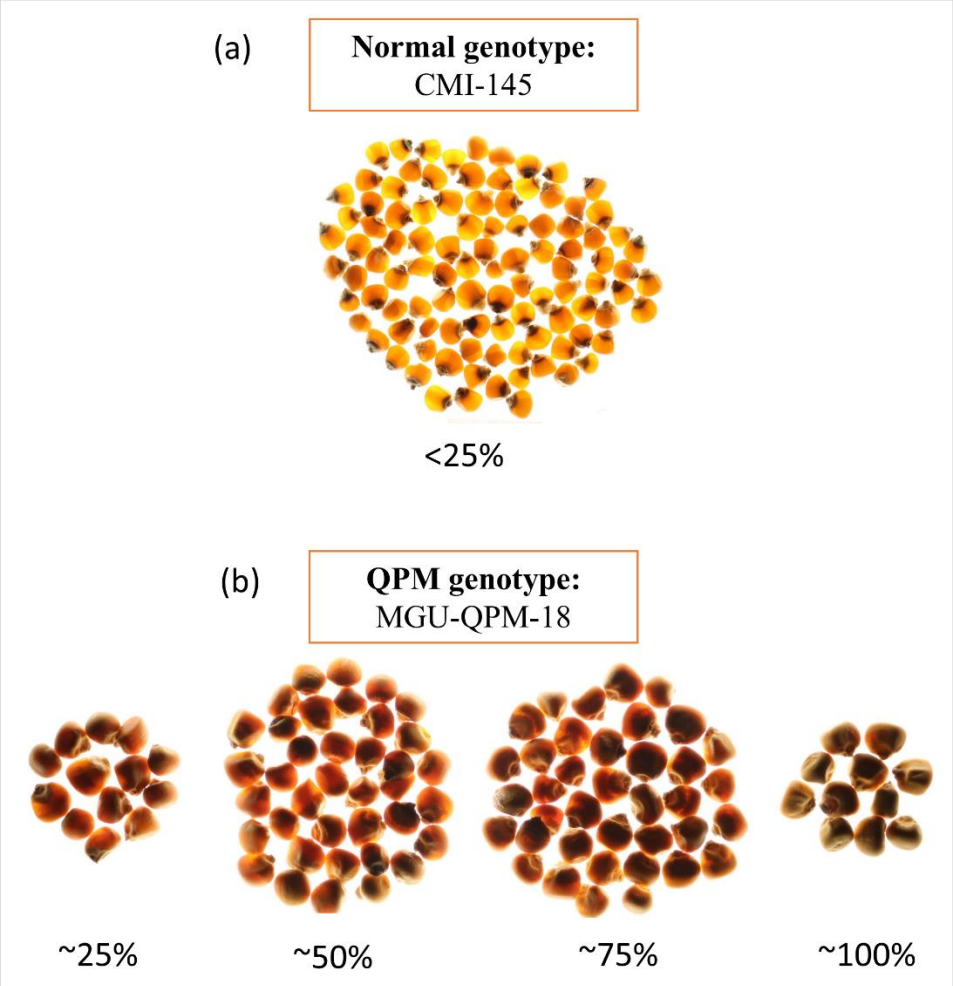


Figure 1. Light-box test based visual differentiation between normal maize and QPM based on endosperm opaqueness.

Impact of High Lysine and Tryptophan Containing Maize on Nutrition

Human nutrition studies conducted in Ghana by Akumoa-Boateng (2002) revealed children who consumed high-lysine/tryptophan maize experienced fewer sick days and had a lower risk of death from diarrhea and other infections compared to those fed regular maize porridge. Additionally, those weaned on high-lysine/tryptophan maize showed

reduced stunting compared to those weaned on regular maize porridge. Children consuming high-lysine/tryptophan maize also exhibited better growth compared to those given normal maize porridge.

A study in Guatemala showed that *o2* maize has 90% of the nutritional value of milk protein, compared to 40% in normal maize for young children (Prasanna *et al.*, 2001). QPM, with increased tryptophan, lysine, and biologically usable protein, also improves the leucine/isoleucine ratio and niacin availability, reducing pellagra risk (Vasal, 2001). Meta-analyses show QPM benefits weight and height gain in young children. In poultry, lysine and tryptophan enhances broiler growth, leading to greater weight gain. Diets containing QPM also reduce the need for fishmeal and synthetic lysine additives, making them more cost-effective.

Conclusion and Future Prospects

QPM is nutritionally and agronomically superior to normal maize and help to combat protein malnutrition in maize dominated developing regions. Future breeding programs should focus on developing QPM varieties with better climate-resilience such as drought, heat, and low soil nitrogen, as well as diseases and pests. Assurance of remunerative prices through minimum support price (MSP) and/or premium price for QPM to incentivize farmers, improving commercial seed availability, and increasing consumer awareness to drive market demand, are some of the key policy requirements for better adoption of QPM in society.

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Soil Health Card: A Key to Sustainable Agriculture and Prosperous Farming

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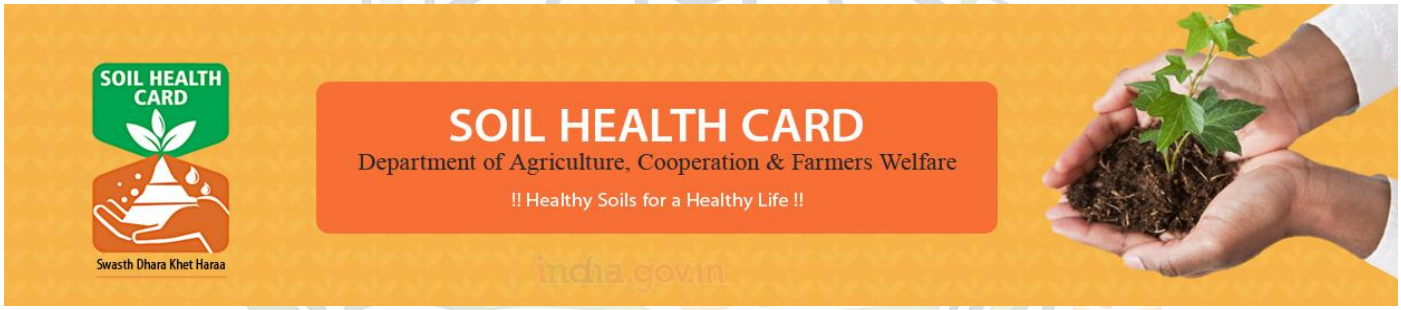
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Summary

Soil is the foundation of agricultural production and plays a crucial role in ensuring food security, environmental sustainability and farmers' livelihoods. However, continuous cultivation, imbalanced fertilizer application, excessive use of chemical inputs and declining organic matter have led to widespread soil degradation. Maintaining soil health has therefore become a national priority. To address this challenge, the Soil Health Card (SHC) Scheme was introduced to provide farmers with scientific information about the nutrient status of their fields and recommend appropriate fertilizer management practices. A Soil Health Card acts as a "medical report" of the soil, helping farmers make informed decisions for improving productivity while conserving natural resources. Further enhance the impact of the Soil Health Card Scheme in Rajasthan and across India, contributing to long-term agricultural sustainability, improved soil fertility and enhanced farmer income.



Introduction

Soil health is a fundamental component of sustainable agriculture, directly influencing crop productivity, nutrient use efficiency, environmental quality and farmers' livelihoods. The Soil Health Card (SHC) Scheme, launched by the Government of India on 19 February 2015 at Suratgarh, Rajasthan, aims to provide farmers with scientific information on the nutrient status of their soils and crop-specific fertilizer recommendations for balanced nutrient management. The scheme evaluates key soil parameters, including pH, electrical conductivity, organic carbon, macronutrients and micronutrients, enabling site-specific nutrient management and reducing indiscriminate fertilizer use. Rajasthan, characterized by diverse agro-climatic zones and predominantly arid and semi-arid conditions, has actively implemented the SHC programme through soil testing laboratories, mobile testing units and the Raj Kisan digital platform. Farmers can access their Soil Health Cards online, promoting timely decision-making and efficient nutrient management. Nationally, more than **25 crore Soil Health Cards** had been distributed by July 2025, supported by over **8,200 soil testing laboratories** across the country. The programme has significantly enhanced awareness regarding balanced fertilization, improved fertilizer-use efficiency, reduced production costs and contributed to sustainable soil resource management. Nevertheless, challenges such as limited farmer awareness, delays in soil sample analysis, inadequate testing infrastructure in remote regions and lower adoption of soil-test-based fertilizer recommendations continue to affect its effectiveness. Strengthening digital agriculture, precision nutrient management, GIS-based soil mapping and farmer extension services will.

What is a Soil Health Card?

A Soil Health Card is a government-issued document that provides detailed information about the physical and chemical properties of a farmer's soil. It contains the results of laboratory analysis of soil samples collected from individual farms and offers crop-specific recommendations for balanced nutrient management.

The card generally includes information on: Soil pH, Electrical Conductivity (EC), Organic Carbon (OC), Available Nitrogen (N), Available Phosphorus (P), Available Potassium (K), Available Sulphur (S), Micronutrients such as Zinc (Zn), Iron (Fe), Copper (Cu), Manganese (Mn) and Boron (B). This scientific assessment enables farmers to understand the nutritional condition of their soil and apply fertilizers according to crop requirements rather than relying on assumptions.

Why is the Soil Health Card Important for Farmers?

1. Balanced Nutrient Management: The Soil Health Card recommends the right type and quantity of fertilizers according to soil nutrient status. This prevents both nutrient deficiency and excessive fertilizer application, thereby improving nutrient use efficiency.

2. Higher Crop Productivity: Healthy soils provide essential nutrients in adequate quantities, leading to better seed germination, vigorous plant growth, improved crop quality and higher yields.

3. Improvement in Soil Fertility: The Soil Health Card encourages balanced fertilization along with the use of organic manures, compost, biofertilizers and micronutrients. These practices enhance soil organic matter, microbial activity and long-term soil fertility.

4. Environmental Protection: Excessive fertilizer use contributes to soil degradation, groundwater contamination and greenhouse gas emissions. Scientific nutrient management minimizes these environmental risks and promotes sustainable agriculture.

5. Better Nutrient Use Efficiency: Balanced fertilization improves nutrient uptake by crops, reducing nutrient losses through leaching, volatilization and runoff. This enhances fertilizer efficiency and supports climate-resilient farming.

6. Improved Crop Quality: Adequate nutrient availability enhances grain filling, protein content, oil quality and overall nutritional value of agricultural produce, thereby increasing market value.

7. Long-Term Sustainability: Regular soil testing helps monitor changes in soil fertility over time and supports the development of sustainable nutrient management strategies that maintain productivity for future generations.

Benefits of Soil Health Card

The Soil Health Card offers several benefits to farmers and the agricultural sector:

1. Provides scientific knowledge of soil nutrient status.
2. Promotes balanced and efficient fertilizer use.
3. Improves crop yield and quality.
4. Reduces cultivation costs.
5. Enhances soil organic carbon and biological activity.
6. Prevents nutrient mining and soil degradation.
7. Supports integrated nutrient management (INM).
8. Increases farmers' income through efficient resource utilization.
9. Encourages sustainable and climate-smart agriculture.

Role of Soil Health Card in Sustainable Agriculture

Sustainable agriculture requires maintaining soil productivity while minimizing environmental impacts. The Soil Health Card contributes to this goal by encouraging evidence-based nutrient management. It supports the integrated use of chemical fertilizers, organic manures, crop residues, green manures and biofertilizers. Such an integrated approach improves soil structure, water-holding capacity, microbial diversity and nutrient cycling, ensuring long-term agricultural sustainability. Moreover, the Soil Health Card serves as an important tool for precision agriculture, where nutrient application is based on actual field conditions rather than generalized recommendations.

Future Perspectives

Emerging technologies such as Geographic Information Systems (GIS), Global Positioning Systems (GPS), remote sensing, artificial intelligence (AI), machine learning, digital agriculture and precision nutrient management are expected to strengthen the Soil Health Card programme. Real-time soil monitoring, digital soil maps, mobile applications and decision-support systems will enable farmers to receive more accurate and location-specific nutrient recommendations. Integration of Soil Health Cards with climate-smart agriculture, precision farming and carbon farming initiatives will further contribute to sustainable agricultural development.

Conclusion

The Soil Health Card is an indispensable tool for modern agriculture that empowers farmers with scientific knowledge about the health of their soil. By promoting balanced nutrient management, reducing production costs, improving crop productivity and conserving natural resources, it contributes significantly to sustainable agricultural development. Regular soil testing and effective utilization of Soil Health Card recommendations can improve soil fertility, enhance farmers' income and ensure long-term food and environmental security. Therefore, every farmer should adopt the practice of periodic soil testing and use the Soil Health Card as a guide for scientific and sustainable farming.

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Mesta: Uses and its Medicinal Importance

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Introduction

Mesta (F: Malvaceae) botanical or scientific name *Hibiscus sabdariffa* (Roselle, red stemmed) and *H. cannabinus* (Kenaf, green stemmed). The native place of mesta is India and Malaysia, and it also cultivated some parts of Africa. Mesta commonly known as Roselle (English), Pitwaa (Hindi), Gongura (Telugu), Mestapat (Bengali), Pulicha Keerai (Tamil), Ambadi (Marathi), Tenga Mora (Assamese) Khata Palanga (Oriya). In India, mesta is widely cultivated in Andhra Pradesh, Tamil Nadu, Telangana, Kerala, Karnataka, Arunachal Pradesh, Tripura, and other northeastern states. Mesta is a perennial plant. Both calyx and leaves are the useful economic parts of the plant. Mesta leaves are used in culinary purposes in making like gongura pickle, gongura pachadi, gongura pappu, gongura chicken, gongura dal and also for medicinal purposes.

Mesta is an excellent source of protein (3.3 gm), carbohydrates (9.2 gm), fat(1.3 gm), good source of crude fiber (1.3gm) and energy (25KCal) The leaves also have a good source of vitamins *viz.*, Vitamin C, Vitamin A, Vitamin B1, Vitamin B2, Vitamin B9 and minerals such as, iron (1.7 mg), magnesium (123 mg), calcium (130 mg), phosphorus (20 mg) and potassium, manganese, zinc, sodium, copper in traces. The mesta plant has central bio-active constituents *viz.*, flavonoids, anthocyanins, polysaccharides and phenolic compounds. Phytochemical analysis from the dried calyces revealed glycosides, tannins, alkaloids, saponins and phenols; while seed oil revealed primary fatty acids like stearic acid and palmitic acid and unsaturated fatty acids such as oleic acid and linoleic acid.

General Uses of Mesta

1. The tender mesta leaves are widely used to make pickles, curries, and chutneys.
2. The dried mesta is the best tasty and healthy spice mix.
3. The dried mesta flowers are used in making syrup, juice, sauce, jam, and tea.
4. Stem, seeds, and pods of the mesta plant are utilized in the pharmaceutical industry.
5. The mesta especially *roselle* plant has beautiful red flowers, used for decoration purposes.
6. The mesta calyx is boiled in water and used to make soups, syrups, and consumed worldwide. The roselle seeds are cooked and consumed in several countries.
7. The mesta oil is extracted from the seeds and is used in culinary to prepare various food items. The roasted seeds are utilized as a coffee substitute. In India, the leaves are used for both medicinal and culinary purposes.
8. The calyx has many medicinal qualities that help to lower blood pressure, sore throat, treat fever, cough, and constipation. The leaf paste is utilized to treat wounds, and the seeds are used to enhance lactation.

Health and Medicinal Uses of Mesta

1. Increases blood quality and protects liver: The mesta leaves and flowers have a cooling effect, so it helps to reduce the heat in human body. It reduces the liver toxins and fat thus improves your liver health. By consuming mesta leaves regularly, the red blood cells will be purified. The leaves are rich in iron, which increases the red blood cells production in blood.

2. Reduces cholesterol level: The mesta leaves have lipid lowering properties that help to prevent cardiovascular diseases. The water extracted from the plant reduces the bad cholesterol levels, LDL, triglyceride and increase your body's good cholesterol. The roselle tea is also known to decrease cholesterol levels.

3. Prevents hypertension: The mesta leaves having potassium and magnesium helps to lower the blood pressure. It also improves high density lipoproteins levels, and these properties make it an excellent food for hypertension people.

4. Enhance eyesight: The mesta leaves are one of the best remedies for visibility issues. The leaves help to enhance eye vision as it has a high amount of vitamin A. Vitamin A boosts eyesight and reduces night blindness. Mesta has high antioxidants that prevent age-related cataracts and macular degeneration.

5. Antispasmodic properties: The extract from mesta flowers has antispasmodic properties, and the roselle tea made using roselle calyx can be utilized to relieve menstrual pain. The presence of polyphenols causes antispasmodic properties.

6. Helps in weight loss: The mesta leaves are excellent source of vitamins, protein, carbohydrates, minerals, and with traces of fat and low in calories. The leaves are highly rich in fiber, which will quench appetite and make feel full for a

long time. The diuretic properties in the leaves, prevents fluid retention by improving the urination frequency and stops weight gain. The mesta leaf extract also has anti-obesity properties that reduce all obesity-related problems and also improves health without adding additional calories.

7. Antioxidant properties: Free radicals are formed in human body as a result of metabolic processes, vulnerability to sunlight, and environmental toxins like cigarette smoke and industrial chemicals that alter DNA, damage cellular membranes, and lead to life-threatening diseases like heart attack and cancer. Therefore regular intake of mesta, enhances extreme level of antioxidants, which ultimately reduce free radicals in human body.

8. Antifungal & antibacterial properties: The mesta plant extract has excellent anti-fungal and antibacterial properties. These properties act as a microbial that protects body from bacterial strains such as Staphylococcus aureus, Micrococcus luteus, Escherichia coli etc. The mesta leaves also possess anti-inflammatory properties that heal boils, ulcers, and wounds. It also helps to treat itchy skin, swelling, ringworm, and scorbutic diseases, etc.

9. Boost digestive health: The mesta is rich in dietary fiber and consumption of mesta makes digestion easier there by boosting digestive health. It normalizes the bowel movements in human body, and also prevents digestive problems such as diarrhea, constipation, and bloating. Mesta includes active antioxidant compounds called anthraquinones which improve muscular activity and fluid secretion in the intestines.

10. Enhance immunity: Regular intake of mesta leaves, increase body's immunity power, and protects body from harmful elements and toxins. The leaves cleanses the digestive tract, liver, and kidneys; it also removes the toxins from body. High vitamin C is obtained from the leaves, an ascorbic acid, which supports the immune function by improving antibodies and white blood cells. It also enhances blood circulation, oxygen supply and improves energy levels.

11. Improve hair health: Mesta leaf extract is a beneficial home remedy for hair problems that can cure dry, damaged and dull hair. Regular consumption of mesta leaves effectively reduces hair loss and the balding process. The leaves are an outstanding tonic for hair significantly prevents early aging of the hair and improve hair strenght, health, and lustre.

12. Prevents anaemia: Mesta is an excellent source of sodium, phosphorus and also includes chlorophyll. The mesta leaves are rich in iron that improve red blood cell production, and reduce iron deficiency which causes heart palpitations, fatigue, weakness, weariness, and shortness of breath.

13. Prevents cancer: According to the research, mesta leaves have antioxidants that can kill malignant cells and stop their growth. It helps to avoid the growth of tumors and cancerous cells in the body. Mesta leaves possessing chlorophyll aids in improving oxygen levels in human body which also reduces the cancerous cells' growth in the body.

14. Maintain bones stronger: The mesta leaves is an excellent magnesium, phosphorus and calcium source, which improve strong and healthy bones in human body. These minerals also prevent osteoporosis and bone loss.

Conclusion

Mesta, is excellent nutraceutical perennial plant with calyx and leaves as the useful economic parts and possessing highly nutritious dietary and major bio-active constituents. The antispasmodic, antioxidant, anti-inflammatory, antifungal and antibacterial properties of mesta catering the medical implications making it imperative for general public health in day-to-day scenario.

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Growing Dragon Fruit in Bundelkhand: A Climate-Smart Option for Degraded Drylands

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Abstract
Bundelkhand's farmers are no strangers to hard choices: shallow, gravelly soils, erratic and often scanty rainfall, and summer temperatures that regularly cross 45°C leave little room for crops with narrow climatic tolerance. Dragon fruit (Hylocereus spp.), a climbing cactus better known by its market name pitaya, is increasingly being tried in exactly this kind of terrain because it tolerates heat and moisture stress far better than most conventional fruit crops, needs comparatively little water once established, and can remain productive for 15-20 years from a single planting. For a region searching for crop options that match its soil-and-water reality rather than fight it, that combination is hard to ignore. Originally native to Central America and Mexico, the crop travelled to South and Southeast Asia around three decades ago and has since become a significant commercial crop in Vietnam, China, Thailand and other producing countries. Within India, its footprint has expanded rapidly since 2018, led by Karnataka, Maharashtra, Gujarat, Telangana, Andhra Pradesh and West Bengal; the overwhelming majority of India's current dragon fruit area is still under young, recently established orchards, which suggests the crop is still in an early, opportunity-rich phase of adoption rather than a saturated one. Bundelkhand, with its semi-arid character and degraded arable and non-arable lands, fits naturally into this expansion story.

Matching the Crop to Bundelkhand's Agro-Climate
Dragon fruit is a CAM (Crassulacean Acid Metabolism) plant, which is precisely why it copes so well with heat and moisture scarcity it opens its stomata at night rather than during the heat of the day, cutting water loss dramatically compared with conventional fruit crops. Reported cultivation ranges from sea level up to about 1,700 m altitude, with annual rainfall requirements typically cited between 700 and 1,500 mm depending on the source and cultivar; established vines can also tolerate brief spells as low as 0°C and as high as 38-40°C, though sustained growth is best between 20°C and 30°C.

Choosing Planting Material and Varieties
A number of cultivars are grown commercially, differing mainly in flesh and skin colour and in fruit size red-fleshed types such as Red Pitaya/Pitaya Roja, yellow-fleshed forms like Pitaya Amarilla, and named selections including American Beauty, Bloody Mary, Cosmic Charlie, Costa Rican Sunset and David Bowie are among those available to growers. Local availability and market preference should guide the final choice more than any single variety being universally 'best'.



Planting, Trellising and Spacing
Planting is best timed with the onset of the monsoon, typically during July-August, when soil moisture supports quick root establishment. Two to four rooted cuttings are usually planted around the base of each post so that the vines can be trained upward together. A spacing of 3 m × 3 m, or slightly wider at 3 m × 4 m or 4 m × 4 m, is commonly followed for single-post systems; this balances light penetration and canopy management against the higher plant population and earlier returns that closer spacing can give in the establishment years.

Nutrition and Water Management

Being a succulent with a shallow, laterally spreading root system concentrated within the top 15-30 cm of soil, dragon fruit responds well to organic-matter-rich feeding. An annual dose of about 15-20 kg farmyard manure per plant, combined with roughly 450 g nitrogen, 350 g phosphorus (P_2O_5) and 300 g potash (K_2O) per plant per year, is a widely cited baseline for sustaining vigorous growth, flowering and fruit quality; these figures are a starting reference and are best fine-tuned against local soil-test values.

Canopy Management and Weed Control

Regular pruning is essential to keep the canopy open and umbrella-shaped, which improves light penetration, air circulation and disease management while stimulating the fresh growth on which the next season's flowering depends. A well-managed vine can throw 30-50 new branches in its first productive year and build up to well over 100 branches by the fourth year, so pruning discipline from an early stage prevents the canopy from becoming an overcrowded, disease-prone tangle.

Flowering, Harvesting and Yield Expectations

Under normal management, dragon fruit begins bearing around 12-18 months after planting. Flowering and fruiting are concentrated in the warmer months, broadly from June to September, and a single orchard can be picked over three to four times in a month during peak season since flushes are not perfectly synchronised. Fruit is ready to harvest when the skin colour turns from green to a bright red or pink, generally 30-35 days after flowering. Yields build up with orchard age: a single well-managed post can produce in the range of 30-35 kg by the third year, with individual fruit weight commonly falling between 300 and 800 g. On an area basis, average annual yields of 8-10 tonnes per hectare are typically reported once orchards reach full bearing. In some production regions, supplementary lighting is used to extend flowering into the off-season and capture premium prices, though this remains an optional, capital-intensive practice rather than a basic requirement.

Managing Pests and Diseases

Dragon fruit is comparatively free of serious pest and disease pressure, which is part of its appeal for low-input dryland farming, but a handful of problems still need routine attention.

Diseases

1. Anthracnose: managed through three sprays at roughly fifteen-day intervals ahead of harvest, using fungicides such as mancozeb (2 g/l), carbendazim (1 g/l), thiophanate-methyl (1 g/l) or chlorothalonil (2 g/l).

2. Brown spot: relies heavily on field sanitation — removing and destroying fallen or infected fruit, leaves and vine segments — together with pruning to reduce canopy density and humidity, and timely copper-based fungicide sprays.

3. Soft (stem) rot: controlled by pruning out dying stems, whitewashing exposed stem surfaces with copper sulphate before symptoms appear, and follow-up sprays of copper oxychloride at about 0.2%.

4. Fruit rot: minimised by keeping the orchard weed-free and promptly removing and destroying any visibly infected stems, fruit or flowers to break the disease cycle.

Insect Pests

1. Aphids: avoid intercropping with alternate host plants, prune to keep the canopy open, and encourage natural enemies through agro-forestry habitat and flowering strips around the field; where chemical control is needed, lambda-cyhalothrin, cypermethrin or acetamiprid can be sprayed at about 1 ml/litre.

2. Thrips: destroy crop residues and volunteer plants by ploughing them under during field preparation, use mulches to disrupt pupation, and apply deltamethrin at about 1 ml/litre where infestation is significant.

3. Mealybug: can be managed with acephate 75SP (1 g/l), quinalphos 25EC (2 ml/l), chlorpyriphos 25EC (2 ml/l) or thiodicarb 75WP (2 g/l).