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Maximizing Resource Efficiency: Food Waste Valorization as India's Agri-Business Growth Engine

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The Indian agri-food sector, characterized by its vast production base and fragmented supply chain, faces a critical challenge: minimizing colossal post-harvest losses and transforming agricultural and food processing by-products from liabilities into valuable assets. This strategic pivot-known as **food valorization**—is the core strategy for agri-businesses in India to achieve resource efficiency, enhance profitability, and drive rural economic growth. The focus is on establishing robust circular economy models tailored to India's unique agricultural landscape.

1. Defining the Scope: The Scale of India's Resource Pool

The opportunity for valorization is directly proportional to the sheer volume and diversity of Indian agricultural output. The total annual economic value of post-harvest losses alone is estimated to be over **₹900 billion** (Jha et al., 2013), necessitating prompt action across all stages of the supply chain. The scope of available feedstock extends across three major domains:

A. Crop Residues (Ex-Situ Management)

India generates approximately **350–480 million tonnes** of gross crop residue annually, a significant portion of which is either left in the field or inefficiently managed (MDPI, 2022; ANDE, 2025). The business focus is **ex-situ** (off-site) management:

- **Lignocellulosic Biomass:** High-volume residues like rice straw, cotton stalks, and sugarcane bagasse are the primary target. Their conversion into **bio-pellets, bio-briquettes, and feedstock for 2nd Generation Ethanol** production represents a massive opportunity to substitute coal in industrial applications and meet biofuel blending targets, simultaneously mitigating the severe air pollution caused by residue burning.
- **Scale of Opportunity:** This waste stream has the potential to generate more than **18,000 MW of power** every year, apart from generating green fertilizer (ICAR, 2024).

B. Industrial Processing By-Products

As India's food processing sector expands, the volume of controlled, centralized by-products from factories and organized dairies increases, offering premium valorization opportunities.

- **Protein and Fibre from Fruit Pomace:** Residues from the juice, spice, and oil milling sectors (e.g., grape pomace, tomato pulp, citrus peels) are excellent sources for high-value compounds. For instance, **Antioxidants, Pectin, and Dietary Fibre** can be isolated from mango peel, and **nutraceutical-rich beverages** can be made from Kinnow peels (ICAR, 2024).
- **Winery and Brewery Waste:** Spent grain and fine wine lees can be fortified and used in baking and confectionery (ICAR, 2024).
- **Dairy Waste:** Whey and other dairy by-products are prime candidates for **protein isolates** and **lactose** extraction, catering to the fast-growing health and wellness market.

C. Market and Community Waste

This includes predictable, high-moisture organic streams from wholesale markets (**mandis**), institutional canteens, and cattle farms.

- **Biomethanation Potential:** This feedstock is ideal for **Anaerobic Digestion (AD)** to produce **Compressed Biogas (CBG)**. India's vast livestock population contributes massive volumes of cattle dung, which, along with market waste, ensures optimal scale and predictable output of CBG and nutrient-rich bio-slurry (MDPI, 2024). Organizations like BARC have developed technologies like **Nisargruna** for efficient conversion of diverse organic waste into biogas and manure (BARC, 2025).

2. Emerging Business Trends & Technological Scope

The shift in the Indian market is towards **integrated, multi-product extraction** and leveraging advanced technologies to manage variability and improve yield.

2.1. Advanced Extraction Technologies

Newer non-conventional techniques are moving to the forefront of high-value extraction, replacing older, less efficient methods.

- **Non-Thermal Concepts:** Technologies like **Pulsed Electric Fields (PEF)**, **Supercritical Fluid Extraction (SFE)**, and **Ultrasound/Microwave-Assisted Extraction** are being adopted for the precise and efficient recovery of valuable chemicals (e.g., polyphenols, flavonoids) from fruit and vegetable waste (Chemical Science Review, 2022). These methods preserve the integrity of heat-sensitive compounds, ensuring a premium product quality.

- **Enzymatic Extraction:** Using targeted enzymes to break down cell walls and release specific compounds from agri-residues is becoming a focus area for creating high-purity functional ingredients.

2.2. The Biorefinery and Cascade Approach

The most profitable model is the **Biorefinery**, where a single waste stream is processed for multiple outputs in a cascading hierarchy of value.

- **Example:** Utilizing banana pseudostem sheath, a biorefinery can extract **cellulose/micro-crystalline cellulose** for pharmaceutical/cosmetic use, produce **fiber** for paper plates or decorative panels, and use the residuals for **low-glycemic flour** or **juice/candy** (ICAR, 2024). This full utilization model significantly boosts profitability compared to single-product outputs.

2.3. The Upcycled Ingredients Market

Globally, the upcycled food products market is projected to reach **USD 119.8 Billion by 2034**, and India is a key market for this growth (InsightAce Analytic, 2024).

- **Market Opportunity:** The trend involves transforming by-products (e.g., de-oiled cakes, brewer's spent grain) into high-protein, gluten-free **upcycled flours, oils, and fibers**. This addresses consumer demand for sustainability and provides a functional, **clean-label** ingredient (MRFR, 2024).
- **Success Stories:** Startups are finding success in creating customized organic fertilizers and soil conditioners from local organic waste, demonstrating the economic viability of localized models with revenues reaching crores (Indian Startup Times, 2025).

3. Financial and Organizational Scope in the Indian Context

The scalability of valorization projects in India is fundamentally tied to overcoming logistical fragmentation and securing capital.

- **FPO-Led Aggregation:** FPOs are instrumental in managing the supply chain. By centralizing collection of crop residues and market waste, they create a reliable, homogenized feedstock supply required by industrial off-takers (e.g., bio-pellet manufacturers). This model not only secures feedstock but also generates **supplementary income** for thousands of farmers.

- **Decentralized Vermicomposting Hubs:** Simple, low-tech, and high-impact models like vermicomposting of farm and community waste into **bio-fertilizers** are proving to be powerful rural enterprise models. Successful ventures have demonstrated annual turnovers exceeding ₹1.5 Crore by supplying high-quality vermicompost to local farmers (ResearchGate, 2025). This localized production reduces transportation costs for both waste and the final product, improving margins significantly.

Food waste valorization in India is rapidly evolving from a niche environmental activity to a mainstream, technologically advanced agri-business strategy defined by multi-product value extraction and strong farmer-industry integration.

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Bharat-VISTAAR: An AI-based Solution for Smart Farming

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In February 2026, the Government of India launched a new AI-powered agriculture platform called Bharat-VISTAAR (*Virtually Integrated System to Access Agricultural Resources*). The platform is designed to provide farmers across the country with reliable, real-time agricultural information and advisory support using cutting-edge Artificial Intelligence technology. Bharat-VISTAAR was announced in the 2026-27 Union Budget, officially launched on 17 February 2026 in Jaipur, Rajasthan and inaugurated by Union Agriculture Minister Shivraj Singh Chouhan with state leadership. (Government of India, 2026).

Bharat-VISTAAR

Bharat-VISTAAR is a digital agriculture infrastructure that brings together weather data, market prices, pest and disease alerts, crop management guidance, soil health insights, and information about central government schemes on one unified platform (Kumari, 2026; Vijayan, 2026). Through AI, it delivers personalised recommendations to farmers in local languages. The platform operates as a Voice-First AI system, meaning even farmers with basic feature phones can access it simply by calling a dedicated helpline number (155261). (The Times of India, 2026).

In addition to phone access, the service can soon be accessed through:

- A mobile Android app
- A web chatbot interface
- Text-based chat systems on partner platforms

Key Features of Bharat-VISTAAR

- **Real-Time Weather Updates:** Provides weather forecasts and alerts to help farmers plan irrigation, planting, and harvesting (Kumari, 2026).
- **Market Prices:** Delivers mandi price information so farmers can make informed sales decisions (Vijayan, 2026).

- **Pest & Disease Advisory:** Offers alerts and advice on managing crop pests and diseases.
- **Soil Health Insights:** Guides farmers based on soil conditions to improve fertility and yields.
- **Government Scheme Information:** Covers at least 10 major central government schemes like PM-KISAN, PMFBY, Soil Health Card, Krishi Sinchayee Yojana and others, including benefit status, eligibility, and grievance tracking (The Economic Times, 2026).
- **Multilingual Support:** Initially available in Hindi and English, with plans to support many regional languages.
- **AI Voice Assistant "Bharati":** Farmers can talk to the AI in conversational language to get answers tailored to their farm needs.

Why Bharat-VISTAAR Matters

Before the introduction of Bharat-VISTAAR, farmers often had to navigate a fragmented information ecosystem. They depended on multiple government portals, local agriculture offices, extension workers, call centers, private input dealers and informal intermediaries to obtain updates on weather forecasts, pest outbreaks, market prices, crop advisories and scheme benefits (The Economic Times, 2026). This process was not only time-consuming but also confusing, especially for small and marginal farmers with limited digital literacy. Information was scattered across departments, frequently delayed, and sometimes inconsistent, making timely decision-making difficult. Bharat-VISTAAR transforms this landscape by functioning as a comprehensive, one-stop digital agricultural advisor. Through a simple voice call or mobile application, farmers can access integrated services that combine weather intelligence, market analytics, pest and disease alerts, soil health recommendations and detailed information about government schemes; all in one unified interface. Its voice-first approach ensures inclusivity, allowing even farmers without smartphones or advanced technical skills to benefit from AI-powered advisory services. The platform's advanced artificial intelligence capabilities analyze vast datasets in real time to generate highly personalized, location-specific, and crop-specific recommendations. By leveraging predictive analytics, natural language processing and machine learning models, Bharat-VISTAAR delivers precise guidance tailored to each farmer's unique conditions. Even farmers in remote and underserved regions can now receive expert-level agricultural advice instantly.

By effectively bridging the long-standing gap between scientific research and on-field agricultural practice, Bharat-VISTAAR strengthens the extension ecosystem. It enhances productivity through informed crop management, reduces production risks through early warnings and predictive alerts, optimizes input usage to lower costs, and ultimately contributes to improved farm profitability. In doing so, the platform represents a significant step toward resilient, technology-driven, and income-secure agriculture across India.

Challenges and Future Prospects

While promising, the full potential of Bharat-VISTAAR will depend on expanding language support, improving rural connectivity, and training farmers to use digital tools effectively (The Economic Times, 2026). As the platform evolves, it is expected to include more regional schemes, support additional languages, and integrate with local agricultural systems.

Conclusion

Bharat-VISTAAR represents a transformative step in India's journey toward technology-driven, inclusive and farmer-centric agriculture. By integrating weather intelligence, market data, pest and disease advisories, soil health guidance, and government scheme information into a single AI-powered ecosystem, the platform simplifies access to critical agricultural knowledge. Its voice-first approach, supported through a dedicated helpline and multilingual capabilities, ensures that even small and marginal farmers with limited digital literacy can benefit from advanced advisory services. More than just a digital tool, Bharat-VISTAAR strengthens the agricultural extension system by bridging the gap between research institutions, government services, and farmers on the ground. Through real-time data analytics and personalized recommendations, it empowers farmers to make timely, informed, and risk-aware decisions that enhance productivity and profitability.

Although challenges such as digital connectivity, language expansion, and user training remain, the platform holds immense potential to reshape India's agricultural landscape. As it continues to evolve and expand, Bharat-VISTAAR is poised to become a cornerstone of resilient, sustainable, and income-secure farming, supporting millions of farmers in building a smarter and more self-reliant agricultural future.

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Plant Growth-Promoting Rhizobacteria (PGPR) as Biofertilizers in Cactus Fruit Crops: Current Advances and Future Perspectives

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1. Introduction

Dragon fruit (*Hylocereus/Selenicereus* spp.) has emerged as a high-value horticultural crop due to its appealing taste, health benefits and adaptability to marginal environments (Karunakaran et al., 2026). Global demand is rising, and cultivation now spans tropical and subtropical regions. However, intensive dragon fruit farming often suffers from poor soil fertility and harsh abiotic conditions. In arid agroecosystems, maintaining soil health and crop productivity without excessive chemical inputs is a major challenge (Basu et al., 2021)

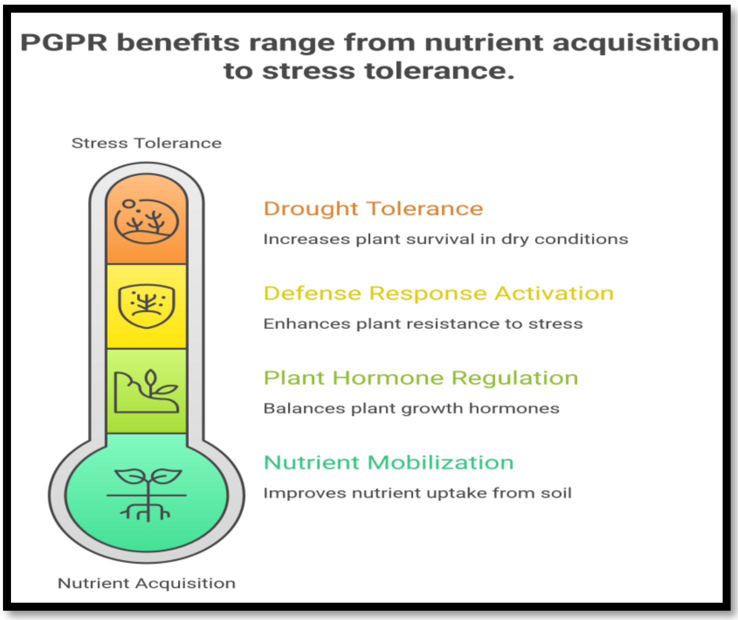

Fig 1: PGPR Benefits

PGPR are beneficial soil bacteria that colonize plant roots and enhance growth through diverse mechanisms. They can improve nutrient acquisition, modulate plant hormones, and trigger defense responses. For example, inoculating crops with PGPR-based biostimulants has been shown to increase biomass and stress tolerance, reducing reliance on synthetic fertilizers and agrochemicals (Backer at al., 2018). In desert farming systems, the plant rhizosphere often becomes enriched with PGPR that confer drought resilience. Marasco et al., (2012) found that *Capsicum annuum* grown under desert conditions recruited *Bacillus*-dominated communities that boosted photosynthesis and biomass by up to 40% under water deficit. Similar strategies are promising for dragon fruit.

2. PGPR Diversity

PGPR encompass many genera of soil bacteria, including *Azospirillum*, *Azotobacter*, *Bacillus*, *Pseudomonas*, *Rhizobium* and *Burkholderia* (Basu et al., 2021). These microbes inhabit the rhizosphere and the endosphere, forming intimate associations with plants. Through this alliance, they perform valuable ecological services.

3. Mechanisms of Plant Growth Promotion

PGPR enhance cactus growth through multiple biochemical routes:

- **Nitrogen Fixation:** Some rhizobacteria (e.g. *Azospirillum*, associative *Rhizobium*) convert atmospheric N_2 into ammonia. In arid soils where nitrogen is limiting, inoculation with N-fixing PGPR can significantly boost plant nitrogen uptake and vegetative growth (de Andrade et al., 2023)
- **Phosphate Solubilization:** In alkaline, calcareous soils common in drylands, phosphorus is often locked in insoluble forms. Phosphate-solubilizing bacteria (PSB) secrete organic acids (gluconic, oxalic) and phosphatases that free bound P, thereby improving phosphorus nutrition and fruit quality (Sun et al., 2024; Alori et al., 2017).
- **Phytohormone Production:** PGPR frequently synthesize indole-3-acetic acid (IAA) and gibberellins, which enhance root elongation and branching. For cactus crops facing drought stress, increased root surface area can improve water acquisition. Additionally, microbial cytokinins can delay leaf senescence and improve nutrient mobilization during fruit development (de Andrade et al. 2023).
- **ACC Deaminase Activity:** Many PGPR produce 1-aminocyclopropane-1-carboxylate (ACC) deaminase, an enzyme that lowers stress ethylene levels in plants. High ethylene under stress causes growth inhibition; ACC deaminase cleaves ACC, the ethylene precursor, thereby alleviating growth arrest. For example, under salinity or drought, ACC deaminase-producing Bacillus and Pseudomonas strains help plants maintain growth (Ha-Tran et al., 2021).
- **Siderophore Production:** Iron is often limited in alkaline soils. PGPR-generated siderophores chelate Fe^{3+} and facilitate its uptake by plants. This not only improves nutrition but can also suppress pathogens (many soil-borne fungi are sensitive to iron limitation) (Backer et al., 2018)
- **Stress-Adaptation Factors:** PGPR can produce exopolysaccharides (EPS) that improve soil aggregation and moisture retention around roots. They also induce host antioxidant systems: treated plants often show higher levels of proline and antioxidant enzymes (superoxide dismutase, catalase) under drought or salt stress. In one study, two drought-tolerant *Bacillus* strains from arid soil produced elevated IAA, gibberellins, siderophores, EPS and antioxidants under simulated drought; their co-inoculation increased seed germination rate and seedling vigor by over 40% (100% germination with inoculated mix vs. much lower in controls) (Ashry et al., 2022).

- **Induced Systemic Resistance (ISR):** Root-colonizing PGPR can trigger ISR, a whole-plant defensive state mediated by jasmonic acid/ethylene signaling. ISR can protect cactus plants from future biotic and abiotic stresses by enhancing stress-responsive gene expression.

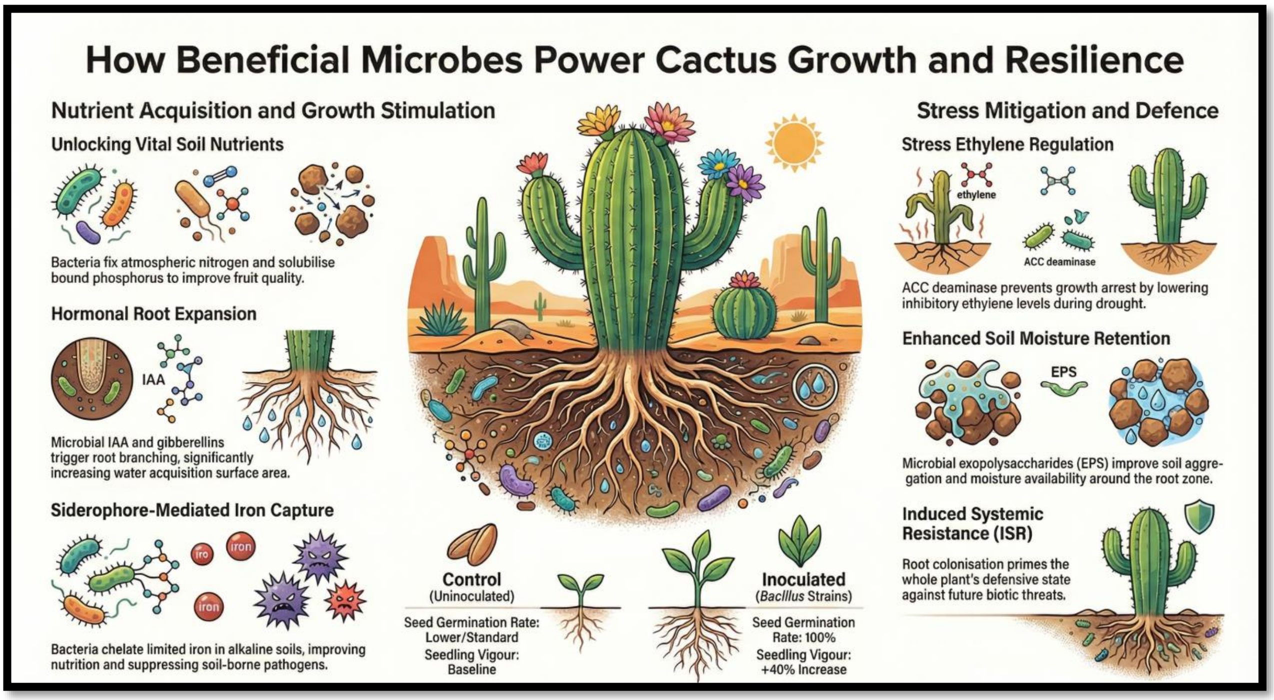

Figure 2: Functions of PGPR

4. Applications in Cactus Fruit Crops

Research specifically on dragon fruit has begun to demonstrate PGPR benefits. Although direct field trials are still limited, preliminary studies and analogous systems suggest promising results. For example, in dragon fruit stem propagation, combining vermicompost with the PGPR *Bacillus amyloliquefaciens* led to 100% cutting emergence and vigorous growth in seedlings, illustrating synergistic effects of microbial inoculants and organic amendments (Karunakaran et al., 2026).

In arid-adapted crops related to cactus (such as certain cucurbits and pepper), native rhizobacteria were found to enhance drought resilience by up to 40% in biomass compared to non-inoculated plants (Marasco et al., 2012). Given the similar challenges in dragon fruit cultivation, analogous outcomes are expected: local Bacillus and Pseudomonas strains isolated from cactus rhizospheres often possess multiple PGP traits (hormone production, N fixation, stress tolerance) and thus likely improve pitaya yields and quality.

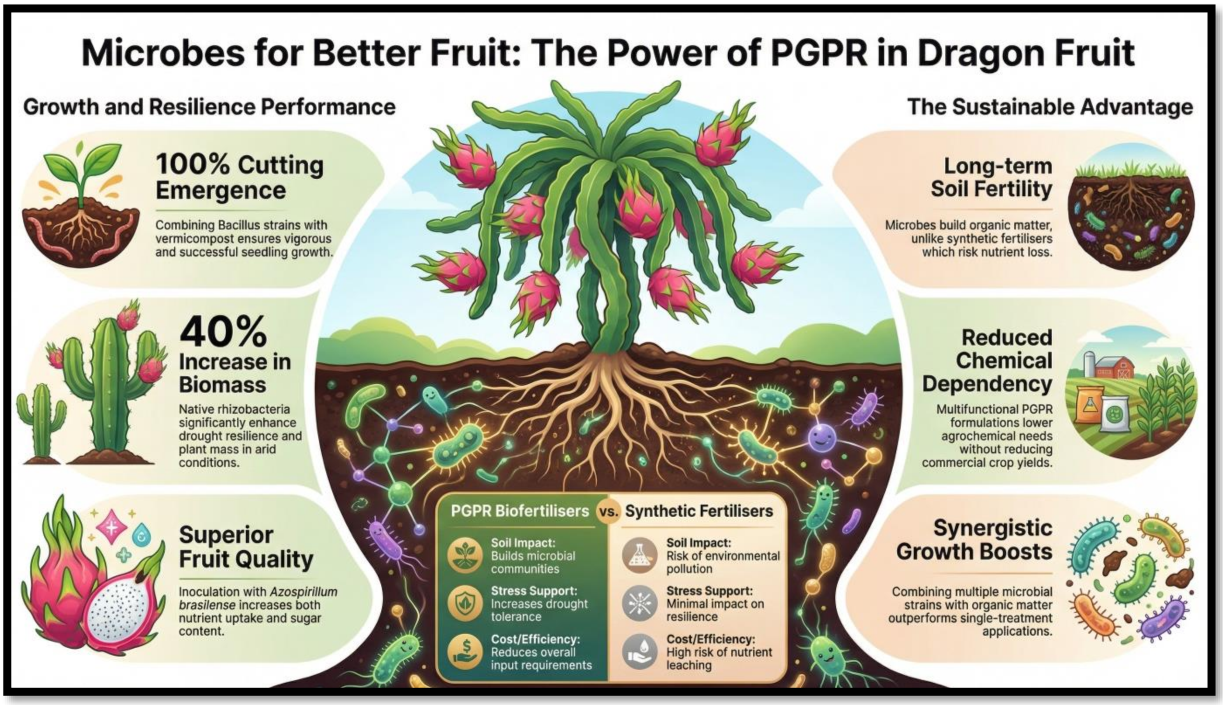

Figure 3: Application of PGPR in Dragon Fruit

To date, specific reports include greenhouse trials where *Azospirillum brasilense* increased nutrient uptake and sugar content in pitaya vines and consortia of rhizobacteria improved drought tolerance in cacti by maintaining root hydraulic conductivity (Marasco et al., 2012). There is also evidence that combining PGPR with other biofertilizers or organic inputs amplifies effects. A co-inoculation of Bacillus and *Azotobacter* with vermicompost, for instance, significantly boosted vegetative growth of dragon fruit compared to either treatment alone.

However, responses can be context-dependent. Soil type, climate, and cactus variety influence PGPR effectiveness. Field validation remains sparse. This underscores the need for on-farm trials. Yet, the body of research strongly indicates that introducing beneficial rhizobacteria is a viable strategy to enhance dragon fruit production sustainably, improving nutrient efficiency, yield and stress resilience.

5. Advantages over Chemical Fertilizers

PGPR biofertilizers offer several advantages relative to conventional inputs. They improve soil health and fertility over the long term by building microbial communities and organic matter. In contrast to synthetic N-P-K fertilizers, PGPR inoculants reduce nutrient losses and environmental pollution. For example, deploying PGPR has been linked to lower fertilizer requirements without yield penalties. Moreover, inoculated plants often show stronger growth under adverse conditions, potentially reducing crop losses in drought or saline soils. As one review notes, the advent of multifunctional PGPR formulations can "minimize the use of synthetic fertilizers and agrochemicals" in agriculture (Backer et al., 2018). Thus, integrating PGPR into dragon fruit cultivation aligns with sustainable agriculture goals, lowering costs and environmental impact.

6. Challenges in Field Application

Despite the promise, practical challenges remain. Many PGPR formulations suffer from limited shelf life and inconsistent colonization under field conditions. Harsh environments in cactus orchards (high UV, extreme heat, salinity) can reduce bacterial survival. Selecting strains that are both highly effective and robust is crucial. Standardizing inoculation methods (seed vs. soil vs. cutting dips) is also an issue. Moreover, benefits seen in controlled trials do not always translate directly to farmers' fields due to local soil microbiomes or agronomic practices. Overcoming these challenges will require rigorous formulation (e.g., encapsulation techniques, carrier materials) and quality control. Additionally, farmer awareness and extension support are needed, since adoption of biofertilizers is still low in many arid regions.

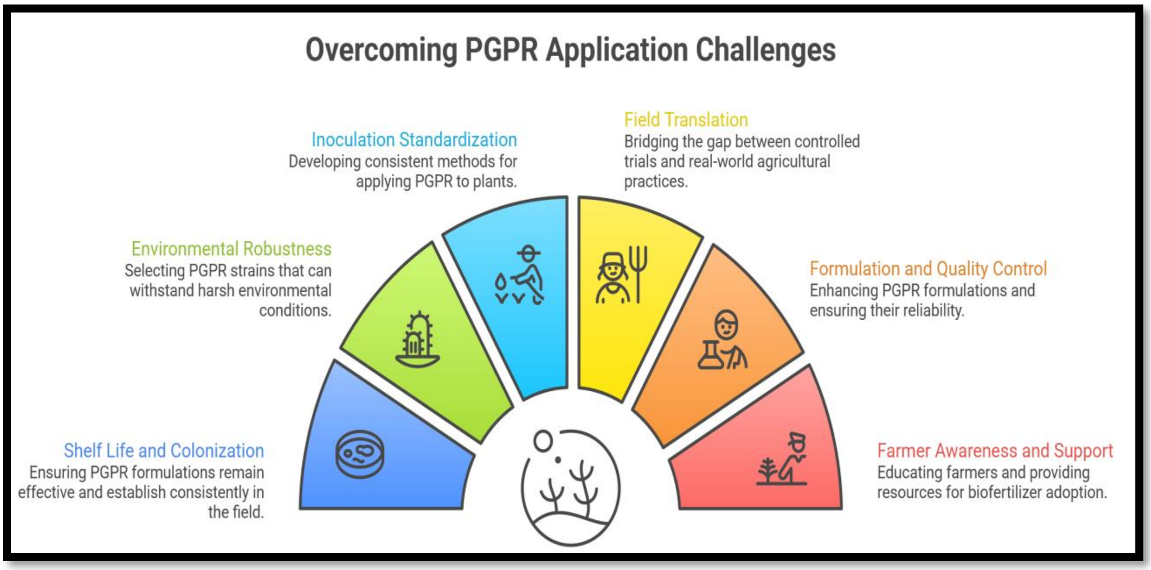

Figure 4: Challenges in Field Application and Solutions

7. Future Perspectives

To fully harness PGPR in cactus fruit systems, future work should focus on:

- **Isolation of Native Strains:** Surveying dragon fruit rhizospheres and endemic arid soils to find local PGPR adapted to specific conditions. Native isolates are more likely to survive and perform well in situ.
- **Multi-omics and Metagenomics:** Applying metagenomic and transcriptomic tools to characterize the microbial community under healthy vs. stressed cactus plants, and to identify key functional genes. This knowledge can guide selection of complementary consortia for inoculation.

- **Consortia Development:** Rather than single strains, developing tailored microbial consortia that combine nitrogen fixers, P solubilizers, ACC deaminase producers, etc., for synergistic effects. For instance, Ashry et al. (2022) showed that a combination of two Bacillus strains outperformed single-strain inoculants under drought.
- **Advanced Formulations:** Innovating carriers and delivery systems, such as biochar-based inoculants or nanoparticle encapsulation, to improve shelf stability and slow release of bacteria in the soil.
- **Field Trials:** Conducting multi-location trials in arid agroecosystems to validate PGPR efficacy under real farming conditions. Trials should measure not only plant growth but also fruit yield and quality parameters.
- **Integration with Organic Practices:** Studying the interactions between PGPR and organic amendments (manures, composts, biofertilizers) to develop integrated nutrient management packages. The synergistic use of PGPR with composts or vermicompost could enhance both fertility and microbial activity.
- **Rhizosphere Engineering:** Ultimately, an ‘omics’-guided approach may enable deliberate engineering of the cactus rhizosphere microbiome for optimal crop outcomes.

Addressing these areas will pave the way for reliable PGPR applications. Given the increasing challenges of climate change and soil degradation, PGPR offer a climate-smart tool: they can enhance drought resilience and nutrient use efficiency in dragon fruit, making cultivation more sustainable.

8. **Conclusion**

PGPR-based biofertilizers represent a promising strategy for sustainable cactus fruit production. Research to date indicates that beneficial rhizobacteria can enhance dragon fruit growth, nutrient uptake, and tolerance to drought or saline stress. Compared to chemical inputs, PGPR improve soil health and reduce environmental impact, aligning with eco-friendly agriculture goals. However, realizing this potential requires overcoming challenges of formulation and field variability. Ongoing research should emphasize isolating effective native strains, developing robust consortia, and validating them in situ. With targeted efforts, PGPR inoculation can become an integral component of dragon fruit cultivation, leading to higher yields and more resilient farming systems.

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Role of Indigenous Seeds and Heirloom Varieties

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Abstract

Indigenous seeds and heirloom varieties constitute the genetic backbone of traditional agricultural systems and represent centuries of farmer-led selection and ecological adaptation. These locally evolved varieties possess unique resilience to climatic stresses, pests, and marginal soils, while contributing significantly to agro-biodiversity, nutritional security, and cultural identity. However, the expansion of uniform hybrid cultivars and commercial seed systems has accelerated genetic erosion, undermining traditional seed sovereignty. This article critically examines the ecological, nutritional, socio-cultural, and economic significance of indigenous seeds and heirloom varieties. It also discusses the institutional, policy, and research interventions required for their revival and integration into climate-smart agricultural frameworks. Strengthening community-based seed systems, participatory breeding, and policy support mechanisms will be central to ensuring sustainable and inclusive agricultural development.

1.1 Introduction

Seeds are not merely inputs in agriculture; they are repositories of genetic memory, adaptation, and cultural heritage. The shift from diversified traditional cropping systems to monoculture-based industrial agriculture has significantly narrowed the genetic base of food crops worldwide. According to the Food and Agriculture Organization (FAO, 2010), nearly 75% of crop genetic diversity was lost during the 20th century due to replacement by genetically uniform high-yielding varieties.

Indigenous seeds, often referred to as landraces, have evolved through natural and farmer-driven selection under specific agro-ecological conditions. Heirloom varieties, typically open-pollinated and maintained for more than 50–100 years, retain stable genetic traits and can be saved and replanted without loss of vigour. Unlike hybrids, these varieties preserve genetic heterogeneity, enabling adaptive resilience.

The dominance of commercial hybrid and genetically uniform varieties has undoubtedly enhanced short-term productivity. However, it has simultaneously contributed to:

- Genetic erosion
- Increased dependence on external inputs
- Vulnerability to climatic variability
- Loss of traditional knowledge

In the era of climate change, soil degradation, and nutritional insecurity, the revival of indigenous seed systems is emerging as a strategic necessity rather than a nostalgic choice (Altieri, 2009).

1.2 Indigenous and Heirloom Seeds

- **Indigenous Seeds:** Indigenous seeds are locally adapted varieties developed through centuries of cultivation within specific agro-climatic zones. They exhibit:
    - High genetic variability
    - Adaptation to local stress conditions
    - Farmer-managed seed systems
    - Low dependence on synthetic inputs
- **Heirloom Varieties:** Heirloom varieties are open-pollinated cultivars maintained across generations for their:
    - Genetic stability
    - Unique taste and nutritional attributes
    - Cultural importance
    - Ability to be saved year after year
- Unlike hybrids, heirloom varieties reproduce true to type, allowing farmers to maintain autonomy over seed production. Brush (2004) emphasized that landraces and heirlooms represent "dynamic reservoirs of evolutionary potential," crucial for future breeding programs.

1.3 Importance in Sustainable Agriculture

1. **Resilience to Local Conditions:** Indigenous seeds are naturally adapted to local temperature, rainfall, and soil types, making them more stable under climatic stress.
2. **Low External Input Requirement:** They often require fewer pesticides and fertilizers due to co-evolution with local biotic pressures.

3. **Climate Change Adaptation:** Their wide genetic base enables natural resistance to drought, floods, salinity, and emerging pathogens.
4. **Support to Agroecology and Organic Farming:** They fit perfectly with ecological farming principles, enhancing soil health and biodiversity

1.4 Nutritional and Cultural Value

- Many indigenous grains, pulses, vegetables, and fruits are richer in micronutrients, antioxidants, and dietary fiber.
- Examples:
    - Traditional millets (ragi, foxtail millet) are rich in iron and calcium.
    - Local rice varieties like Chakhao (Manipur) and Njavara (Kerala) have medicinal value.
- These varieties also hold cultural significance linked to rituals, festivals, and community identity.

1.5 Role in Biodiversity Conservation

Indigenous seeds maintain genetic diversity, which is crucial for:

- Breeding climate-resilient crop varieties
- Reducing vulnerability to pests and diseases
- Conserving rare and endangered landraces

Seed diversity increases ecosystem resilience and supports pollinators and beneficial insects.

1.6 Role of Farmers and Community Seed Systems

Farmers act as custodians of traditional seeds through:

- Seed saving and exchange
- Participatory varietal selection
- Community seed banks
- Organic and natural farming groups

These community-led seed systems empower local farmers and reduce dependency on commercial seed markets.

1.7 Challenges Facing Indigenous Seeds

- Market Dominance of Hybrids and GM Seeds

- Loss of Traditional Knowledge
- Policy Gaps
- Limited Research Support

1.8 Policy and Institutional Support

- Recognise farmers' varieties under the Protection of Plant Varieties and Farmers' Rights Act (PPV&FRA).
- Strengthen national and state-level seed missions to include indigenous varieties.

1.8.1 Community-Based Seed Banks

- Expand seed banks for conservation, exchange, and multiplication.
- Encourage the participation of women, who play a key role in seed preservation.

1.8.2 Research and Breeding

- Promote participatory plant breeding (PPB) with farmers.
- Document climate-resilient traits and improve local cultivars while retaining genetic integrity.

1.8.3 Awareness and Market Linkages

- Develop value chains for traditional foods (millets, indigenous rice, vegetables).
- Promote geographical indication (GI) tagging and branding of unique landraces.

1.8.4 Integration With Climate-Smart Agriculture

- Incorporate indigenous seeds into government programs such as:
  - National Mission on Sustainable Agriculture (NMSA)
  - Paramparagat Krishi Vikas Yojana (PKVY)
  - Millet Mission

Conclusions

Indigenous seeds and heirloom varieties represent far more than relics of the past; they are foundational assets for future food systems. Their genetic diversity enhances resilience, their nutritional richness combats hidden hunger, and their cultural relevance strengthens community identity. In an era marked by climate uncertainty and biodiversity erosion, reinforcing traditional seed systems is imperative. A multi-dimensional approach encompassing policy reform, participatory research, community empowerment, and market integration can transform indigenous seed revival into a cornerstone of sustainable agricultural development.

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Rice Straw to Resource: Crop Residue Management in Chhattisgarh

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Abstract

Agriculture produces large volumes of crop residues including straw, stubble, stalks, husks and leaves particularly in cereal-based production systems. In regions dominated by rice-wheat cropping, inadequate residue management often leads to open-field burning, causing severe air pollution, greenhouse gas emissions, nutrient depletion, and soil degradation. Amid rising climate variability and increasing pressure on natural resources, sustainable crop residue management has become essential for climate-resilient and environmentally responsible agriculture. The concept, types and scientific management of crop residues through both in-situ and ex-situ approaches. In-situ practices such as mulching and soil incorporation improve soil organic carbon, moisture retention and nutrient cycling, while ex-situ uses including composting, bioenergy production, livestock applications and industrial processing convert residues into valuable economic resources. Despite clear environmental, agronomic and economic benefits, adoption remains constrained by high machinery costs, limited awareness, tight cropping schedules, and weak market linkages. The study emphasizes that an integrated, policy-driven approach combining technological innovation, farmer capacity building, financial support, and strong extension services is crucial to eliminate residue burning. Treating crop residues as productive assets rather than waste is key to enhancing soil health, boosting farm income, ensuring environmental sustainability, and securing long-term food security.

Introduction

Agriculture generates a large quantity of crop residues in the form of straw, stubble, stalks, husks, and leaves after harvesting. In cereal-dominated regions, particularly rice-growing areas, crop residue management has become a major environmental and agronomic concern (Lal, 2005). Farmers often resort to open-field burning of residues to clear fields quickly for the next crop. While this practice saves time and labour, it results in severe air pollution, loss of valuable soil nutrients, decline in soil organic matter, and emission of greenhouse gases (Pathak *et al.,* 2010).

With increasing climate variability, soil degradation, and pressure on natural resources, sustainable management of crop residues has become essential (FAO, 2017). Proper crop residue management not only prevents environmental damage but also improves soil health, enhances productivity, and contributes to climate-resilient agriculture (Government of India, 2018).

Crop Residue Management

Crop residue management refers to the scientific handling, utilization, and disposal of crop residues in a manner that maintains soil fertility, improves resource-use efficiency, and minimizes negative environmental impacts (FAO, 2017). Residue management can be broadly classified into in-situ management, where residues are retained and managed within the field and ex-situ management, where residues are removed and used for other productive purposes (Government of India, 2018).

Types of Crop Residues

1. **Field Residues**: Residues left on the field after harvesting, such as paddy straw, wheat straw, maize stalks, and stubble.
2. **Processing Residues**: Residues generated during crop processing, such as rice husk, sugarcane bagasse, and oilseed cakes.

Both types of residues have significant potential for improving soil health, generating energy, and creating value-added products if managed properly.

Crop Residue Management Practices

1. In-situ Residue Management: In-situ management involves retaining residues in the field through mulching, surface retention, or incorporation into the soil. These practices improve soil organic carbon, enhance moisture retention, reduce erosion, and strengthen nutrient cycling (FAO, 2017). Conservation agriculture-based technologies such as the Happy Seeder have demonstrated significant potential for managing rice residues while enabling timely wheat sowing (Sidhu *et al.,* 2015).

2. Ex-situ Residue Management: In the ex-situ approach, residues are collected and utilized for composting, livestock feed, mushroom cultivation, bioenergy production, and industrial processing. Crop residues also serve as a valuable source of biomass for renewable energy and biofuel generation (Lal, 2005). Their utilization in bioenergy systems contributes to greenhouse gas mitigation and reduces dependence on fossil fuels (Pathak *et al.,* 2010).

Uses and Importance of Crop Residue Management

Crop residues have multiple productive uses in agriculture and allied sectors. They can be converted into compost and organic manure, supporting sustainable soil nutrition, and are widely used in mushroom cultivation (Pathak *et al.,* 2010). Residues also serve as livestock bedding and treated fodder, while their role in bioenergy generation such as biogas, bio-CNG, briquettes, and biomass-based power is expanding rapidly. In addition, industries utilize crop residues for paper, pulp, and biodegradable packaging materials, creating value-added products from what was once considered waste. The importance of crop residue management extends across environmental, agronomic, and economic dimensions. Environmentally, it helps prevent air pollution caused by stubble burning, reduces greenhouse gas emissions, and conserves essential soil nutrients like nitrogen, phosphorus, and potassium. Agronomically, it improves soil fertility, enhances moisture retention, stabilizes yields, and supports conservation agriculture practices. Economically, it lowers farmers' dependence on chemical fertilizers and irrigation, promotes residue-based rural enterprises, and strengthens farm income and livelihood security. According to Food and Agriculture Organization, effective crop residue management is a key pillar of sustainable and climate-smart agricultural systems FAO (2017).

Challenges in Crop Residue Management

Despite its significant benefits, widespread adoption of crop residue management remains constrained by structural and practical challenges. Many small and marginal farmers lack access to affordable machinery and the high cost of equipment such as happy seeders and balers discourages investment (Government of India, 2018). Limited awareness about the long-term agronomic and economic gains further slows adoption, particularly in regions where traditional residue burning is deeply entrenched.

Additionally, the short turnaround time between harvesting one crop and sowing the next often compels farmers to opt for quicker residue disposal methods. Weak market linkages for residue-based products, such as biomass fuel or packaging material, also reduce economic incentives. Addressing these challenges through policy support, subsidies, awareness campaigns, and improved rural infrastructure will be essential to unlock the full potential of sustainable crop residue management (Government of India, 2018).

Way Forward: The future of crop residue management requires an integrated and policy-supported approach:

- Promoting in-situ residue management through conservation agriculture practices (FAO, 2017).
- Providing subsidies and custom hiring centres for residue management machinery.

- Encouraging residue-based value addition such as composting, bioenergy and mushroom cultivation.
- Strengthening extension services and farmer training.
- Supporting research and innovation in decomposers and low-cost technologies.
- Implementing incentive-based policies to discourage residue burning.

Conclusion

Crop residue management stands at the heart of sustainable and climate-resilient agriculture. When managed scientifically, crop residues enrich soil organic matter, improve nutrient cycling, conserve moisture, and significantly reduce environmental pollution caused by open-field burning. Rather than viewing residues as agricultural waste, recognizing them as valuable on-farm resources can transform farming systems into more efficient, regenerative, and environmentally responsible models of production. Shifting from residue burning to productive utilization, however, requires coordinated action among farmers, researchers, extension agencies, industries, and policymakers. Strengthening access to affordable machinery, promoting awareness of long-term agronomic and economic benefits, improving rural market linkages, and supporting residue-based enterprises are essential steps in this transition. With the right policy support and technological innovation, crop residues can contribute to bioenergy generation, organic nutrient management, livestock sustainability, and eco-friendly industrial production. Ultimately, effective crop residue management enhances farm productivity, reduces input costs, creates additional income opportunities and supports rural livelihoods. More importantly, it safeguards environmental sustainability and food security for future generations. As agriculture faces increasing climate and resource challenges, crop residue management is not merely an alternative practice it is a strategic imperative for building a resilient, profitable, and climate-smart agricultural future.

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Living Lanterns: The Hidden Science Behind Insect Bioluminescence

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1. Introduction

The natural world is illuminated not only by the sun and stars but also by living organisms capable of producing their own light. Among terrestrial organisms, bioluminescent insects represent one of the most fascinating examples of evolutionary innovation. On warm summer nights, the rhythmic flashes of fireflies transform dark landscapes into glowing spectacles. However, beyond their aesthetic beauty, these insects embody a highly efficient biochemical system that has revolutionized modern science.

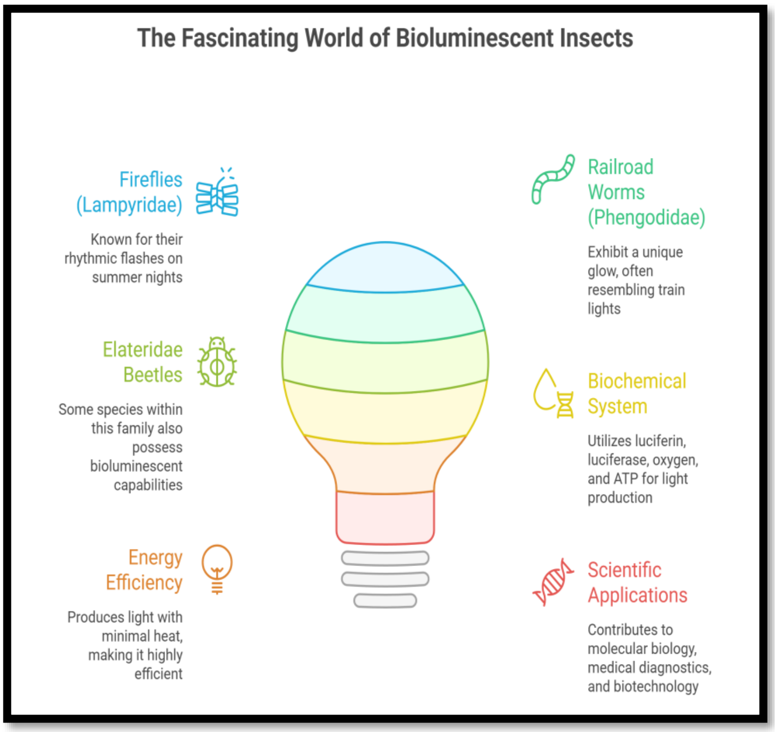

Figure 5: The Fascinating World of Bioluminescent

Bioluminescence refers to the production and emission of light by living organisms through a biochemical reaction involving luciferin (substrate), luciferase (enzyme), oxygen, and adenosine triphosphate (ATP). The reaction produces visible light with minimal heat generation, making it one of the most energy-efficient light-producing systems known (Srivastava and Katiyar, 2021).

Insects belonging primarily to the beetle families **Lampyridae** (fireflies), **Phengodidae** (railroad worms), and certain members of **Elateridae** have evolved specialized light organs. Over time, the study of these organisms has extended far beyond entomology, becoming central to molecular biology, medical diagnostics, environmental monitoring, and biotechnology.

2. Mechanism of Bioluminescence in Insects

The biochemical basis of insect bioluminescence involves the oxidation of luciferin catalyzed by luciferase in the presence of ATP and oxygen. This reaction produces oxyluciferin, carbon dioxide, AMP, and light. Firefly luciferase is among the most studied enzymes due to its stability and high quantum efficiency.

Research by Srivastava and Katiyar (2021) suggests that firefly luciferin may have originally evolved as an antioxidant molecule before being co-opted into a light-emitting system. Further evolutionary insights indicate that luciferase likely originated from fatty acyl-CoA synthetase enzymes through gene duplication and functional divergence (Orlova et al. 2003).

Genomic studies have also revealed key genes involved in luciferin biosynthesis and regulation in fireflies, providing deeper insight into the molecular evolution of bioluminescence (Hiremath, 2025).

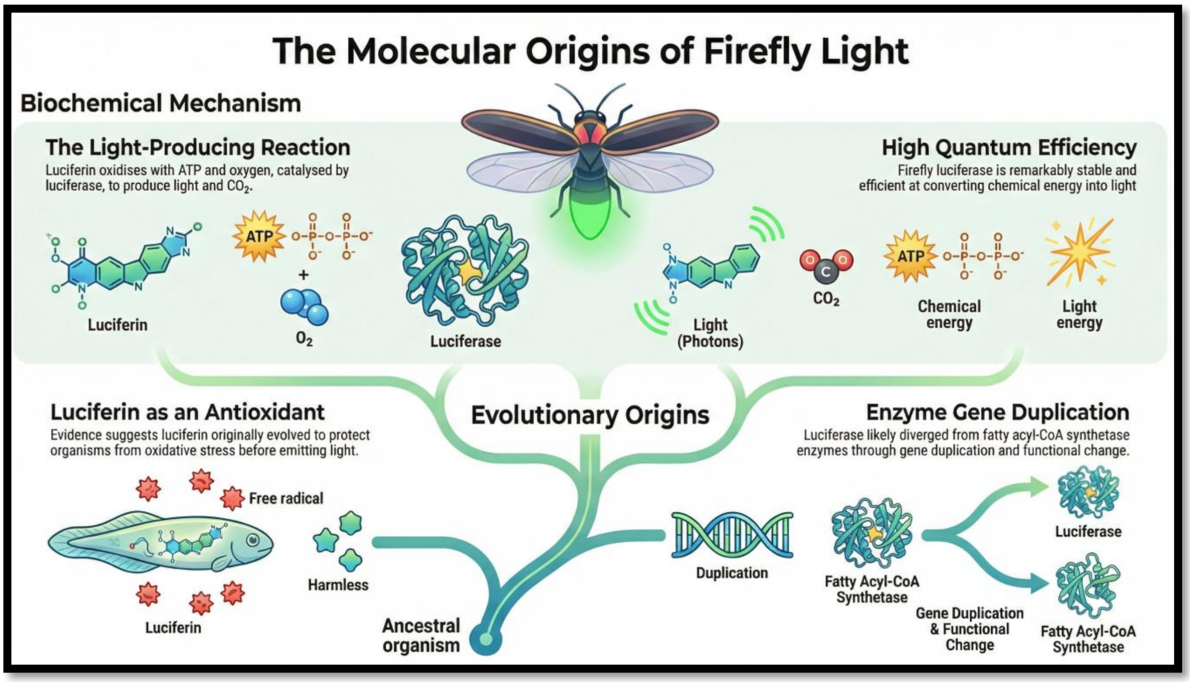

Figure 6: The Molecular Origins of Firefly Light

3. Ecological Significance of Insect Bioluminescence

Bioluminescence in insects serves multiple ecological functions:

a) Mating Communication

In fireflies (family Lampyridae), species-specific flashing patterns function as sexual signals. Males emit characteristic light pulses and females respond with precise timing, ensuring reproductive isolation.

b) Defense Mechanism

Some bioluminescent beetles use continuous glow as aposematic (warning) signals to predators, indicating chemical defenses.

c) Prey Attraction

Glowworm larvae such as *Arachnocampa luminosa* produce light to attract prey. Interestingly, research shows that although glowworms possess a firefly-like luciferase, they utilize a chemically distinct luciferin (Longkumer and Kumar, 2018) highlighting convergent evolution in luminescent systems.

4. Biomedical Applications

The luciferase-luciferin system derived primarily from fireflies has transformed biomedical research.

a) Bioluminescence Imaging (BLI)

Luciferase genes are inserted into cells or organisms to monitor biological processes in real time. This technique allows visualization of tumor growth, gene expression, infection spread, and drug response without invasive procedures (Al- Handawi et al. 2022).

b) ATP Detection Assays

Because the light output is directly proportional to ATP concentration, firefly luciferase is widely used in clinical diagnostics, food safety testing, and microbial contamination detection.

c) Molecular and Cellular Research

Engineered luciferase variants emitting near-infrared light have improved deep-tissue imaging sensitivity, expanding their applications in cancer biology and neuroscience (Thakar and Patel, 2023).

5. Environmental and Industrial Applications

Bioluminescent systems also contribute to environmental and industrial innovation:

- **Biosensors:** Luciferase-tagged bacteria are used to detect toxins, heavy metals, and pollutants.
- **Agricultural monitoring:** Reporter genes based on luciferase help track gene expression in genetically modified crops.
- **Synthetic biology:** Efforts are ongoing to engineer sustainable bio-lighting systems inspired by insect luciferase chemistry.

These applications demonstrate how an evolutionary adaptation for communication has become a cornerstone of biotechnology.

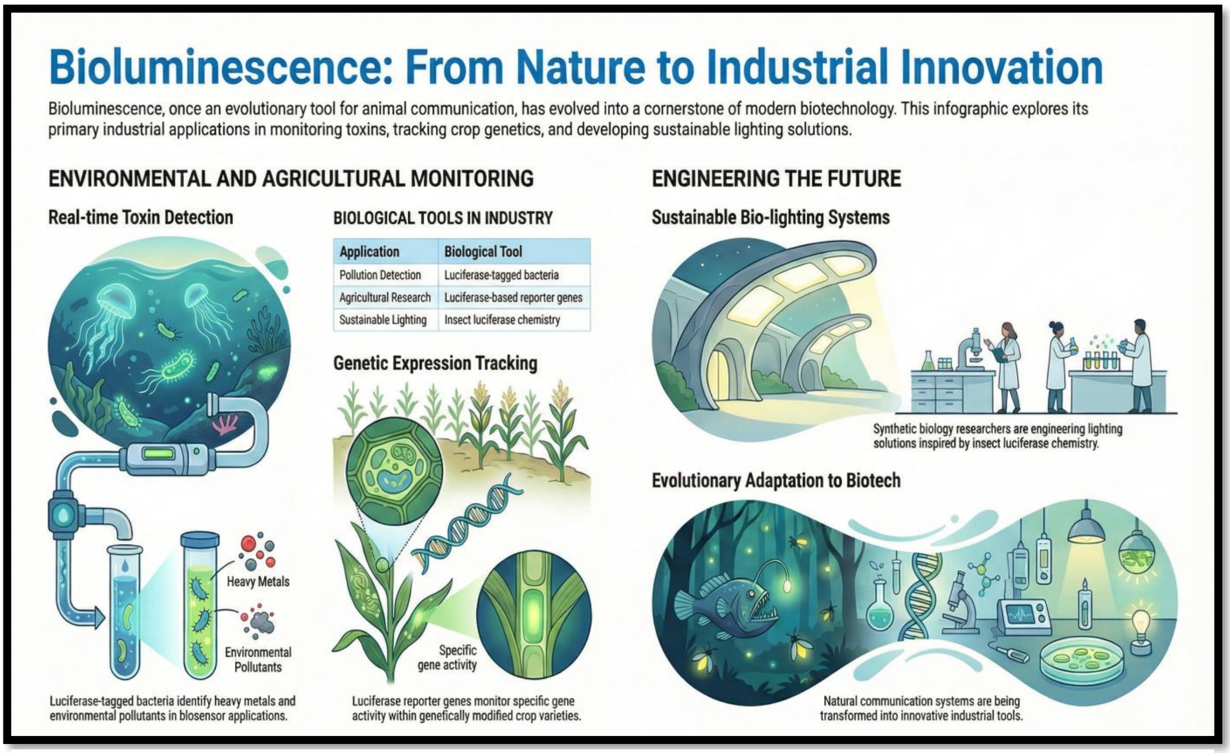

Figure 7: Bioluminescence: From Nature to Industrial Innovation

6. Future Prospects and Conservation Concerns

Despite their scientific value, bioluminescent insect populations—especially fireflies—are declining due to habitat loss, pesticide use, and light pollution. Conservation efforts are essential not only for biodiversity preservation but also for safeguarding biological resources critical to research and innovation.

Future research directions include:

- Development of brighter and more stable luciferase variants
- Exploration of novel luciferins from diverse insect taxa
- Sustainable bio-illumination technologies

7. Conclusion

Bioluminescence in insects represents a remarkable intersection of ecology, evolution, and human innovation. What began as a natural signaling mechanism in beetles has evolved into a powerful analytical tool shaping medicine, molecular biology, and environmental science. As research advances, the continued study and conservation of bioluminescent insects will remain vital for both ecological balance and technological progress.

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Resistance to Microbial Agents: A Growing Challenge in Sustainable Pest Management

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1. Introduction

Sustainable agriculture increasingly relies on biological control agents to reduce dependence on chemical pesticides. Among these, microbial biocontrol agents- including bacteria, viruses and fungi- have emerged as eco-friendly and target-specific alternatives. *Bacillus thuringiensis* (Bt), nucleopolyhedroviruses (NPVs), granuloviruses (GVs) and entomopathogenic fungi such as *Beauveria bassiana* and *Metarhizium anisopliae* are widely used for managing insect pests in agricultural ecosystems.

Initially, microbial agents were considered less likely to induce resistance compared to synthetic insecticides. However, continuous exposure, large-scale adoption of Bt crops and repeated field applications have led to the evolution of resistant insect populations. Resistance to microbial agents refers to a heritable reduction in susceptibility that enables insects to survive doses that previously caused mortality. This emerging issue poses a serious threat to the long-term sustainability of biological pest management (Cory, 2017).

2. Microbial Biocontrol Agents and Their Mode of Action

Microbial agents suppress insect pests through highly specific infection or toxin-mediated mechanisms.

2.1 Entomopathogenic Bacteria

Bacillus thuringiensis produces crystalline (Cry) proteins during sporulation. When ingested by susceptible larvae these protoxins are activated in the alkaline midgut and bind to specific epithelial receptors such as cadherins, aminopeptidase N (APN), alkaline phosphatase (ALP) and ABC transporters. Binding results in pore formation, midgut cell lysis, septicemia and eventual larval death (Cory and Franklin, 2012).

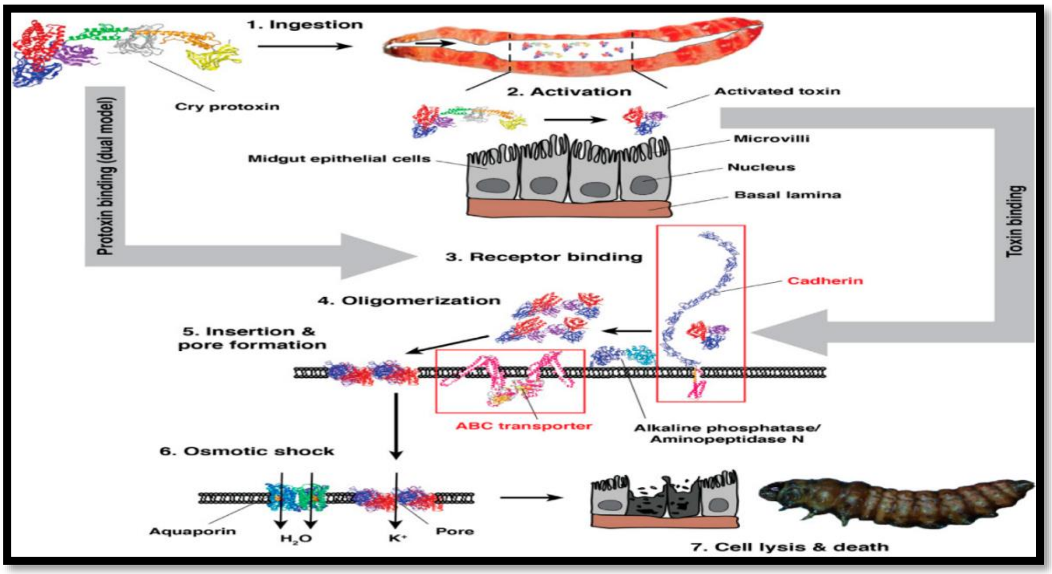

Figure 8: Mode of action of entomopathogenic bacteria

2.2 Entomopathogenic Viruses

Baculoviruses infect insects through ingestion of occlusion bodies. In the alkaline midgut, these occlusion bodies dissolve and release virions that invade epithelial cells. The virus multiplies systemically, causing tissue breakdown and liquefaction of the larva, thereby releasing new infectious particles into the environment (McGuire et al. 2001).

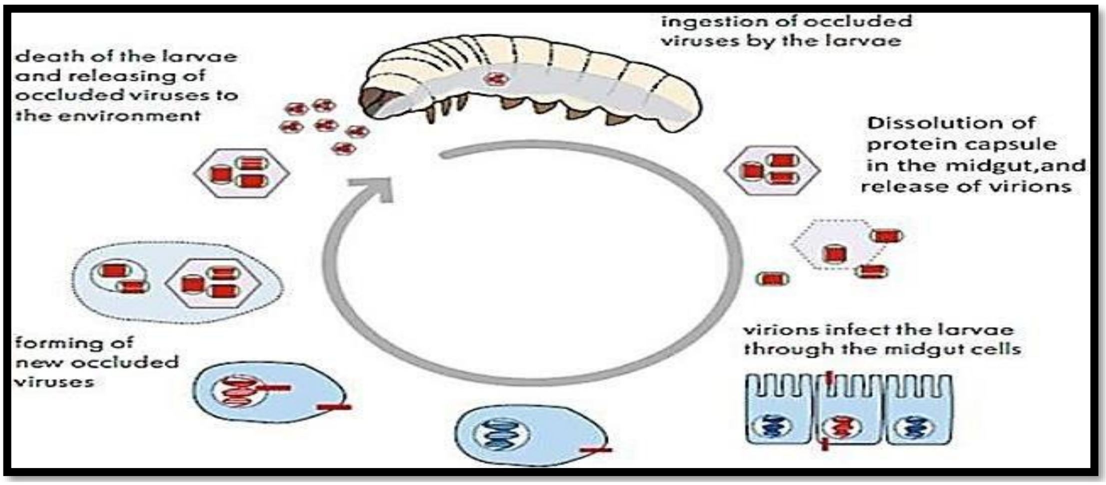

Figure 9: Mode of action of entomopathogenic virus

2.3 Entomopathogenic Fungi

Unlike bacteria and viruses, fungi infect insects by direct contact. Fungal conidia attach to the insect cuticle, germinate and penetrate through mechanical pressure and enzymatic degradation. Once inside the hemocoel, the fungus proliferates, produces toxins and causes host death (Rai et al. 2014).

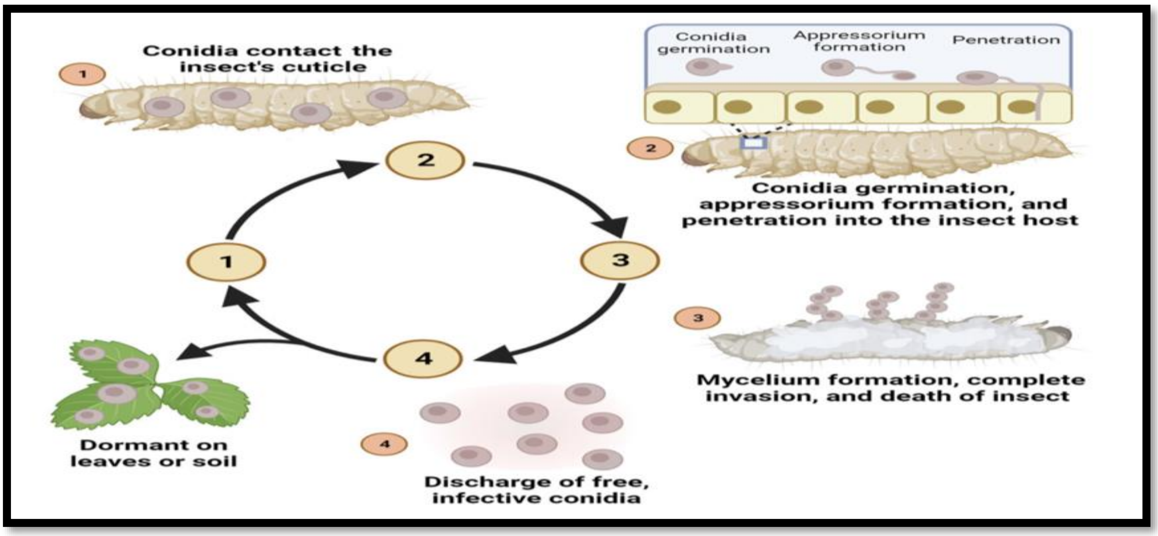

Figure 10 : Mode of action of entomopathogenic fungi

3. Mechanisms of Resistance to Microbial Agents

Insects possess diverse physiological and genetic mechanisms that enable survival under microbial exposure.

3.1 Metabolic Resistance

Insects may enhance detoxification systems by increasing the production of proteases, cytochrome P450 monooxygenases, glutathione-S-transferases and antioxidant enzymes. In Bt-resistant populations, altered gut protease activity may prevent proper activation of Cry protoxins (Altinok et al. 2019).

3.2 Altered Target-Site Resistance

Mutations or reduced expression of midgut receptor proteins such as cadherins, APN, ALP or ABC transporters can prevent effective binding of Bt toxins. Without proper binding, pore formation does not occur, allowing larvae to survive toxin ingestion.

3.3 Midgut Barrier and Immune Responses

In the case of viral resistance, strengthened peritrophic matrix (PM) integrity can block viral entry into midgut cells. Insects may also activate immune pathways including RNA interference (RNAi), melanization and apoptosis of infected cells, limiting viral replication.

3.4 Cuticular Modifications

For fungal pathogens, resistance may arise through increased cuticle thickness, altered surface lipids or enhanced melanization, which reduce fungal adhesion and penetration.

3.5 Behavioral Resistance

Insects may avoid treated foliage, reduce feeding, or increase grooming behavior to remove fungal spores. These behavioral adaptations reduce exposure and infection probability (Altinok et al. 2019).

3.6 Role of Gut Microbiota

Recent studies suggest that native gut bacteria can influence susceptibility to viral pathogens. Disruption of the gut microbial community has been shown to increase viral infection intensity, indicating that symbiotic microbes may contribute to resistance mechanisms.

4. Current Status of Resistance

Field-evolved resistance to Bt toxins has been documented in several major agricultural pests, including cotton bollworm, pink bollworm, fall armyworm and diamondback moth in different regions of the world. Resistance to codling moth granulovirus (CpGV) has also been reported in Europe.

Genetic studies indicate that resistance is often autosomal and polygenic and in many cases partially recessive. However, continuous selection pressure can rapidly increase resistance allele frequency, especially in systems lacking proper resistance management strategies (Lacey and Goettel, 1995).

5. Impact on Sustainable Agriculture

The development of resistance to microbial agents has significant agronomic and ecological consequences:

- Reduced effectiveness of biocontrol agents
- Increased reliance on chemical insecticides
- Disruption of Integrated Pest Management (IPM) programs
- Economic losses due to reduced yield and higher input costs
- Acceleration of resistance to other control methods
- Threat to climate-smart and sustainable agriculture goals

Failure of microbial agents may push farmers back toward heavy chemical usage, undermining environmental and human health benefits achieved through biological control.

6. Management Strategies for Delaying Resistance

Sustainable use of microbial agents requires proactive resistance management.

6.1 Refugia Strategy

Planting non-Bt refugia maintains susceptible insect populations that dilute resistance alleles through interbreeding.

6.2 Gene Pyramiding

Incorporating multiple Bt toxins with different modes of action into a single crop variety reduces the probability of simultaneous resistance development (Zahiri et al. 2002).

6.3 Integration with IPM

Combining microbial agents with cultural practices, biological control and limited chemical use reduces selection pressure and prolongs effectiveness.

6.4 Genetic and Molecular Innovations

Recombinant microbial strains, RNAi-based approaches and improved formulations offer promising avenues for enhancing virulence and overcoming resistance (Zahiri et al. 2002).

6.5 **Regular Monitoring**

Surveillance programs and bioassays are essential for early detection of resistance and timely corrective measures (Sarwar, 2015).

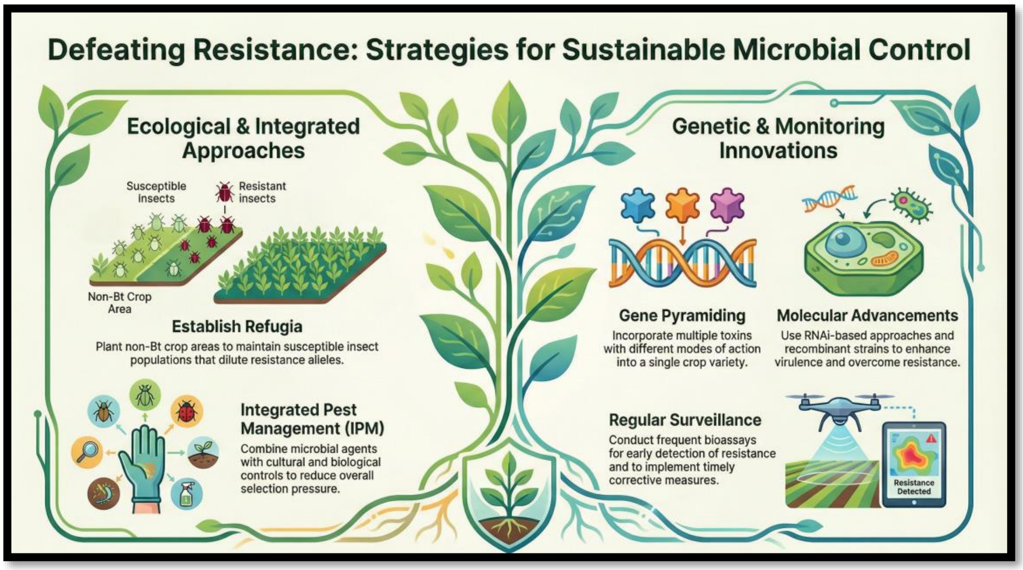

Figure 11: Strategies for Sustainable Microbial Control

7. Future Perspectives

Understanding host–pathogen interactions, genetic basis of resistance and microbiome-mediated defense mechanisms will be critical for developing next-generation strategies. Advances in molecular biology, nanotechnology and microbial strain improvement may enhance the durability of biocontrol agents.

For long-term sustainability, microbial agents must be deployed within diversified and adaptive management frameworks rather than as standalone solutions.

8. Conclusion

Microbial biocontrol agents remain vital tools in environmentally sustainable pest management. However, insect pests possess remarkable adaptive capacity, enabling them to evolve resistance through metabolic, genetic, structural, immunological and behavioral mechanisms.

To safeguard the efficacy of microbial agents, integrated resistance management strategies such as refugia, gene pyramiding, IPM integration and continuous monitoring are essential. A balanced and science-based approach will ensure that microbial biocontrol continues to contribute to resilient and sustainable agricultural systems.

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Beekeeping in Modern Indian Agriculture: A Sustainable Approach to Crop Pollination, Farm Income, and Ecological Balance

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Abstract

Beekeeping (apiculture) is increasingly vital in modern Indian agriculture for enhancing productivity, ecological sustainability and rural livelihoods. It serves as a low-input, eco-friendly enterprise that improves crop yields through effective pollination, supporting food security. The article outlines key honeybee species in India, such as *Apis cerana indica* and *Apis mellifera*, detailing their characteristics and honey production capabilities. Beekeeping also yields valuable by-products like bee wax and royal jelly, enhancing economic viability and fostering entrepreneurship among small farmers. Moreover, beekeeping promotes sustainable agriculture by conserving biodiversity and reducing chemical input dependence, positioning it as a strategic component for sustainable agricultural development and ecological balance in India.

Introduction

Indian agriculture is gradually shifting from traditional subsistence practices to diversified, sustainable and income-oriented farming systems due to increasing population pressure, climate change and market demands (FAO, 2018). In this context, allied agricultural activities have become essential for enhancing farmers' income, nutritional security, and ecological stability (Government of India, 2020). Beekeeping, also known as apiculture is a low-input and eco-friendly enterprise that plays a significant role in modern Indian farming. Besides honey production, beekeeping contributes substantially to crop pollination, biodiversity conservation and sustainable agricultural development, making it an integral component of climate-smart and integrated farming systems (Klein *et al*., 2007; FAO, 2019).

Role of Beekeeping in Crop Pollination

Pollination is one of the most critical ecosystem services provided by honeybees. Honeybees are highly efficient pollinators of several agricultural crops including oilseeds, fruits, vegetables and plantation crops (Free, 1993). Bee-mediated pollination improves fruit set, seed development, yield stability and crop quality (Klein *et al*., 2007). Research studies have reported that effective pollination by honeybees can increase crop yields by 15–50%, thereby directly contributing to higher agricultural productivity and farm profitability (Partap, 2011; FAO, 2019).

1. Enhancing Farm Productivity and Income

Beekeeping requires minimal land, modest capital investment and can be easily integrated with crop production systems without interfering with routine farm activities (Verma, 2018). It provides additional income through honey and other valuable by-products such as beeswax, royal jelly, pollen, propolis and bee venom. In India, beekeeping has emerged as an important subsidiary occupation for small and marginal farmers, landless labourers and rural women, offering year-round employment and income security (NBHM, 2020).

2. Supporting Sustainable and Eco-friendly Farming

Sustainability has become a central objective of modern Indian agriculture. Beekeeping promotes environmentally sound farming by enhancing biodiversity and maintaining ecological balance (Potts *et al*., 2016). Healthy bee populations are indicators of a stable agro-ecosystem. Honeybees facilitate cross-pollination, increase genetic diversity in crops and improve resilience against biotic and abiotic stresses. Organic and natural farming systems particularly benefit from beekeeping, as reduced chemical use supports pollinator health and ecosystem services (FAO, 2018).

3. Contribution to Nutritional and Food Security

Honey and other bee products possess high nutritional, therapeutic and medicinal value. Honey is a natural source of carbohydrates, enzymes, antioxidants, and antimicrobial compounds, while products like pollen, propolis and royal jelly are widely used in nutraceutical and pharmaceutical industries (Crane, 1999). Moreover, by enhancing pollination efficiency, beekeeping indirectly increases the availability, diversity and quality of nutrient-rich foods such as fruits, vegetables, oilseeds and nuts, thus strengthening food and nutritional security in India (Smith *et al*., 2015).

4. Employment Generation and Rural Development

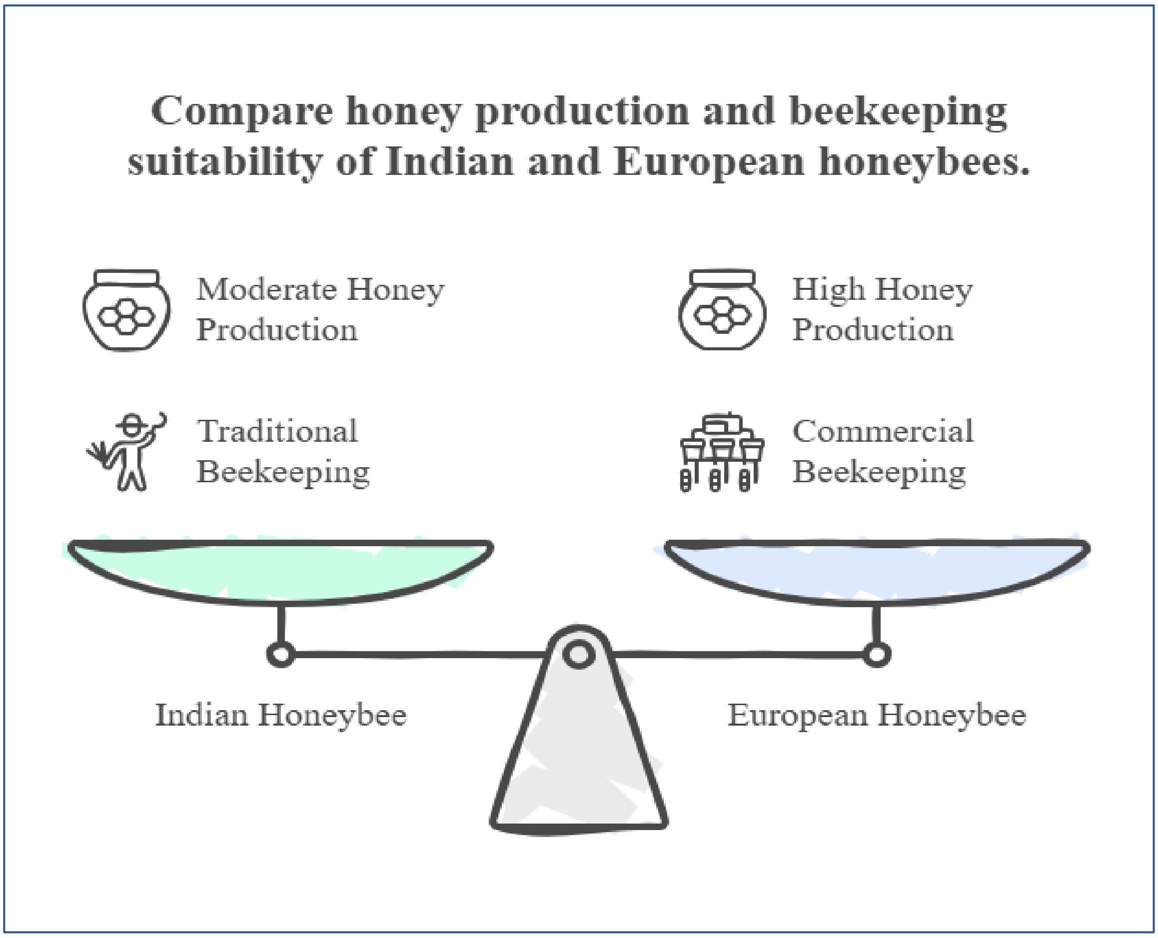
Beekeeping is a labour-intensive enterprise that creates employment opportunities in hive management, honey processing, value addition, packaging and marketing (Verma, 2018). Government initiatives such as the National Beekeeping and Honey Mission (NBHM) have promoted scientific beekeeping, infrastructure development and market integration across the country (Government of India, 2020). These initiatives have significantly contributed to rural development, women empowerment, and youth entrepreneurship in India.

5. Beekeeping under Climate Change Scenario

Climate change has emerged as a major challenge to Indian agriculture due to erratic rainfall, rising temperatures, and declining crop productivity (IPCC, 2022). Beekeeping enhances climate resilience by improving pollination efficiency and stabilizing crop yields under changing climatic conditions (Potts *et al*., 2016). Migratory beekeeping enables efficient utilization of floral resources across seasons and regions, ensuring continuous honey production and sustained pollination services even under climatic stress (Partap, 2011).

Major Honeybee Species in India

Common Name	**Scientific Name**	**Family**	**Life Cycle**	**Honey Production Potential**
Indian honeybee	*Apis cerana indica*	Apidae	Complete metamorphosis (Egg → Larva → Pupa → Adult); life cycle completed in about 21 days for workers	Moderate (8–10 kg/colony/year); widely used in traditional and modern beekeeping
European / Italian honeybee	*Apis mellifera*	Apidae	Complete metamorphosis; worker development completed in ~21 days	High (25–40 kg/colony/year); most preferred species for commercial beekeeping
Rock honeybee	*Apis dorsata*	Apidae	Complete metamorphosis; wild and migratory species	Very high per colony, but not suitable for domestication
Little honeybee	*Apis florea*	Apidae	Complete metamorphosis; small colonies with short foraging range	Low (0.5–1 kg/colony/year); not suitable for commercial honey production



Important By-products of Honey Bees

Bee By-product	Source / Produced by	Major Uses	Importance
Honey	Nectar collected and processed by worker bees	Food, medicine, natural sweetener, immunity booster	Major commercial product; rich in carbohydrates, enzymes, antioxidants
Beeswax	Secreted by worker bees from wax glands	Candle making, cosmetics, pharmaceuticals, polishes	Valuable industrial raw material
Royal Jelly	Secreted by nurse worker bees	Health supplements, cosmetics, fertility and vitality products	Highly nutritious; fed exclusively to queen bee

Bee Pollen	Collected pollen grains mixed with nectar	Health foods, protein supplements	Rich source of proteins, vitamins, minerals
Propolis	Resin collected from plant buds by bees	Medicines, antiseptics, cosmetics	Strong antibacterial, antifungal, and antiviral properties
Bee Venom	Secreted by sting glands of worker bees	Apitherapy, treatment of arthritis and nerve disorders	High medicinal value in controlled doses

Conclusion

Beekeeping plays a crucial role in modern Indian agriculture by enhancing crop pollination, which improves yield, quality and food security. With a diverse range of honeybee species like *Apis cerana indica* and *Apis mellifera*, beekeeping supports various agro-climatic conditions. It not only yields honey but also by-products such as beeswax, royal jelly and propolis, fostering agri-entrepreneurship and increasing farmer income. Furthermore, beekeeping encourages eco-friendly practices, supports biodiversity and reduces chemical dependency. Government initiatives like the National Beekeeping and Honey Mission further enhance the significance of apiculture in rural development, making it an effective and sustainable agricultural enterprise in India.

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HORTICULTURE 4.0: WHERE TRADITION MEETS TECHNOLOGY

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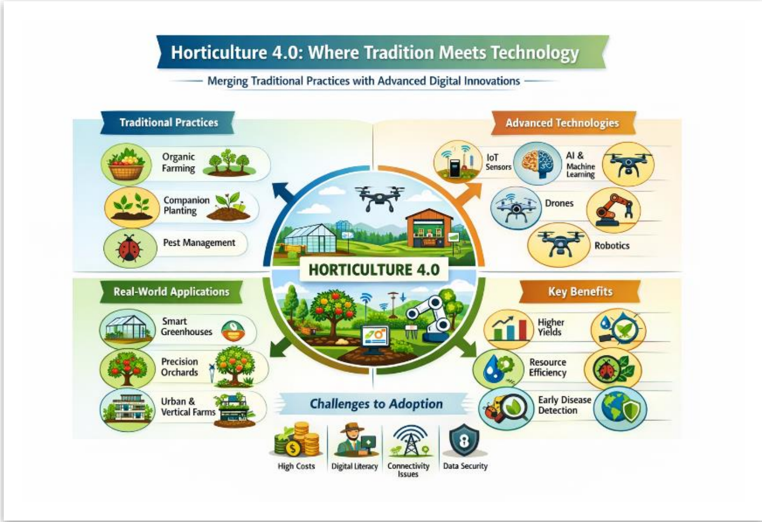
Abstract

Horticulture has traditionally relied on indigenous knowledge, experiential learning and ecological understanding developed over generations. However, increasing pressures from climate change, population growth, resource scarcity, labour shortages and demand for high-quality produce necessitate a paradigm shift in horticultural production systems. Horticulture 4.0 represents this transformation by integrating advanced digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), big data analytics, robotics, remote sensing and automation with conventional horticultural practices. This approach emphasizes precision, sustainability, real-time decision-making and resource-use efficiency while preserving traditional wisdom. The present article discusses the concept, technological components, applications, benefits, challenges and future prospects of Horticulture 4.0, highlighting how tradition and technology can synergistically shape the future of sustainable horticulture.

Keywords: Horticulture 4.0; Precision horticulture; Internet of Things; Artificial intelligence; Smart farming; Sustainable horticulture.

1. Introduction

Horticulture plays a crucial role in ensuring nutritional security, livelihood generation, and economic development, particularly in developing countries. Traditionally, horticultural practices were guided by farmers experiential knowledge, seasonal indicators, crop diversity, and natural resource management strategies. While these systems were largely sustainable, modern horticulture faces unprecedented challenges such as climate variability, declining natural resources, rising production costs and increasing consumer expectations for quality and safety (Singh et al.2025).



In response to these challenges, digital transformation has emerged as a key driver of change in agriculture. Inspired by the principles of Industry 4.0, Horticulture 4.0 integrates digital, biological and physical systems to enable data-driven, intelligent and sustainable horticultural production (Rajan, 2025). This approach does not replace traditional practices but enhances them through precision technologies and real-time decision support.

2. Concept of Horticulture 4.0

Horticulture 4.0 refers to the application of advanced digital technologies to horticultural systems for optimizing crop production, input management, postharvest handling and supply chains. It is characterized by the use of cyber–physical systems, smart sensors, automation and artificial intelligence to monitor, analyse and manage crop production processes in real time (Meena et al. 2025).

The core objective of Horticulture 4.0 is to improve productivity, quality, and sustainability while minimizing environmental impacts and production risks. By combining traditional horticultural knowledge with modern technologies, this approach supports climate-resilient and resource-efficient farming systems.

3. Key Technologies Driving Horticulture 4.0

3.1 Internet of Things (IoT)

IoT plays a central role in Horticulture 4.0 by enabling continuous monitoring of soil moisture, temperature, humidity, nutrient status and microclimatic conditions. Sensor-based systems facilitate precision irrigation and fertigation, reducing water and fertilizer wastage while improving crop performance (Kumar et al. 2025).

3.2 Artificial Intelligence and Machine Learning

AI and machine learning algorithms analyze large datasets generated from sensors, drones, and farm records to predict pest and disease outbreaks, optimize irrigation scheduling, estimate yields and determine optimal harvest time. These technologies enhance decision-making accuracy and reduce dependence on subjective judgment (Rajan, 2025; Singh et al. 2025).

3.3 Precision Horticulture

Precision horticulture focuses on managing spatial and temporal variability within fields and orchards. Technologies such as GPS-guided machinery, variable-rate input application and decision support systems ensure that resources are applied only where and when required, thereby improving efficiency and sustainability (Meena et al. 2025).

3.4 Robotics and Automation

Robotics and automation are increasingly being adopted in nursery management, transplanting, pruning, spraying, harvesting and grading operations. Automated systems reduce labor dependency, improve operational efficiency and ensure uniformity and safety in horticultural operations (Patel et al. 2025).

3.5 Remote Sensing and Drones

Remote sensing technologies, including drones and satellite imagery, provide high-resolution data on crop health, canopy vigor, water stress and nutrient deficiencies. These tools enable early detection of stress factors and timely corrective measures, thereby reducing crop losses (Kumar et al. 2025).

3.6 Smart Protected Cultivation

Smart greenhouses and net houses equipped with automated climate control systems regulate temperature, humidity, light intensity and carbon dioxide concentration. Such systems enhance productivity, quality and year-round production of high-value horticultural crops (Singh et al. 2025).

4. Integration of Traditional Knowledge

Traditional horticultural knowledge related to crop diversity, mixed cropping, organic nutrient management, biological pest control and seasonal indicators remains highly relevant. Horticulture 4.0 integrates this indigenous wisdom by digitizing traditional practices, validating them through scientific data, and scaling them using modern tools. For instance, traditional pest monitoring methods can be enhanced through digital traps and image recognition systems, while organic nutrient management can be optimized using sensor-based soil diagnostics (Rajan, 2025).

5. Applications of Horticulture 4.0

- **Smart Orchards:** Real-time monitoring of fruit trees for irrigation scheduling, pest management and yield forecasting (Singh et al. 2025).
- **Urban and Vertical Farming:** Sensor-controlled hydroponic and aeroponic systems enable efficient production in limited spaces with minimal resource use (Meena et al. 2025).
- **Postharvest Management:** Digital monitoring of temperature, humidity, and atmospheric composition improves storage life and reduces postharvest losses (Kumar et al. 2025).
- **Supply Chain Traceability:** Digital platforms and blockchain-based systems enhance transparency, quality assurance and consumer trust.

6. Benefits of Horticulture 4.0

The adoption of Horticulture 4.0 offers multiple benefits, including increased productivity, improved resource-use efficiency, reduced environmental footprint, enhanced product quality and safety, better risk management and increased profitability for growers (Singh et al.2025; Meena et al.2025).

7. Challenges and Constraints

Despite its potential, the large-scale adoption of Horticulture 4.0 faces challenges such as high initial investment costs, limited digital literacy among small and marginal farmers, inadequate rural infrastructure, data privacy concerns and the need for location-specific customization of technologies (Patel et al.2025). Addressing these challenges requires supportive policies, capacity building, and public–private partnerships.

8. Future Prospects

The future of horticulture lies in intelligent, climate-resilient, and sustainable systems. Advances in AI, digital twins, genomics, nanotechnology and climate-smart analytics are expected to further strengthen Horticulture 4.0. The development of low-cost sensors, mobile-based advisory services and farmer-friendly digital platforms will accelerate adoption, particularly in developing countries (Rajan, 2025; Singh et al. 2025).

9. Conclusion

Horticulture 4.0 represents a convergence of tradition and technology, where ancestral wisdom meets digital innovation. By integrating advanced technologies with ecological principles and local knowledge, Horticulture 4.0 provides a pathway toward sustainable, resilient and profitable horticultural systems. Embracing this approach is essential to meet future food and nutritional demands while preserving environmental integrity and cultural heritage.

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FROM FARM TO FORK: SMART SUPPLY CHAIN MANAGEMENT OF PERISHABLES

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Abstract

Perishable commodities such as fruits, vegetables, flowers, dairy, meat, and seafood are highly sensitive to time, temperature, humidity, and handling conditions. Inefficient supply chain management (SCM) of perishables leads to significant quantitative and qualitative losses, threatening food security, farmer incomes, and sustainability. Modern supply chain management of perishables integrates traditional handling practices with advanced technologies such as cold-chain logistics, Internet of Things (IoT), artificial intelligence (AI), blockchain, and intelligent packaging to ensure quality preservation, traceability, and timely delivery. This article discusses the concept, components, technological interventions, benefits, challenges, and future prospects of perishable supply chain management, with emphasis on recent advancements and sustainable approaches.

Keywords: Perishables; Supply chain management; Cold chain; Postharvest losses; Traceability; Smart logistics.

1. Introduction

Perishable agricultural commodities form the backbone of nutritional security and agri-based economies, particularly in developing countries. However, their short shelf life and susceptibility to spoilage make them vulnerable to losses during harvesting, handling, storage, transportation, and marketing. Globally, nearly one-third of perishable food is lost or wasted annually, primarily due to inefficient supply chain infrastructure and poor postharvest management practices (Anusha et al. 2024; Satheeshkumar et al. 2025).

In India, postharvest losses of fruits and vegetables alone account for substantial economic losses, highlighting the urgent need for efficient supply chain systems. Supply chain management of perishables aims to maintain product quality and safety from farm to fork by integrating coordinated logistics, cold-chain infrastructure, information flow, and technological innovations (Ministry of Agriculture, 2025).

2. Concept of Supply Chain Management of Perishables

Supply chain management of perishables refers to the integrated management of material flow, information flow, and financial flow involved in the production, postharvest handling, storage, transportation, processing, distribution, and retailing of perishable commodities. The primary objective is to minimize quality deterioration, microbial spoilage, and losses while ensuring timely delivery to markets and consumers (Ghosh et al.2025).

Unlike non-perishable goods, perishable supply chains are time- and temperature-sensitive, requiring strict control over environmental conditions and rapid decision-making across all supply chain nodes.

3. Key Components of Perishable Supply Chain

3.1 Harvesting and On-Farm Handling

Proper harvesting at optimum maturity, use of clean harvesting tools, field sorting, and pre-cooling are critical first steps in maintaining quality. Traditional knowledge of harvest indices combined with scientific maturity assessment ensures better shelf life and marketability (Satheeshkumar et al. 2025).

3.2 Pre-Cooling and Cold Storage

Pre-cooling methods such as forced-air cooling, hydro-cooling, vacuum cooling, and icing remove field heat and slow down respiration. Cold storage facilities maintain optimal temperature and relative humidity, significantly extending shelf life and reducing physiological losses (Chang et al. 2025).

3.3 Cold Chain Logistics

Cold chain logistics involves temperature-controlled transportation and storage throughout the supply chain. Refrigerated vehicles, cold rooms, ripening chambers, and reefer containers are essential for preserving quality and preventing microbial growth during transit (Revathi et al. 2025).

Fig.2. Cold chain logistics

3.4 Transportation and Distribution

Efficient transportation systems with proper packaging, cushioning, and stacking reduce mechanical damage. Route optimization and real-time monitoring ensure timely delivery and reduce transit losses (Ghosh et al. 2025).

3.5 Packaging and Handling

Advanced packaging systems, including modified atmosphere packaging (MAP), active packaging, and intelligent packaging, help regulate gas composition, control moisture loss, and inhibit microbial growth, thereby extending shelf life (Ashaq et al. 2025).

4. Role of Advanced Technologies in Perishable SCM

4.1 Internet of Things (IoT)

IoT-enabled sensors continuously monitor temperature, humidity, and gas composition during storage and transportation. Real-time alerts help prevent temperature abuse and quality deterioration (Kumar et al. 2025).

4.2 Artificial Intelligence and Big Data Analytics

AI-based predictive models analyze historical and real-time data to forecast demand, optimize inventory, predict shelf life, and reduce food waste. Machine learning algorithms support decision-making across logistics and distribution networks (Rajan, 2025).

4.3 Blockchain and Traceability Systems

Blockchain technology ensures transparent and tamper-proof traceability of perishable products across the supply chain. It enhances food safety, quality assurance, and consumer trust by enabling rapid recall and origin verification (Ghosh et al. 2025).

4.4 Smart Packaging and Nanosensors

Smart packaging integrated with nanosensors provides real-time information on freshness, spoilage, and microbial activity. These systems improve quality monitoring and reduce unnecessary food disposal (Ashaq et al. 2025).

5. Benefits of Efficient Perishable Supply Chain Management

- Reduction in postharvest losses and food waste
- Improved shelf life, quality, and safety of produce
- Enhanced market access and price realization for farmers
- Increased consumer confidence through traceability
- Lower environmental footprint and greenhouse gas emissions
- Improved overall efficiency and profitability (Satheeshkumar et al.2025; Ghosh et al. 2025)

6. Challenges and Constraints

Despite technological advancements, several challenges hinder efficient perishable supply chain management:

- Inadequate cold-chain infrastructure
- High capital investment and operational costs
- Fragmented supply chains and poor coordination
- Limited technical knowledge and skilled manpower
- Energy-intensive cold storage systems
- Regulatory and standardization issues (Ministry of Agriculture, 2025)

7. Future Prospects and Sustainable Approaches

The future of perishable supply chain management lies in intelligent, sustainable, and resilient systems. Integration of renewable energy-powered cold storage, AI-driven logistics optimization, digital twins, and smart packaging will enhance efficiency while reducing environmental impact. Community-based cold-chain models, mobile cold storage units, and inclusive digital platforms will support smallholder farmers and reduce losses at the grassroots level (Rajan, 2025; Satheeshkumar et al. 2025).

8. Conclusion

Efficient supply chain management of perishables is essential for reducing postharvest losses, improving food security, and enhancing farmer incomes. By integrating traditional handling practices with advanced technologies such as cold-chain logistics, IoT, AI, blockchain, and intelligent packaging, perishable supply chains can become more resilient, transparent, and sustainable. Strategic investments, supportive policies, and capacity building are critical for the successful transformation of perishable supply chains worldwide.

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Mimicry in Insects and Its Role in Survival of Insects

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1. Introduction

Insects are the most diverse group of animals on Earth, occupying nearly every terrestrial and freshwater habitat. Despite their ecological success, most insects are small, soft-bodied, and vulnerable to a wide range of predators such as birds, reptiles, amphibians, mammals, spiders, and other insects. Consequently, natural selection has favored the evolution of highly effective defensive and offensive strategies. Among these, mimicry stands out as one of the most sophisticated adaptations for survival.

Mimicry is defined as the evolutionary phenomenon in which one organism (the mimic) evolves to resemble another organism (the model) or a component of its environment in order to deceive a third party (usually a predator or prey). This resemblance may involve coloration, shape, behavior, sound, or even chemical signals. Through mimicry, insects can avoid predation, approach prey undetected, or enhance reproductive success.

Recent advances in evolutionary biology, genomics, and behavioral ecology have revealed that mimicry systems are more complex than previously thought. They often involve multiple interacting species, predator learning processes, and genetic constraints that shape how closely a mimic can resemble its model (Jamie et al. 2025).

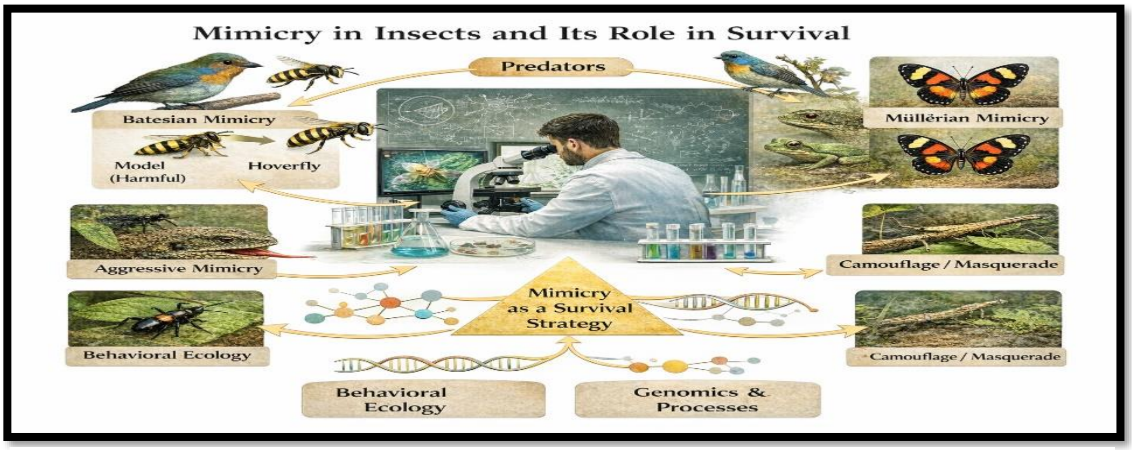

Figure 12: Mimicry and its role in insect survival

2. Types of Mimicry in Insects

- **Batesian Mimicry**

In Batesian mimicry, a harmless species resembles a harmful or unpalatable one. Predators that have learned to avoid the dangerous model also avoid the mimic.

Many flies mimic stinging bees or wasps through coloration, body shape, and flight behavior. This deceptive resemblance reduces predation risk even though the mimics lack defenses.

- **Müllerian Mimicry**

Müllerian mimicry involves multiple harmful species converging on similar warning signals. This shared appearance strengthens predator learning and reduces attacks on all participants.

Genetic studies of mimetic insects show that natural selection drives convergence in coloration and patterns among toxic species, though developmental constraints may limit perfect resemblance (Van Belleghem et al. 2020).

- **Aggressive Mimicry**

Aggressive mimics resemble harmless organisms or environmental elements to approach prey undetected. Some predatory insects mimic flowers, ants, or other insects to capture victims.

- **Camouflage and Masquerade**

Camouflage (crypsis) allows insects to blend into their surroundings, while masquerade involves resembling specific objects such as leaves, bark, or twigs.

Fossil and modern evidence indicates that plant mimicry—such as leaf or twig resemblance—has been a successful survival strategy for millions of years (Yang et al. 2022).

3. Evolutionary Mechanisms of Mimicry

Mimicry evolves through natural selection acting on heritable variation within populations. Individuals that more closely resemble protective models or environmental objects are less likely to be attacked and therefore more likely to survive and reproduce.

- **Predator Perception and Learning**

Predators play a central role in shaping mimicry systems. Many predators learn from experience and avoid prey associated with unpleasant outcomes such as toxicity or painful stings. Studies show that visual signals—especially colour—often carry more weight than precise shape or size, explaining why imperfect mimics can still succeed (Corral-Lopez et al. 2021).

- **Genetic and Developmental Constraints**

Recent genomic research has identified key genetic regions responsible for coloration and pattern formation. However, developmental pathways may restrict how closely a mimic can resemble its model leading to variation among mimics (Van Belleghem et al. 2020).

- **Deep Evolutionary History**

Fossil discoveries reveal that mimicry is not a recent innovation but has deep evolutionary roots. Mimetic adaptations in Cretaceous insects indicate that predator-driven selection has shaped insect morphology for over 100 million years (Tihelka et al. 2020).

4. Role of Mimicry in Insect Survival

- **Predator Avoidance**

The primary function of mimicry is protection from predators. By resembling toxic species or blending into the environment, insects reduce the probability of detection or attack. This directly increases survival and longevity.

- **Enhanced Predation**

Aggressive mimics gain advantages in capturing prey. By appearing harmless or attractive, they can approach prey without triggering escape responses.

- **Adaptation to Environmental Conditions**

Camouflage and masquerade allow insects to survive in habitats where concealment is essential, such as open vegetation or bark surfaces. Debris-carrying camouflage and plant mimicry help insects occupy ecological niches that would otherwise be too risky (Wang et al. 2022).

- **Evolutionary Stability and Biodiversity**

Mimicry influences species interactions and community dynamics. In some cases, groups of species form mimicry complexes that can mask hidden genetic diversity, as morphologically similar species may actually be distinct evolutionary lineages (Chiocchio et al. 2021).

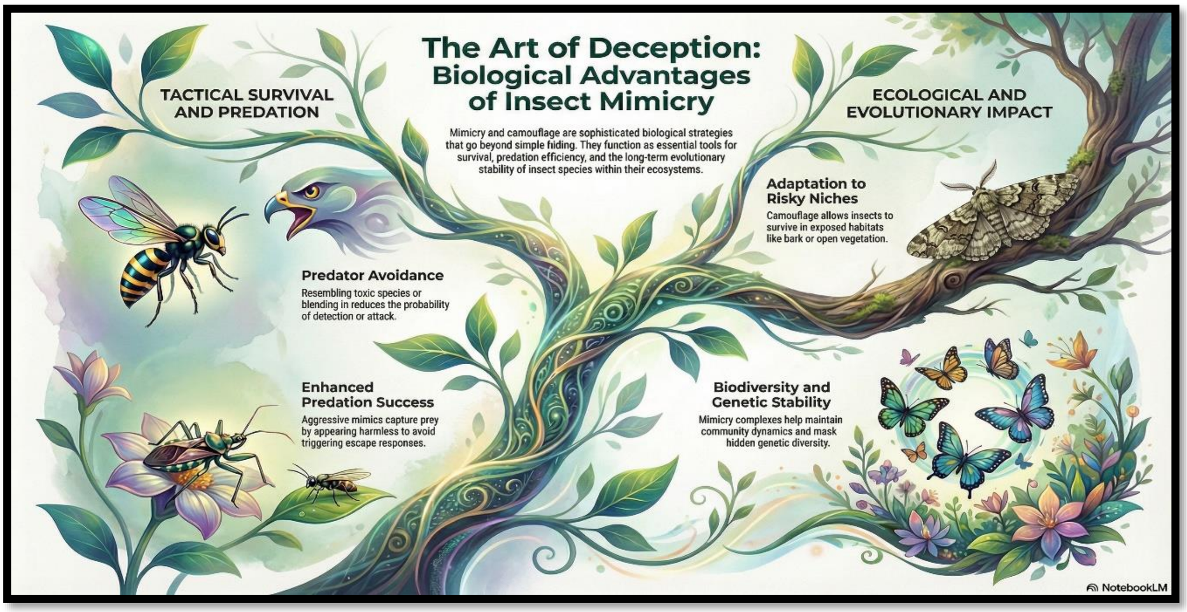

Figure 13: Biological advantages of insect mimicry

5. Importance in Modern Research

Mimicry remains a major focus of contemporary evolutionary research. Advances in genomic sequencing, behavioural experiments, and computational modelling are revealing how mimicry evolves, how predators perceive signals, and how environmental changes influence mimicry systems.

Modern studies also explore applications beyond biology, such as biomimetic design and robotics inspired by camouflage strategies. The integration of palaeontology, ecology, and molecular biology is providing a comprehensive understanding of mimicry across time (Jamie et al. 2025).

6. Conclusion

Mimicry is one of the most effective and versatile survival strategies in insects. Through deceptive resemblance—whether to harmful species, environmental objects, or attractive signals—insects can avoid predation, capture prey efficiently, and adapt to diverse habitats. Fossil evidence, ecological studies, and genetic research collectively demonstrate that mimicry has shaped insect evolution for millions of years and continues to play a crucial role in maintaining biodiversity and ecological balance. Understanding mimicry not only deepens our knowledge of insect survival strategies but also provides insights into evolutionary processes that govern life on Earth.

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