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Recent Advances in Biological Control

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India is one of the world's largest agricultural countries, with more than 60% of the population employed in agriculture and related activities. Agriculture in India contributes an 18.6% share of the national GDP. India produces almost all crops, including cereals, vegetables and cash crops. Pest management methods have experienced various devel opments and advancements over time to minimize their environmental impact. The overuse of chemical pesticides has led to the development of various adverse consequences such as resistance, residue, resurgence, and secondary pest outbreaks in different parts of the world. Pesticides are regarded as the most effective weapons and play a crucial role in crop protection against agricultural insect-pests, but the rampant use of chemical fertilisers and other pesticides has resulted in several undesirable effects on human health, the environment, and the overall sustainability of agro-ecosystems. Biological control, in this sense, is a well-established strategy for controlling pest populations by releasing parasitoids, predators, antagonist populations, or microbial pathogens into the field to keep pest populations below the threshold level. It is likely to be less adaptive by the majority of farm ers than other physical or chemical control methods due to slower perpetuation and environmental dependency, but is usually more stable and long-lasting. One reason for biological control methods' increasing popularity is their safety to non-target organisms over the last 100 years, which is considered the era of modern biological control. Biological control can defined as the use of living organisms to suppress pest populations, remains a central pillar of integrated pest management (IPM), with deep roots in pre-modern agriculture and extensive validation across decades of empirical research. The global concern over pesticide resistance, environmental contamination, and biodiversity decline has accelerated research into next-generation biocontrol agents and systemic approaches. Recent progress features novel technologies, improved microbial formulations, precision agriculture, genomic tools, and a systems-level One Health perspective.

Technological Innovations in Mass Production and Application

Microbial Pesticides and Formulation Advances

Recent work has established high-efficacy microbial biopesticides, such as *Trichoderma* and *Bacillus* species, with advanced mechanisms of antagonism, mycoparasitism, antibiosis, induced systemic resistance (ISR), and lipopeptide production (Sun *et al.*, 2021). Innovations such as layer- by-layer encapsulation, biopolymer-based emulsions, and cell-cap encapsulation have improved agent stability, viability, and effective delivery.

- Genetic enhancement and CRISPR-based modification have increased microbial metabolic activity and target specificity, generating strains with superior pathogen suppression.

- Commercial advancements include recombinant DNA applications, such as Mycogen CellCap® encapsulation, to deliver fragile biopesticide molecules to the field environment (Pitterna *et al.*, 2009).

Precision Agriculture and Data-Driven Deployment

The integration of real-time pest population monitoring and predictive analytics has enabled targeted biocontrol applications, optimizing field outcomes and reducing environmental impact. Sensors, remote-sensing platforms, and algorithmic threshold models inform the timing, location, and dosage of biological agents, revolutionizing pest management strategies.

Genetic and Molecular Tools

Genomic Understanding and RNA Interference (RNAi)

Genomic tools have illuminated host-pathogen interactions and signaling pathways critical to advancing biocontrol efficacy (Hubbard *et al.*, 2020). RNA interference is now deployed to silence critical pest genes, either directly or via symbiotic microbes, yielding species-specific suppression with minimal off-target effects.

- Transgenic crops expressing Bacillus thuringiensis cry genes confer resistance to insect pests, reducing the need for chemical interventions.
- Synthetic symbionts and engineered gut microbiomes emerge as next-generation solutions for pest suppression with enhanced stability and environmental safety.

1. Sterile Insect Technique (SIT) Upgraded for Screwworm Control

USDA researchers at the Knipling-Bushland lab near Kerrville, Texas, are modernizing the classic sterile insect technique (SIT) to combat the New World screwworm fly (U.S. Department of Agriculture, 2025) Innovations include:

- More selective attractants and traps aimed at capturing only females**,** while preserving sterile males for population suppression.
- Genomic surveillance that tracks origins of outbreak strains, like connection of Florida cases to populations in the Dominican Republic and Trinidad & Tobago, informing better containment strategies.

2. RNA Pesticides: Precision against Varroa Mites

GreenLight Biosciences is advancing an “RNA pesticide” designed to target genes unique to the destructive varroa mite: without harming bees or other beneficial species. Delivered *via* sugar syrup given to worker bees, this technique interrupts mite development at the molecular level. It has shown promise in lab settings and reflects a growing trend toward highly specific, eco-friendly control measures.

3. Tiny Wasps as Eco-Friendly Moth Guards

Rentokil has begun using entosite parasitoid wasps, tiny insects less than half a millimeter in size: to control moth infestations in museums, historic homes, and other spaces with delicate textiles. The wasps lay their eggs inside moth eggs, stopping larvae from hatching. This non-toxic strategy offers continuous protection without harming fragile artifacts and aligns with successful past uses of parasitoids in agriculture.

4. Drone-Assisted Biocontrol: UAV-IQ’s Aerial Releases

Agritech startup UAV-IQ is leveraging drones to deploy beneficial insects, like predatory mites and parasitoids—over crops with unprecedented precision. Their drone system supports targeted releases in vineyards, offering:

- Efficient coverage over fields.
- Reduced labour costs.
- Better integration with existing Integrated Pest Management (IPM) practices. One key project, funded by the California Department of Food and Agriculture, focuses on controlling vine mealybugs using predators (*Cryptolaemus montrouzieri*) and parasitoids (*Anagyrus pseudococci*) *via* drone delivery.

5. Microbial Consortia & Biopesticides: Fighter Teams against Nematodes

A 2025 review highlights a surge in research using bacteria and fungi, alone or as microbial consortia, to suppress phytoparasitic nematodes. These blends offer multiple modes of action and more reliable persistence than single-strain agents. Although still emerging in commercialization, they hold promise for sustainable, broad-spectrum nematode control.

6. Biopesticides & RNAi: Targeted Molecular Attacks

- **Microbial biopesticides**, using bacteria, fungi, or viruses, are becoming more potent and refined, offering targeted pest suppression with minimal non-target impact.
- **RNA interference (RNAi)** technologies allow silencing of pest-specific genes. The first such U.S.-approved insecticide, Calantha, targets a critical gene in the Colorado potato beetle.
- Advances such as encapsulating dsRNA in nanoparticles improve stability and field efficacy of RNAi-based solutions.

7. Smart Tech & Biocontrol: AI, IoT, and Policy Drivers

Emerging technologies, including AI, real-time sensors, and the Internet of Things, are enabling smarter monitoring and deployment of biocontrol agents. Reinforced by evolving policies that favor non-chemical pest management, these innovations are accelerating adoption of advanced biocontrol worldwide.

Summary Table: Advances at a Glance

Innovation	Key Advantage
Modernized SIT (screwworm)	Genomic surveillance + improved female-specific trapping
RNA pesticides (varroa mite)	Species-specific targeting via feeding behavior
Parasitoid wasps	Non-toxic, continuousmoth control for delicate environments
Drone-based insect releases	Precise, labor-efficient deployment in agriculture
Microbial consortia	Enhanced efficacy & resilience vs. single agents
RNAi & microbial biopesticides	Eco-friendly, accurate molecular pest disruption
AI/IoT + supportive policy	Data-driven deployment + favorable regulatory environment

One Health Contributions

A One Health perspective connects biological control to human, animal, plant, and environmental health, mitigating risks from chemical pollution, biocide resistance, and biodiversity loss (Schaffner *et al.*, 2024). Biological control has controlled at least 15 weed and 12 insect species in natural habitats, supporting restoration and ecosystem resilience.

- Notable cases: Biocontrol of cassava mealybug in Asia reduced tropical deforestation; fungal control of locusts decreased aerial insecticide use, enhancing multi-sectoral health outcomes.

Mechanisms of Action

Recent reviews clarify the biological and chemical interactions underlying successful control. *Trichoderma* species employ mycoparasitism and antibiosis, while *Bacillus* species utilize lipopeptides and siderophores, directly inhibiting pathogen growth (Ferreira Filho *et al.*, 2020). Application of surfactants such as Silwet L-77 increases microbial penetration into plant tissues, improving efficacy (Johnson *et al.*, 1996)

Regulatory and Commercial Trends

Formulation stability, commercial viability, and regulatory approval remain central challenges (Muras *et al.*, 2021). Layer-by-layer encapsulation and polymeric emulsions have increased shelf- life (Løvschall *et al.*, 2024), while genetic enhancement strategies like mutagenesis, recombinant gene integration, drive agent potency and specificity.

- Regulatory harmonization across borders is essential for global deployment of biocontrol products.
- Societal awareness of food safety and environmental sustainability promotes biocontrol adoption.

Future Directions and Research Priorities

Multidisciplinary Collaboration

Recent studies advocate integrated approaches that transcend disciplinary boundaries, leveraging plant pathology, entomology, molecular biology, and ecology. Cooperation among scientists, practitioners, and policymakers aims to realize the full public health and environmental potential of biological control.

Sustainability and Resilience

Future research will focus on:

- Further optimizing genetic tools for biocontrol agent improvement.
- Harnessing ecological intelligence for landscape-level resilience.
- Enhancing data-driven deployment for cost-effective application.
- Evaluating long-term ecosystem effects and non-target safety.

Conclusion

Biological control stands at a frontier of sustainable agriculture and ecosystem management. Recent advances in microbial agents, genetic engineering, precision agriculture, and ecological integration demonstrate both scientific innovation and real-world relevance. The One Health framework underscores its multifaceted benefits, and continued interdisciplinary collaboration will ensure biological control remains pivotal amidst future agricultural and environmental challenges.

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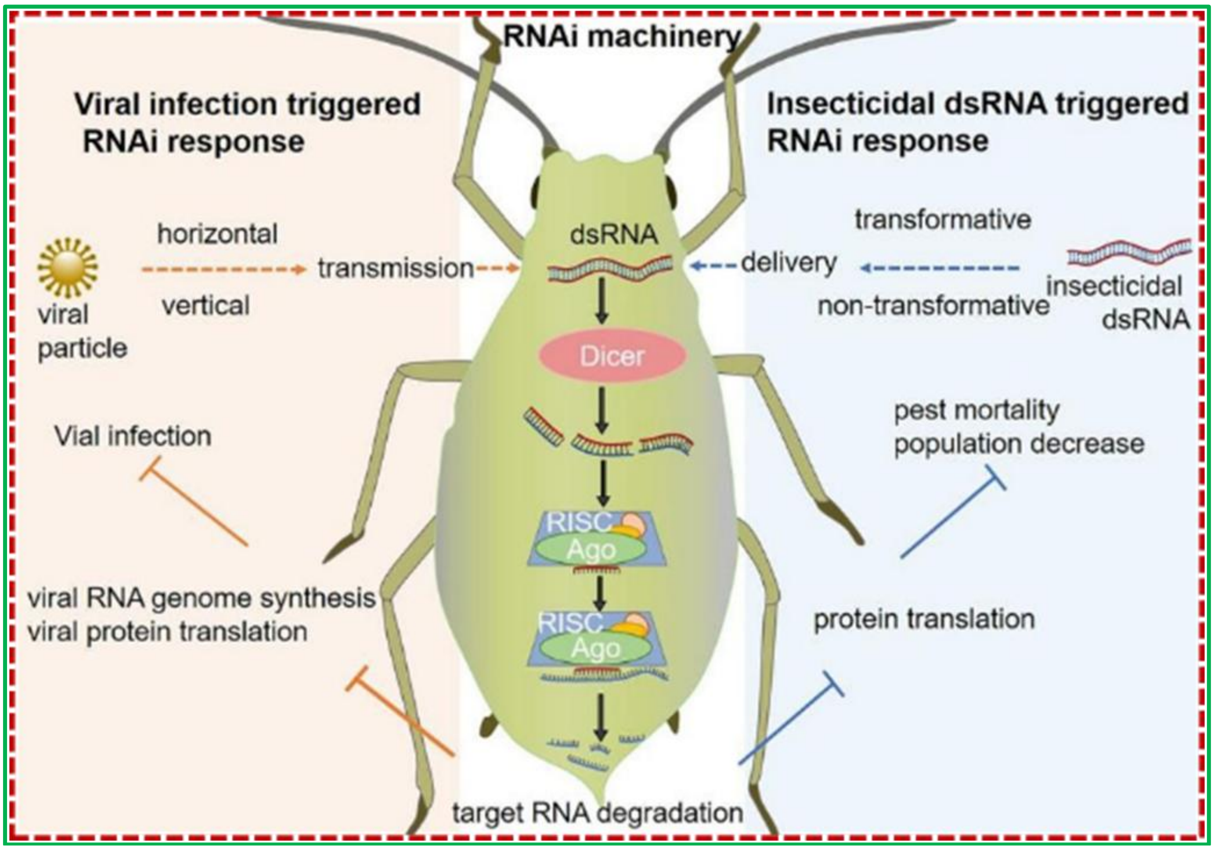
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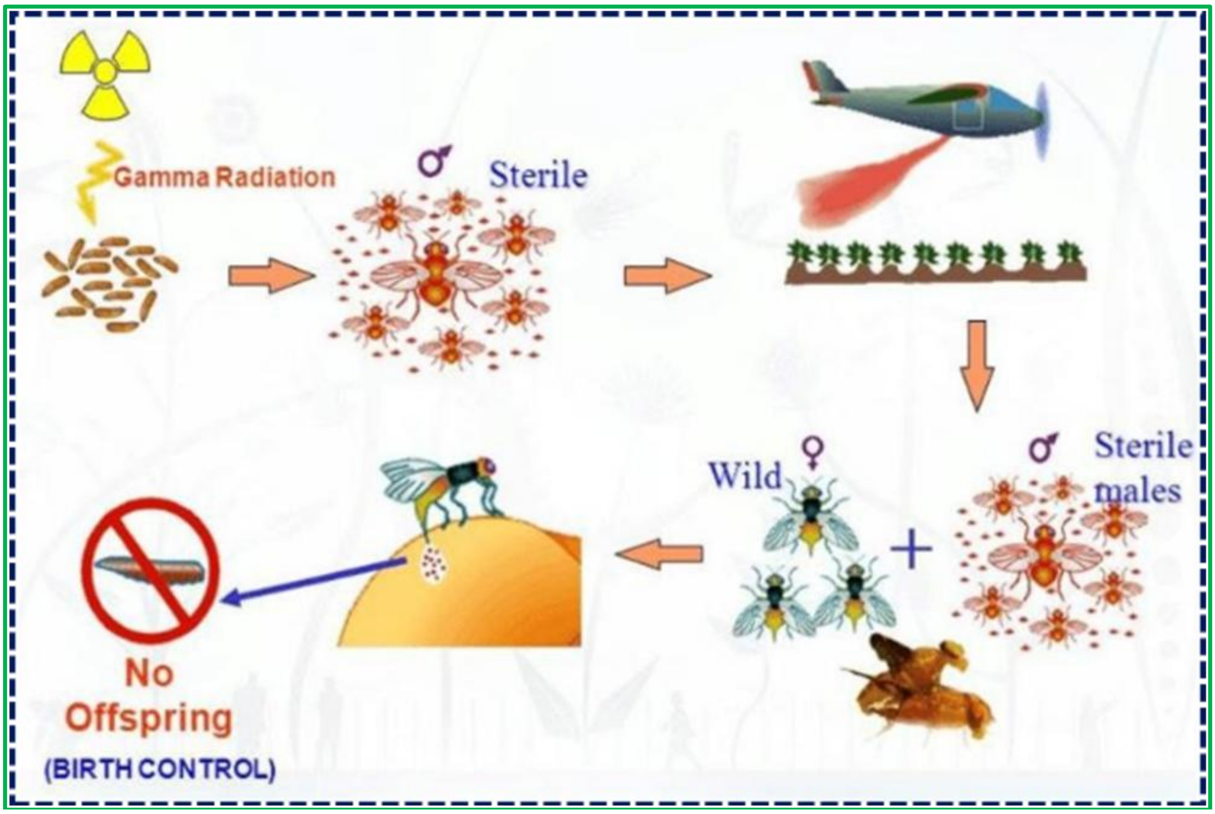
Gamma Radiation
♂ Sterile
Wild ♀
♂ Sterile males
+
No Offspring
(BIRTH CONTROL)