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Recent advances in biological control in India: A sustainable approach to insect pest management

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Abstract
India, with its rich agricultural heritage and diverse ecosystems, has long been a hub for exploring innovative pest control methods. As the country grapples with issues such as pesticide resistance, environmental degradation, and the rising cost of chemical inputs, biological control has emerged as a promising and sustainable solution to pest management. The last few years have witnessed significant advances in this field, driven by research, government support, and the adoption of newer technologies. Over the past decade, new advancements in biological control research have led to the identification of a superior strain of *Trichogramma chilonis* Ishii, which has proven effective in controlling pests in cotton, sugarcane, and tomato crops. This has resulted in improved pest suppression. Additionally, efforts have been made to develop release schedules for natural enemies to manage pests like sugarcane borers, scale insects, *Pyrilla*, coconut black-headed caterpillars, rhinoceros beetles, maize stem borers, and various fruit crop pests. A Bio-intensive Integrated Pest Management (BIPM) system has been developed for managing pests in tobacco, rice, cotton, and vegetable crops. The implementation of BIPM in these crops has led to significant reductions in pesticide use and improved cost-benefit ratios. Ongoing efforts are now focused on utilizing nematophagous fungi and bacteria to control plant-parasitic nematodes, as well as using fungal and bacterial antagonists to manage plant diseases, particularly in crops like sunflower, groundnut, cotton, rice, wheat, and potato. This article highlights some of the most recent developments in biological control in India.

Keywords: Biological control, Bio-intensive integrated pest management, nanoparticles, plant-parasitic nematodes, RNAi, *Trichogramma* spp

Introduction
Biological control is a systematic way of using living organisms to control pests. It may operate alone or can be inculcated as a component of integrated pest management.
Of the most widely used and successful method, the introduction and establishment of appropriate organisms, aims at providing permanent control against a particular pest. Biological control by inoculation, augmentation or inundation is also practiced worldwide, but this requires constant or periodic mass-rearing of control agents for release. Beneficial organisms which are already present in the crop can be conserved and multiplied to enhance their impact on the pest with temporary or permanent results. The most frequently used biological control agents are insect, nematode and fungal pathogen which are released to control both insect pests of crops and weeds. The advantageous qualities of these agents include their great diversity, high degree of specificity and ease of handling.
Biological control may provide long-term or even permanent effects, causes no pollution and poses no risk to human health, it should always be a preferred control measure when economically competitive with other methods. In developing countries, like India, it will be a special application where the cost of chemical control is somewhat expensive and where the inappropriate or excessive use of chemicals has resulted in high levels of residues and pest resistance. Biological control using natural enemies offers environmentally safe and sustainable options for managing insect pests and plant pathogens in agriculture. Recent technological advances have led to promising innovations in mass production, advanced formulation and strategic application of biological control agents (BCAs) including parasitoids, predators, microbial antagonists and semiochemicals. Genomic tools have also enabled better understanding of mechanisms of antagonism, host-pathogen interactions and molecular signaling leading greater efficacy. Nanoparticle based delivery systems,

RNAi technology, synthetic symbionts, endophytes and transgenic resistance offer tremendous scope for devising novel biological control tactics. Overall, biological control is a valuable tool in IPM programs. It offers a sustainable and environmentally responsible approach of managing insect pests.

Historical context

Biological control has a long history and could be said to date from the domestication of cats and their employment to protect stored food from the ravages of mice and rats. The introduction of exotic species to suppress pests developed in island communities and the first successful introduction for this purpose is claimed to be that of the Indian Mynah into Mauritius in 1762 for control of the Red Locust (*Nomadacris septemfasciata*).It was not until the 19th century that the possibility of employing beneficial insects and microbes was appreciated and various proposals made, but spectacular results were not obtained until 1888. In that year, Australian ladybird (*Novius cardinalis*) was imported into California for control of the cottony cushion scale (*Icerya purchasi*), a pest which threatened to destroy the California citrus industry. This resulted in complete suppression of this pest and was widely publicized.

The history of biological control of weeds dates back to the late eighteenth century and since then a great deal of success has been achieved in biological methods of weed control. In fact, the first accidental success of biological control of prickly pear in India during the year, 1795 by *Dactylopius ceylonicus, a* cochineal insect introduced from South America, led the world to use natural enemies against alien weeds. Other notable success stories of controlling water hyacinth and parthenium weed led to the efficient approach of biological control for weed management.

Until high-powered synthetic pesticides became freely available after World War II, pest control necessarily depended on the application of all available methods; cultural, mechanical, chemical and biological. Over the last 30 years, the dominance of agro-chemicals stifled the development and application of other approaches particularly biological. Traditional insect control techniques, such as chemicals, are expensive, labor-intensive and require frequent application. Their injudicious use over the years has resulted in problems like pest resurgence, secondary pest outbreaks, pesticide resistance and environmental pollution, which all have deteriorated human and animal health. Because of the disadvantages of traditional chemical control approaches, biological control of insect pests is increasingly taken into consideration and applied as a safe and cost-effective solution to the invasive pest problems.

Fig 1, 2, 3: Pictures depicting predator-prey relationship

Table 1: Some popular bio-control agents for sustainable pest management

Types of biocontrol agent	Description	Examples
1. Fungi	Acts as natural biocontrol agent against soil-borne pathogens such as *Fusarium, Rhizoctonia and Sclerotium species* which affect crops like cotton, vegetables and pulses.	*Trichoderma harzianum, T. virens*
2. Entomopathogenic nematodes	Successfully employed for controlling soil-dwelling pests like root borers and white grubs. These nematodes are naturally occurring parasites of insect larvae, and their use has been promoted as part of integrated pest management (IPM).	*Steinernema carpocapsae* and *Heterorhabditis bacteriphora.*
3. Parasitoid	Parasitoids deposit their eggs on or inside a host insect, and as the larvae grow, they feed on the host, ultimately causing its death.	*Trichogramma* spp., *Aphidius* spp., *Telenomus remus* are few of the examples.
4. Predatory mites	In cotton and vegetable crops, the use of predatory mites has been a promising biological control approach to manage whitefly infestations. These mites feed on whitefly nymphs and eggs, helping control their population without harming the crops. The adoption of this method has been promoted in regions like Punjab and Rajasthan.	*Amblyseius* and *Neoseiulus* spp.
5. Microbial agents	These are microbial organisms like bacteria, fungi and viruses that control pests by various mechanisms such as competition and parasitism.	*Amblyseius* and *Neoseiulus* spp.

Recent Approaches in Biological Control:

Modern advances in biological control have significantly enhanced our ability to manage and control insect pests in a sustainable and eco-friendly way. Some of the notable recent advances that led to the rise of advanced technologies in biological control are as follows:

Based on Genomic Tools and Biotechnology

Understanding the mechanisms

Genomic tools like DNA sequencing and gene editing have allowed researchers to gain knowledge about the interactions between pests, hosts, their natural enemies and the environment. This technology can be utilized to develop more

effective biocontrol strategies.

- **Improvement of Natural Enemies**

The phylogenetic traits of natural enemies and predators can be enhanced by genetic modification techniques, which improves their biotic and abiotic stress tolerances, increases resistance to pesticides or improves the foraging abilities.

- **RNA Interference (RNAi)**

RNAi technology can be used to silence our gene of interest in pest insects, leading to their death or reduced reproductive capacity. This offers a highly targeted and specific approach to pest. This technology has shown results against Colorado potato beetle (*Leptinotarsa decemlineata*), cotton bollworm (*Helicoverpa armigera*), corn root worm (*Diabrotica virgifera virgifera*), wheat stem rust (*Puccinia graminis tritici*) and green peach aphid (*Myzus persicae*).

Based on Advanced Formulation and Delivery System

- **Efficacy Improvement**

A number of innovative formulations and delivery systems have been developed by many scientists for biocontrol agents, such as encapsulated bacteria or microencapsulated parasitoids. These formulations can protect the agents from environment stresses and improve their persistence and efficacy.

- **Targeted Application**

Using of drones and robotic systems for precision application techniques, can be used to deliver bio-control agents directly to target areas, minimizing off-target effects and maximizing their impact.

Integrated Pest Management

- **Synergistic Effects**

Here, biological control is often integrated with other pest management integrated with other pest management strategies, such as cultural control, physical control, to achieve optimal results. This synergistic approach often leads to more effective and sustainable pest management than relying solely on any single method.

- **Management of Habitat**

Conservation biological control involves creating and maintaining habitats that actually favors the natural enemies, such as providing food and shelter, which will encourage their populations and control pests. Apart from it, continuous monitoring of pest and natural enemy populations is required to access the effectiveness of biological control programs.

- **Growing of natural-enemy attracting floral plants**

By strategically planting flowering plants, a heaven for beneficial insects like ladybugs, lacewings and parasitic wasps can be created. For annual plants swe*et al*yssum, buckwheat, cosmos and for perennials lavender, marigolds, yarrow can be grown.

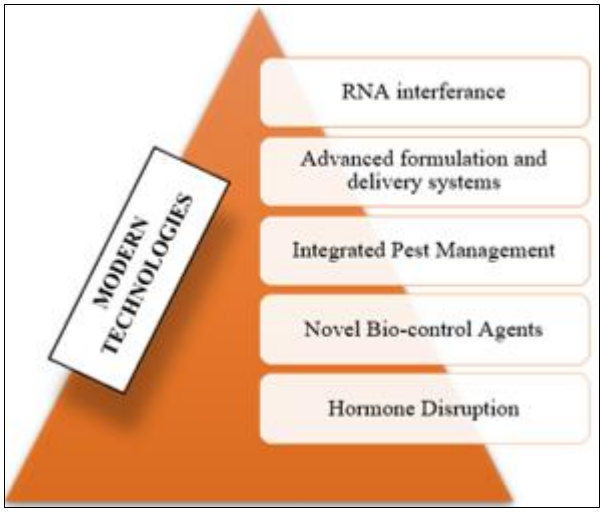

Fig 4: Some advanced approaches

Towards pest management

1. Pheromone and Hormone Disruption

- **Disruption of Mating**

Pheromones and hormone can be utilized to disrupt the mating behavior of many pests, reducing their reproductive success. This method totally relies on natural chemicals and does not involve the introduction of foreign organisms. It is particularly specific to target pests only.

2. Use of Novel Biocontrol Agents

- **Microbial Biopesticides**

Researchers are exploring the various use of bacteria, fungi and viruses as satisfactory biocontrol agents. These microorganisms can directly infect and kill pests, offering a safe and effective alternative to chemical pesticides. Some common microbial biopesticides used are *Bacillus thuringiensis*, *Trichoderma* species.

- **Insect Pathogens**

Insect pathogens such as baculoviruses, nucleopolyhedroviruses and entomopathogenic fungi (*Beauveria bassiana* and *Metarhizium anisopliae*) are being developed as biocontrol agents. These pathogens can infect and kill specific pest species, minimizing harm to beneficial insects.

These modern biological control techniques offer promising solutions for sustainable pest management. These advances are driving the development of more effective, targeted and sustainable biological control strategies, helping to reduce our resilience on chemical pesticides and protect the eco-system.By understanding their strengths and limitations, researchers and farmers can select the most appropriate methods to protect crops and minimize environmental harm.

Bio-control Centers: India has several biological control centers, both government-funded and private, dedicated to researching, developing and implementing biological control strategies for various pest and weeds.

Some prominent ones are listed here:

Government-funded centers

- ICAR-Indian Institute of Sugarcane Research (IISR), Biological Control Centre, Pravaranagar, Maharashtra: This center focuses on biological control of sugarcane pets and diseases.
- National Bureau of Agricultural Insect Resources (NBAIR), Bengaluru: It conducts research on biological control of various agricultural pests.
- State Agricultural Universities and Research Institutes: Many such institutes have biological control laboratories and programs.

Private Sector

Several private companies and organizations are involved in biological control, producing and supplying biocontrol products to the farmers. These institutions work together to develop and promote sustainable pest and weed management practices in India.

Biopesticide Trend in India: The biopesticides market in India is experiencing significant growth, driven by various factors such as increasing awareness about the harmful effects of agro-chemicals, government support and growing consumer demand for organic and natural products.In 2021, the Indian biopesticides market size was USD 64.73 million. The market is projected to grow from USD 69.62 million in 2022 to USD 130.37 million by 2029. It is estimated to grow at a CAGR of 9-10% during the forecast period of 2024 to 2029.

Table 2: Bio-control Laboratories present in India

Sl. No.	Type of Lab	Number of Labs
1.	CIPMCs	35
2.	SBCL	98
3.	ICAR	49
4.	SBCLs (Grant in aid)	38
5.	Private	141
Total		361

SOURCE: DPPQS, Faridabad

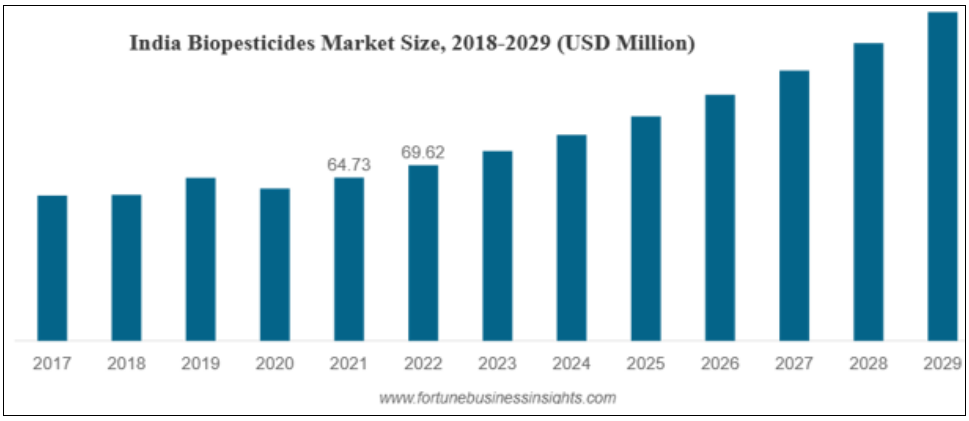

Fig 5: Growth Trend of India

Some Recent Success Stories of Biological Control

- **Biological control of Papaya Mealybugs:** This devastating pest, papaya mealybug (*Paracoccus marginatus*) is native to Mexico, which was recorded in Coimbatore in 2008 and later spread to other South Indian states. Three exotic parasitoids, *Acerophagus papayae*, *Pseudleptomastix mexicana* and *Anagyrus loecki*, which effectively suppressed the papaya mealy bug in its native range, were imported from Puerto Rico. Then the parasitoids were successfully propagated and distributed to other states.
- **Biocontrol saved Sugarcane from Woolly Aphid:** Sugarcane woolly aphid (*Ceratovacuna lanigera*) was controlled using a combination of indigenous predators, *Dipha aphidivora* and *Micromus igorotus*along with the parasitoid, *Encarsia flavoscutellum*. Its practical result enabled farmers to lower the use of chemical pesticides.
- **Management of Eucalyptus Gall Wasp:**This invasive pest (*Leptocybe invasa*) was effectively controlled by using an exotic parasitoid,*Quadrastichus mendeli*which was imported from Israel. *Megastigmus* sp. one of the most dominant indigenous parasitoid provided around 90.74% parasitismupon this gall wasp.
- **Tackling Rugose Spiralling Whitefly in Coconut:** Rugose spiralling whitefly (*Aleurodicus rugioperculatus*) infested several crops like coconut, banana, custard apple in several South Indian states. The pest was successfully controlled by the natural enemy, *E. guadeloupae.*
- **Biocontrol of Fall army Worm:** Fall Army Worm (*Spodoptera frugiperda*) is an invasive pest which created a severe damage in Karnataka and also in other states. After complex experiments and surveys, it has been found that a strategic combination of various predators, parasitoids and entomopathogenic fungus, will give fruitful result. A combination of egg parasitoids like *Telenomus* sp. and *Trichogramma* sp.; egg larval parasitoid *Chelonus* sp., larval parasitoid *Glyptapanteles creatonoti*, *Campoletis chlorideae* and ichneumonid larval pupal parasitoid, predatory bugs like*Andrallus spinidens* and *Eocanthecona furcellata*, along with *Metarhizium anisopliae* and*Beauveria bassiana*have given satisfactory results.

These successful stories proved that agro-economically harmful pests can be controlled by relying on indigenous natural enemies or by classical and augmentative biological control and also encouraged the farmers not to blindly trust upon the harmful pesticides.

Conclusion

Biological control offers a sustainable and environmentally friendly approach to pest management. By utilizing natural predators, parasites, and pathogens to control pest populations, it reduces the reliance on chemical pesticides,

minimizing their negative impact on ecosystems, human health, and biodiversity. Biological control promotes long-term pest regulation, enhances ecosystem resilience, and supports agricultural practices that are both economically and environmentally viable. As an integral part of integrated pest management (IPM) strategies, biological control contributes to a more balanced and sustainable approach to managing pests in various agricultural and ecological settings. Moreover, biological control aligns with the principles of sustainability by fostering natural ecological processes. Unlike chemical methods, which often lead to resistance in pest populations, biological control can provide long-lasting solutions with minimal environmental disturbance. By encouraging biodiversity, biological control helps maintain healthy ecosystems where pest populations are naturally kept in check by their predators.

However, it is important to note that biological control requires careful planning and monitoring to ensure that introduced species do not become invasive or disrupt existing ecological balances. Ongoing research and field trials are essential to refine these methods and ensure their effectiveness in different environments. When implemented as part of an integrated pest management strategy, biological control not only enhances crop protection but also supports sustainable agriculture practices that protect natural resources for future generations.

In summary, biological control is a promising and responsible approach to pest management, offering a balance between agricultural productivity and ecological health. By embracing this method, we can reduce the environmental footprint of pest control and move towards more sustainable, nature-based solutions.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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