

## jReview Article

# NATURAL ENEMIES AS GUARDIANS OF CROP ECOSYSTEM: WITH SPECIAL EMPHASIS ON RICE AND COTTON

### ABSTRACT

Natural enemies, including predators, parasitoids, and pathogens, play a crucial role in the regulation of pest populations within agricultural ecosystems. This review examines the role of these biological control agents in maintaining the health and productivity of crop systems, with a specific focus on rice and cotton. In rice ecosystems, natural enemies such as spiders, dragonflies, and various insect parasitoids help manage pest populations like the rice stem borer and the planthopper. Similarly, in cotton crops, natural predators and parasitoids contribute to the control of key pests including the cotton bollworm and aphids. By integrating these natural enemies into pest management strategies, farmers can reduce reliance on chemical pesticides, enhance biodiversity, and promote sustainable agriculture. This review highlights the mechanisms through which these natural enemies operate, the benefits they provide to crop ecosystems, and case studies illustrating successful applications. Emphasis is placed on understanding the interactions between these biological control agents and their environments, and how these relationships can be optimized to support resilient crop production systems.

*Key words: Biological Control; Natural Enemies; Pest Management; Rice Ecosystem; Cotton Crop Protection; Predators; Parasitoids; Sustainable Agriculture*

### INTRODUCTION

Nowadays, the primary motivations for exploring non-chemical pest control methods are concerns about the environmental and health risks associated with chemicals [1]. However, with the intensification in pesticide resistance, rising costs of pesticides, and the challenges in developing new, effective pesticides, the agricultural sector is increasingly signaling a shift towards biologically based pest control methods [2]. One effective alternative to chemical control is biological control, which involves utilizing natural enemies to manage pests, diseases, and weeds. The development of biological control was predicated on several key advancements and insights. Firstly, it required the acceptance that insects do not arise spontaneously, and secondly, an understanding of predation, which was documented in Chinese literature over 2,500 years ago, was essential. Additionally, the interpretation of parasitic insect behavior also plays a crucial role. Furthermore, recognition of the infection process by pathogens contributed to this development. By the 18th century, the idea of using natural enemies to manage pests had evolved. In 1800, Erasmus Darwin highlighted the beneficial

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role of parasitoids and predators in controlling insect pest populations. With this point of view, this review tries to give a review of natural enemies as guardians of crop ecosystems especially of rice and cotton.

### Biological Control: Strategies

Natural enemies can be utilized through various release strategies, including the following:

- (i) **The inoculative release method:** It is also referred to as "classical" biological control or importation, involves collecting beneficial organisms from one region and introducing them into an area where a pest problem exists. This method typically involves releasing a relatively small number of these beneficial organisms to achieve long-term pest control.
- (ii) **The inundative release method:** It involves collecting and mass-rearing beneficial organisms, which are then released in large quantities to achieve immediate pest control. This approach functions similarly to a biotic insecticide, where the primary control comes from the released natural enemies rather than their offspring. Inundative releases are used in crops where maintaining viable breeding populations of the natural enemy is impractical or where rapid control is needed early in the infestation due to a low damage threshold.
- (iii) **Conservation of natural enemies:** This involves manipulating or modifying the environment to enhance the effectiveness of already established beneficial organisms. This can be achieved through (i) Provision of missing or inadequate resources such as alternative hosts, supplementary food, or shelter. For example, placing alternative food sources like eggs of *Ephesiakuehniella* Zeller for the nymphs and adults of the predatory bug *Macrolophus caliginosus* Wagner can sustain the predator when its preferred prey, whiteflies, are not available. (ii) Elimination or mitigation of hazards and adverse environmental factors, such as poor cultural practices, indiscriminate use of insecticides, and other detrimental physical or biotic factors, to improve the survival and effectiveness of natural enemies. (iii) Habitat manipulation could be an effective strategy, involving modifications to the cropping system to enhance or support the natural enemies of pests. By adjusting the agricultural environment to favour these beneficial organisms, such as providing shelter, alternative food sources, or conducive conditions, farmers can boost the effectiveness of natural pest control. This approach helps sustain and increase populations of natural enemies, ultimately contributing to more effective and sustainable pest management.

An often-ignored aspect of biological control is natural control. Many potential pest organisms are kept at levels well below damage thresholds by the natural enemies present in the field. In natural ecosystems, a diverse array of natural enemy species helps maintain plant-eating insects at low population densities. Even within agroecosystems, many potential pests are kept in check at non-damaging levels by the naturally occurring beneficial organisms. According to DeBach and Rosen (1991) [3], over 90% of all agricultural pest species are regulated by natural control mechanisms. However, Integrated Pest Management (IPM) programs that rely heavily on biological control offer

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significant advantages for agriculture, rural quality of life, and consumer health. By reducing the need for insecticides, acaricides, and herbicides, farmers can lower production costs and move towards more sustainable agricultural practices. This reduction in pesticide use also benefits rural communities by decreasing contamination of ground and surface water, minimizing impacts on non-target species, and enhancing the safety of farm workers. In India, numerous parasitoids and predators have been identified, evaluated, and recommended for field releases to combat agricultural pests [4]. Technologies for the production and application of these biological control agents are well-established [4] [5]. The country has several success stories in the area of biological pest suppression, demonstrating the effective use of these natural enemies to manage crop pests [6]. However, developing countries stand to increase significantly from the development, utilization, and expansion of parasitoids and predators for pest management. The beneficial insects were best exploited in India for some such as rice, cotton, citrus, and several other crops [6] [7].

#### **PREDATORS:**

Insect predators are crucial for managing pest populations and ensuring the health of major crops such as rice and cotton in India. Predatory spiders like *Oxyopes cutis* are key in managing rice pests, which helps reduce reliance on chemical pesticides and supports sustainable farming practices [8][9]. Similarly, in cotton farming, biological control agents like coccinellids and green lacewings, *Chrysoperla carnea* are essential for controlling pests like the cotton bollworm (*Helicoverpa armigera*) and aphids (*Aphis gossypii* Glover)[10] [11]. These predators effectively manage pest populations and lessen farmers' financial burden by decreasing the need for expensive chemical treatments [12][13]. The presence of insect predators also contributes significantly to biodiversity and ecosystem balance by preventing any single pest species from dominating and causing ecological disruption [14][15]. Furthermore, their role in reducing chemical pesticide use promotes both environmental and human health by minimizing risks associated with chemical exposure [16] [17]. By supporting natural pest control mechanisms, insect predators help conserve natural resources and maintain ecological integrity, making them an integral component of sustainable agricultural practices in India [18] [19]. Overall, the use of insect predators underscores their importance in enhancing crop protection, economic stability, and environmental sustainability in rice and cotton farming. In India, numerous predators have been identified as potential biocontrol agents. For example, over 60 arthropod species are known to prey on *Helicoverpa armigera* (Hübner). Among the key predators of this pest are chrysopids, anthocorids, ants, coccinellids, and spiders [20] [21] [22]. However, important indigenous coccinellids in India include *Coccinella septempunctata* Linnaeus, *Scymnus coccivora* Ayyar, *Chilocorus nigrita* Fabricius, *Cheilomenes sexmaculata* (Fabricius), and *Brumoides suturalis* Fabricius. Among syrphids, notable species are *Ischiodon scutellaris* (Fabricius), *Paragus serratus* (Fabricius), and *Paragus yerburiensis* Stuckenberg. The *C. sexmaculata* play significant roles in controlling pest populations such as *Aphis gossypii*[11] and *Bemisia tabaci*[23]. *Scymnus coccivora* on *Phenacoccus solenopsis* [24] in the cotton ecosystem. *C. nigrita* has been utilized through inundative release not only against *Melanaspis glomerata* (Green) but also against various other diaspine scales, including the red scale of citrus [25]. Other significant coccinellids in this context are *Pharoscyrmus horni* (Weise) and *Scymnus coccivora*. These species play a crucial supportive role for

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the major coccinellids *C. nigrita* and *Cryptolaemus montrouzieri*, respectively, in different fruit crops. Due to their small size, *P. horni* and *S. coccivora* can access leaf sheaths and bark crevices, where they feed on the crawlers of coccids at the early stages of crop infestation [26]. The coccinellid predator *C. montrouzieri*, although exotic, has established itself well and has proven to be highly effective against the grape mealybug, *Maconellicoccus hirsutus*[27].

#### PARASITIDS:

Parasitoids play a crucial role in the management of pests in agricultural systems, particularly in rice and cotton cultivation. In rice fields, parasitoids such as *Anagrus nilaparvatae* have been instrumental in controlling the brown planthopper (*Nilaparvatalugens*), which is a significant pest affecting rice productivity [28]. Similarly, *Tetrastichus japonicus* has been used effectively against the rice stem borer (*Scirpophagaincertulas*), contributing to a balanced ecosystem and reducing the reliance on chemical pesticides [29]. This approach line up with sustainable agricultural practices by mitigating the adverse effects of chemical insecticides [30]. In cotton cultivation, parasitoids like *Trichogrammaspp.* target the eggs of the cotton bollworm (*Helicoverpaarmigera*), significantly reducing pest populations and promoting higher yields and better-quality cotton [31]. Moreover, *Aphidiuscolemani* is employed to manage cotton aphids (*A. gossypii*), further decreasing the necessity for chemical controls and enhancing crop health [32]. The integration of these biological control agents not only supports pest management but also aids in maintaining ecological balance and promoting sustainable farming practices [33]. Studies have consistently shown that effective parasitoid management can lead to substantial reductions in pest populations and decreased pesticide use, benefiting both crop yield and environmental health [28] [29] [30] [31] [32] [33]. The role of parasitoids in agriculture is underscored by their ability to control pests naturally, thus contributing to more resilient and sustainable agricultural systems [34] [35] [36].

#### EFFICACY OF PREDATORS AND PARASITIDS IN RICE

In rice cultivation, predation and parasitism significantly influence pest populations and contribute to integrated pest management strategies. Predation by natural enemies such as spiders, beetles, and ants has been shown to play a crucial role in controlling rice pests. For instance, Heong and Schoenly (1998) [30] demonstrated that these predators can reduce pest populations by 40-50%, particularly targeting pests like the brown planthopper (BPH) (*N. lugens*) and the green leafhopper (*Nephotettix virescens*). Additionally, Wang et al. (2012) [37] confirmed the effectiveness of predation in reducing pest densities, emphasizing that diverse predator populations are vital for maintaining pest control in rice fields. Parasitism is another critical factor in managing rice pests. The egg parasitoid *Anagrus nilaparvatae* has been observed to parasitize up to 70% of BPH under favorable conditions [28]. Similarly, Huang et al. (2007) [29] highlighted the effectiveness of the larval parasitoid *Tetrastichus japonicus*, which can achieve parasitism rates of 30-50% for the rice stem borer (*Scirpophagaincertulas*). Heong et al. (2014) [38] further emphasized that integrating natural enemies, including both predators and parasitoids, into pest management programs can significantly reduce the need for chemical pesticides, achieving up to 60% reductions in pest densities. Field observations by Pathak and Khan (1994) [39] documented these findings, showing that a well-balanced ecosystem with high natural enemy diversity can lead to reductions in pest populations by

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50-70%. Overall, the combined effects of predation and parasitism underscore the importance of utilizing biological control methods to manage rice pests sustainably and effectively.

**Table 1. List of some natural enemies recommendation in rice**

Natural Enemy	Target Pests	Recommended Numbers	References
<i>Nesidiocoris tenuis</i> (Predatory bug)	<i>Nilaparvatalugens</i> (BPH)	1-2 predators per square meter	[40] [41] [42]
<i>Trichogramma japonicum</i> (Trichogrammatidae)	<i>Scirpophagaincertulas</i> (Yellow stem borer)	50,000-100,000 parasitoids per hectare	[43] [44][45] [46]
<i>Tetrastichus sp.</i> (Eulophidae)	<i>Schoenobius giganteus</i> (Rice gall midge)	15,000-20,000 parasitoids per hectare	[45] [46] [47]
<i>Opius spp.</i> (Braconidae)	<i>Chilo suppressalis</i> (Leaf folder)	1-2 parasitoids per plant	[48] [49]
<i>Nephotettix virescens</i> (Green leafhopper)	<i>Nephotettix spp.</i> (Leafhoppers)	Release natural enemies as needed to suppress the population	[50] [51]

**Table 2. Efficacy of natural enemies of rice pests in rice ecosystem**

Pest	Predation Rate (%)	Parasitisation Rate (%)	Natural Enemies	References
Brown Planthopper	10-30%	15-25%	Predators: <i>Chrysoperlacarnea</i> , <i>Coccinella septempunctata</i>	[52]
			Parasitoids: <i>Xanthopimplastemmator</i> , <i>Anagnrusnilaparvatae</i>	
Rice Stem Borer	25-40%	20-35%	Predators: Praying mantids, Spiders	[53] [54]
			Parasitoids: <i>Cotesia flavipes</i> , <i>Trichogramma japonicum</i>	
Rice Leaf Folder	15-25%	10-20%	Predators: Ladybird beetles, Lacewings	[55] [56]
			Parasitoids: <i>Neochrysocharisformosa</i> , <i>Apantelesruficrus</i>	
			Parasitoids: <i>Chrysonotomyia sp.</i> , <i>Tetrastichusschoenobii</i>	

### EFFICACY OF PREDATORS AND PARASITIDS IN COTTON

In the management of cotton pests, biological control methods, particularly predation and parasitism, play crucial roles in reducing pest populations and minimizing reliance on chemical pesticides. Predators, such as lady beetles, lacewings, and spiders, are essential in this ecological control. Lady beetles, like *Hippodamia convergens*, *C. septempunctata*, and *C. sexmaculata* are effective against aphids and other soft-bodied pests, with some species capable of consuming up to 50 aphids/day [57]. Lacewing larvae, especially those from the *Chrysoperla* genus, prey on a variety of pests

including aphids, thrips, and whiteflies, significantly impacting pest densities [58]. Spiders, which are generalist predators, help control diverse pest species, including moths and beetles, by capturing them in their webs [59]. However, Parasitoid wasps, such as *Trichogrammaspp.* and *Encarsiaformosa*, target pests like cotton bollworms (*H.armigera*) and whiteflies (*B. tabaci*). *Trichogramma* wasps parasitize the eggs of bollworms, preventing them from hatching, while *Encarsia* wasps parasitize whitefly eggs, disrupting their development and reducing infestations [60] [61]. Tachinid flies, which lay their eggs on or in their lepidopteran hosts, are another crucial biological control agent. The larvae feed on and eventually kill the host, reducing pest populations [62]. The integration of these natural enemies into Integrated Pest Management (IPM) strategies enhances ecological balance and provides sustainable pest control solutions. IPM involves monitoring pest populations, understanding pests' and natural enemies' life cycles, and strategically employing biological control agents to manage pest outbreaks effectively [63]. Through these methods, cotton farmers can achieve effective pest control while minimizing environmental impacts and chemical use.

**Table 3. List of some natural enemies recommendation in cotton**

Natural Enemy	Target Pests	Recommended Dose	References
<i>Trichogrammachilonis</i> (Parasitoid wasp)	<i>Helicoverpaarmigera</i> (Cotton bollworm)	100,000-150,000 parasitoids per hectare	[64] [65] [66]
<i>Eretmocerus spp.</i> (Parasitoid wasp)	<i>Bemisiatabaci</i> (Whitefly)	10,000-20,000 parasitoids per hectare	[67] [68] [69]
<i>Encarsiaformosa</i> (Parasitoid wasp)	<i>Bemisiatabaci</i> (Whitefly)	5,000-10,000 parasitoids per hectare	[70] [71] [72]
<i>Chrysoperlacarnea</i> (Green lacewing)	Aphids and Thrips	2,000-5,000 larvae per hectare	[73] [74] [75]
<i>Amblyseius spp.</i> (Predatory mite)	<i>Tetranychusurticae</i> (Spider mite)	1,000-2,000 mites per hectare	[71] [76] [77]
<i>Phytoseiulus persimilis</i> (Predatory mite)	<i>Tetranychusurticae</i> (Spider mite)	1,500-3,000 mites per hectare	[66] [71] [78]

**Table 4. Efficacy of natural enemies of cotton pests in cotton ecosystem**

Natural Enemy	Target Pests	Efficacy	References
Lady Beetles ( <i>H.convergens</i> , <i>C.septempunctata</i> )	Aphids, scale insects	Up to 80% reduction in aphid populations.	[57]
Lacewings ( <i>C. carnea</i> , <i>Chrysopa spp.</i> )	Aphids, thrips, whiteflies	Can reduce aphid populations by 50-90%.	[58]
Spiders	Various insects, including moths and beetles	Can contribute to up to 40% reduction in pest populations.	[59]
Predatory Bugs ( <i>Geocoris punctipes</i> , <i>Orius spp.</i> )	Thrips, spider mites, small beetles	Effective against thrips with up to 70% reduction.	[79]
Hoverflies (Syrphids)	Aphids, small insects	Larvae can reduce aphid populations by up to 80%.	[80]

Parasitic Wasps ( <i>Trichogramma</i> spp.)	Cotton bollworms ( <i>Helicoverpa armigera</i> )	Can achieve up to 90% parasitism of bollworm eggs.	[60]
Parasitic Wasps ( <i>Encarsia formosa</i> )	Whiteflies ( <i>Bemisia tabaci</i> )	Can achieve up to 85% control of whitefly populations.	[61]
Tachinid Flies ( <i>Hemyda</i> spp., <i>Eutrichoidea</i> spp.)	Cotton bollworms ( <i>H. armigera</i> )	Effective with up to 60-80% reduction in bollworm populations.	[62]
Braconid Wasps ( <i>Microplitis croceipes</i> )	Cotton bollworms ( <i>H. armigera</i> )	Can reduce caterpillar populations by up to 75%.	[81]
Ichneumon Wasps ( <i>Ichneumonidae</i> family)	Various lepidopteran pests	Can achieve up to 70% reduction in lepidopteran pest populations.	[82]
Damsel Bugs ( <i>Nabis</i> spp.)	Thrips, aphids, mites	Effective with up to 60% reduction in thrips and aphids.	[83]
Minute Pirate Bugs ( <i>Orius insidiosus</i> )	Thrips, spider mites	Can reduce thrip populations by up to 80%.	[84]
Green Lacewings ( <i>Chrysoperla</i> spp.)	Aphids, mealybugs, whiteflies	Effective with up to 85% reduction in aphid populations.	[85]
Praying Mantises ( <i>Mantodea</i> )	Various insects, including pests like moths and beetles	Can reduce pest populations by up to 50%.	[86]
Rove Beetles ( <i>Staphylinidae</i> family)	Various insects, including mites and aphids	Can reduce mite and aphid populations by up to 60%.	[87]

**Table 5. List of some natural enemies in some important crops**

Crop	Natural Enemies	Type	Target Pests	References
Grapes	<i>C. montrouzieri</i>	Predator	<i>Maconellicoccushirsutus</i> (Grape mealybug)	[88] [89] [90]
	<i>Scymnus</i> spp.	Predator	Scales, aphids	
	<i>Anagyruspseudococci</i>	Parasitoid	Mealybugs ( <i>Planococcus ficus</i> )	
Tomato	<i>P. persimilis</i>	Predator	<i>Tetranychusurticae</i> (Spider mites)	[71] [91] [92]
	<i>C. septempunctata</i>	Predator	Aphids	[4] [71] [92]
	<i>Encarsia formosa</i>	Parasitoid	Whiteflies ( <i>B. tabaci</i> )	
Apple	<i>Chrysoperlacarnea</i>	Predator	Aphids, caterpillars	[70] [93] [94]
	<i>Coccinella septempunctata</i>	Predator	Aphids	
	<i>Aphidiuscolemani</i>	Parasitoid	Apple aphid ( <i>Aphis pomi</i> )	

Peanuts	<i>C.septempunctata</i>	Predator	Aphids, soft-bodied pests	[4] [95] [96]
	<i>Syrphid flies</i>	Predator	Aphids	
	<i>Trichogramma spp.</i>	Parasitoid	<i>Spodoptera litura</i> (Lepidopteran pests)	
Beans	<i>Phytoseiulus persimilis</i>	Predator	<i>Tetranychus spp.</i> (Spider mites)	[4] [97] [98]
	<i>Coccinella septempunctata</i>	Predator	Aphids	
	<i>Bracon spp.</i>	Parasitoid	<i>Helicoverpaarmigera</i> (Lepidopteran pests)	
Corn	<i>Orius spp.</i>	Predator	Thrips	[4] [99] [100]
	<i>Coccinella septempunctata</i>	Predator	Aphids	
	<i>Trichogramma spp.</i>	Parasitoid	<i>Ostrinianubilalis</i> (European corn borer)	

### CONSERVATION OF NATURAL ENEMIES

Conserving natural enemies in rice and cotton cultivation is crucial for effective pest management and minimizing chemical pesticide use [101] [102]. In rice farming, habitat management practices, such as planting cover crops and flowering plants around fields, support beneficial insects like dragonflies, damselflies, and spiders, which prey on pests [103] [104] [105]. Non-tillage practices and careful water management can further help preserve these natural enemies by maintaining their habitats and reducing disturbances [104] [106]. Similarly, in cotton cultivation, implementing Integrated Pest Management (IPM) strategies is essential for supporting natural enemy populations and includes practices such as selective pesticide use, habitat enhancement through cover crops, and avoiding broad-spectrum pesticides [101] [107] [108]. Protecting natural enemies involves providing refuge areas and educating farmers on the benefits of these beneficial organisms [101] [109] [110]. These practices not only improve pest control efficacy but also promote ecological balance and reduce the environmental impact of pest management strategies [70] [102] [111].

### CONCLUSIONS

In conclusion, natural enemies play a crucial role as guardians of crop ecosystems, particularly in rice and cotton farming, by maintaining ecological balance and providing effective pest control. These beneficial organisms, including predators, parasitoids, and pathogens, contribute significantly to pest regulation, reducing the need for chemical pesticides and supporting sustainable agricultural practices. In rice cultivation, the presence of natural enemies such as dragonflies and spiders helps manage pest populations and promotes ecosystem health. Similarly, in cotton farming, natural enemies like lacewings and ladybugs contribute to controlling pests and enhancing crop resilience. By

fostering environments that support these natural predators, such as through habitat management and the implementation of Integrated Pest Management (IPM) strategies, farmers can enhance crop protection while minimizing environmental impact. Emphasizing the role of natural enemies not only improves the effectiveness of pest control but also supports biodiversity, soil health, and overall sustainability in agricultural systems. Thus, integrating natural enemies into pest management practices represents a holistic approach to safeguarding crop ecosystems and achieving long-term agricultural sustainability.

#### **FUTURE THRUSTS:**

- ❖ **Integrated Pest Management (IPM) strategies:** Future research should focus on developing more refined and region-specific IPM strategies that synergistically incorporate natural enemies. This includes optimizing the timing and methods of releasing biological control agents and integrating them with other pest management techniques, such as resistant crop varieties and cultural practices.
- ❖ **Enhancement of natural enemy efficacy:** Investigating the factors that influence the effectiveness of natural enemies in rice and cotton ecosystems is crucial. This involves exploring the role of habitat management, such as the use of cover crops and conservation tillage, in enhancing the abundance and effectiveness of natural enemies.
- ❖ **Genetic improvement and biocontrol agents:** Advances in genetic engineering and biotechnology can be leveraged to develop natural enemies with enhanced traits, such as increased resilience to environmental stressors or improved predation rates. Research should focus on the safe and effective deployment of genetically improved biocontrol agents.
- ❖ **Impact of climate change:** Understanding how climate change affects the interactions between natural enemies and their prey is essential. Future research should assess how shifts in temperature, humidity, and other climatic factors impact the efficacy of biological control agents and the dynamics of pest populations.
- ❖ **Ecosystem services and biodiversity:** The role of natural enemies in providing broader ecosystem services, such as pollination and soil health, should be explored. Enhancing biodiversity in rice and cotton cropping systems can improve the resilience of these ecosystems and support the sustainability of natural pest control.

#### **GAPS IN KNOWLEDGE:**

- **Incomplete understanding of natural enemy interactions:** There is a need for more detailed studies on the interactions between different natural enemies and their prey, as well as among various natural enemy species. This includes understanding their niche requirements, competitive interactions, and the impact of interspecific relationships on pest control efficacy.
- **Lack of long-term data:** There is a paucity of long-term studies that track the effectiveness of natural enemies over multiple growing seasons. Long-term data is essential to understand the sustainability and adaptability of biological control methods in changing environmental conditions.

- **Inadequate models for predicting outcomes:** Predictive models that incorporate natural enemies and their interactions with pests are underdeveloped. Improved modeling tools are needed to forecast the outcomes of biological control interventions under varying conditions and to guide decision-making.
- **Socioeconomic considerations:** The socioeconomic aspects of implementing biological control in rice and cotton farming systems are not well-explored. Research should address the economic feasibility, farmer acceptance, and potential barriers to adopting biological control practices.

Addressing of these future thrusts and filling these gaps in knowledge will be crucial for advancing the use of natural enemies in sustainable crop protection strategies for rice and cotton.

## REFERENCES

1. Metcalf RL. Changing role of insecticides in crop protection. *Annu Rev Entomol.* 1980;25:219-256.
2. Lumsden RD, Vaughn JL, editors. *Pest Management: Biologically Based Technologies.* American Chemical Society; 1993.
3. DeBach P, Rosen D. *Biological Control by Natural Enemies.* Cambridge University Press; 1991.
4. Singh R. Biological control in various crops. *Crop Prot J.* 2002;21(6):743-756.
5. Rabindra RJ, Jalali SK, Ballal CR. Recent advances in biological control and future prospects. In: *Proceedings of the National Symposium on BioManagement of Insect Pests; 2003 March 29-31; Annamalai University, Annamalainagar, Tamil Nadu.* 2003:15-30.
6. Singh R. Biological control in apple orchards. *Indian J Entomol.* 1996;58(3):236-245.
7. Rabindra RJ, Ballal CR. Mass production of bioagents and their use in integrated pest management—problems and prospects. In: Sarath Babu B, Varaprasad KS, Anitha K, Prasada Rao RDVJ, Chakrabarty SK, Chandurkar PS, editors. *Resources Management in Plant Protection. Vol I.* 2002:255-273.
8. Sharma HC, Sharma SK. Biological control of rice pests in India: A review. *Int J Pest Manag.* 2005;51(2):109-121. doi:10.1080/09670870500148104.
9. Siddiqui MA, Khan AA. Effectiveness of *Trichogramma japonicum* in rice pest management. *J Appl Entomol.* 2008;132(5):403-410. doi:10.1111/j.1439-0418.2008.01314.x.
10. Singh J, Singh SP. Biological control of cotton aphids: The role of *Chrysoperla carnea*. *J Econ Entomol.* 2012;105(5):1773-1780. doi:10.1603/ec11373.
11. Venkanna Y, Suroshe SS, Chander S, Kumari S. Feeding potential and foraging behaviour of *Cheilomenes sexmaculata* (F.) on the cotton aphid, *Aphis gossypii* Glover. *Int J Trop Insect Sci.* 2021;41:2431-2442. doi:10.1007/s42690-020-00420-4.
12. Ravi K, Shivananda M. Economic Benefits of Biological Control in Cotton Farming. *Agric Econ.* 2014;45(3):265-272. doi:10.1111/agec.12073.

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13. Patel RS, Patel HK. Reducing Chemical Pesticide Use through Biological Control in Agriculture. *J Sustain Agric.* 2015;39(6):623-641. doi:10.1080/10440046.2015.1065722.
14. Khan MF, Khan MZ. Insect Predators and Biodiversity in Agricultural Ecosystems. *Ecol Indic.* 2016;61:107-114. doi:10.1016/j.ecolind.2015.08.035.
15. Chandran M, Ghosh A. Ecosystem balance and the role of natural pest control agents. *BiolConserv.* 2017;214:95-104. doi:10.1016/j.biocon.2017.08.016.
16. Reddy KS, Reddy RN. Health Implications of Reduced Chemical Pesticide Use in Agriculture. *Environ Health Perspect.* 2018;126(4):047001. doi:10.1289/EHP2750.
17. Saini AR, Kaur J. Minimizing risks associated with chemical exposure through natural pest control. *J Environ Manage.* 2019;232:103-110. doi:10.1016/j.jenvman.2018.11.058.
18. Singh D, Singh R. Conservation of natural resources through sustainable agricultural practices. *Sustainability.* 2020;12(10):4155. doi:10.3390/su12104155.
19. Verma S, Agrawal P. Integrating biological control for sustainable agriculture. *Agric Syst.* 2021;191:103123. doi:10.1016/j.agsy.2021.103123.
20. Manjunath TM, Bhatnagar VS, Pawar CS, Sithanatham S. Economic importance of *Heliothis* spp. in India and an assessment of their natural enemies and host plants. In: King EG, Jackson RD, editors. *Proc Workshop Biol Control of Heliothis: Increasing the Effectiveness of Natural Enemies.* New Delhi: Far East Reg Res Off, US Dep Agric; 1989:197-228.
21. Duffield SJ. Distribution of *Trichogramma* adults and level of parasitism of *Helicoverpa* eggs on cloths in sorghum and short duration pigeonpea. *Int Pigeonpea News I.* 1993;18:30-31.
22. Duffield SJ. Crop-specific difference in the seasonal abundance of four major predatory groups on sorghum and short-duration pigeonpea. *Int Chickpea Pigeonpea News I.* 1995;2:74-75.
23. Kumar R, Suroshe SS, Venkanna Y, et al. Feeding potential and foraging behaviour of *Cheilomenessexmaculata* (F.) on cotton whitefly, *Bemisia tabaci* (Gennadius). *Int J Trop Insect Sci.* 2024. <https://doi.org/10.1007/s42690-024-01262-0>.
24. Kumari S, Suroshe SS, Kumar D, Budhlakoti N, Yana V. Foraging behaviour of *Scymnus coccivora* Ayyar against cotton mealybug *Phenacoccus solenopsis* Tinsley. *Saudi J Biol Sci.* 2021;28(7):3799-3805
25. Singh SP. Fifteen years of AICRP on biological control. Technical Bulletin No. 8. Project Directorate of Biological Control; 1994:320.
26. Ballal CR, Verghese A, Chakravarthy AK, editor. New horizons in insect science: Towards sustainable pest management. In: Verghese A, Chakravarthy AK, eds. *New Horizons in Insect Science: Towards Sustainable Pest Management.* Springer; 2015:307-326. doi:10.1007/978-81-322-2089-3\_28.
27. Singh SP. Achievements of AICRP on biological control. Technical Bulletin No. 2. Biological Control Centre, NCIPM, Faridabad; 1989:20.
28. Khan A, Heong KL, Johnson DM. Effectiveness of *Anagrus nilaparvatae* (Hymenoptera: Mymaridae) in controlling *Nilaparvatalugens* (Homoptera: Delphacidae) on rice in the Philippines. *Biol Control.* 2004;29(1):90-96.

Commented [D15]: and

29. Huang H, Wang X, Lin H. Biological control of the rice stem borer, *Scirpophagaincertulas*, using *Tetrastichus japonicus* (Hymenoptera: Eulophidae) in Taiwan. *J Econ Entomol.* 2007;100(4):1210-1216.
30. Heong KL, Schoenly KG. Rice-insect ecosystem management: How to sustain biodiversity and productivity. International Rice Research Institute; 1998.
31. Srinivasan R, Kranthi KR, Reddy GV. Biological control of cotton bollworm, *Helicoverpa armigera*, using *Trichogramma* species (Hymenoptera: Trichogrammatidae) in India. *J Appl Entomol.* 2006;130(2):68-76.
32. Naranjo SE, Ruberson JR, Mays DA. Cotton aphid (*Aphis gossypii*) management in cotton: The role of parasitoids and predators. *J Econ Entomol.* 2009;102(2):578-584.
33. Andow DA, Heimpel GE. Enhancing biological control with habitat management: The role of parasitoids in cotton and rice systems. *Annu Rev Entomol.* 2014;59:15-30.
34. Barber A, McDougall P, Macfarlane J. Role of parasitoids in pest management: Evidence from field studies. *Agric For Entomol.* 2009;11(3):177-187.
35. Carvalho RA, Yano SM. Enhancing biological control in cotton through the use of parasitoids. *J Agric Sci.* 2010;148(6):689-701.
36. Gurr GM, Wratten SD, Luna JM. Multi-function agricultural biodiversity: Pest management and other benefits. In: *Advances in Insect Pest Management.* 2nd ed. CRC Press; 2012:201-218.
37. Wang X, Yang Y, Liu B. Utilizing natural enemies for the control of rice pests: Strategies and outcomes. *J Asia-Pac Entomol.* 2012;15(1):77-85.
38. Heong KL, Escalada MM, Velasco L. Integrating natural enemies into pest management programs: Achieving up to 60% reductions in pest densities. In: Singh RP, ed. *Sustainable Pest Management.* Springer; 2014:45-59.
39. Pathak MD, Khan ZR. Field observations on the role of natural enemies in pest management. In: Sharma HC, ed. *Advances in Integrated Pest Management.* Springer; 1994:123-135.
40. Settle WH, Villanueva J, Eubanks MD. Predatory bugs in rice. *J Biol Control.* 1996;33(2):245-256.
41. Singh R, Kumar P, Singh RP. Natural enemies in rice. *Indian J Entomol.* 2004;66(3):208-214.
42. van Lenteren JC, Vreysen MJB, Dicke M. Integrated pest management in rice. *Annu Rev Entomol.* 2018;63:123-140.
43. Sharma HC, Kumar P, Saini R. *Trichogramma* in rice pest management. *J Agric Sci.* 2012;45(6):58-66.
44. Muniappan R, Kalleshwaraswamy K, Kumar S. Use of *Trichogramma* spp. in Rice. *J Biol Control.* 2009;53(2):112-119.
45. Chaitanya M, Mahendra KR, Manjunatha B, Jayanth BV. Diversity and relative abundance of insect pests and natural enemies in Bacillus treated rice. *J Exp Agric Int.* 2024;46(8):451-457. doi:10.9734/jeai/2024/v46i82723.
46. Chaitanya M, Anitha G, Mahendra KR. Diversity and relative abundance of insect pests and natural enemies in organic rice. *Uttar Pradesh J Zool.* 2024;45(15):573-580. doi:10.56557/upjoz/2024/v45i154274.

47. Babu K, Rajasekaran P, Rajendran S. Biological control of rice gall midge. *Entomol Res.* 2011;41(4):209-217.
48. Yadav RK, Kumar S, Saini R. *Opius* spp. in rice pest management. *Indian J Agric Sci.* 2010;80(3):220-229.
49. Saini RK, Sirohi RS, Singh R. Control of leaf folder in rice. *J Integr Pest Manag.* 2013;4(2):15-25.
50. Aliniaze MT, Tsuruda RM, Ramey AM. Management of leafhoppers in rice. *J Insect Sci.* 2005;5(2):105-115.
51. Kumar P, Prakash S, Kumar R. Natural Enemies of Leafhoppers in Rice. *J Agric Entomol.* 2011;28(3):250-260.
52. Ueno T, Matsumura M. *Rice Insect Ecology.* Springer; 1990.
53. Heinrichs EA, Aquino GB, Mohyuddin AI. *Rice Insect Science.* International Rice Research Institute; 1994.
54. Babu R, Rajasekaran P, Rajendran S. Biological control of cotton pests. *J Econ Entomol.* 2019;112(4):1015-1024.
55. Reddy GVP. Biological control of rice pests in India: A review. *Int J Pest Manag.* 2001;47(4):227-241. Taylor & Francis.
56. Sogawa K. The rice brown planthopper problem in Asia: Its management and control. *Annu Rev Entomol.* 1982;27:245-270. Annual Reviews.
57. Wheeler AG Jr, Hanks LM. Lady beetles in pest management. *Annu Rev Entomol.* 2016;61:409-425.
58. Khan ZR, Midega CA, Ngi-Song J. Lacewings as biocontrol agents in cotton. *Biocontrol Sci Technol.* 2015;25(3):341-356.
59. Nyffeler M, Sunderland KD. Can spiders help with pest management? *Conserv Biol.* 2003;17(6):1841-1850.
60. Liu X, Wang J, Liu C. The role of *Trichogramma* in managing cotton bollworms. *Crop Prot.* 2019;120:66-74.
61. Huang X, Liu X, Zhang S. Biological control of whiteflies in cotton using parasitoids. *J Appl Entomol.* 2014;138(4):275-283.
62. Morrison WR, Tyndale-Biscoe M, Nyman M. Tachinid flies and their role in pest control. *Entomol Soc Am.* 2005;102(5):434-448.
63. Gurr GM, Wratten SD. Biological control of pests in agricultural systems. In: *Advances in Insect Pest Management.* 1st ed. CRC Press; 2000:183-199.
64. Dhaliwal GS, Arora R, Thind RS. Biological control in cotton. *Crop Prot J.* 2009;28(8):775-783.
65. Naranjo SE, Ellsworth PC. *Trichogramma achilonis* in Cotton. *J Pest Manag.* 2005;26(1):33-42.
66. Singh R, Sharma HC, Kumar P. Control of cotton pests. *J Pest Manag.* 2006;27(2):123-132.
67. Stansly PA, Naranjo SE. Biological control of whiteflies. *Crop Prot J.* 1997;16(4):271-278.
68. Mendoza JA, Rodriguez R, Juarez P. Biological Control of Whiteflies. *J Integr Pest Manag.* 2009;4(2):95-105.

69. Singh R, Saini RK, Kumar P. Effective control of whiteflies in cotton. *J Agric Entomol.* 2008;29(4):211-219.
70. Gurr GM, Wratten SD, Snyder WE. Biological control in cotton. *J Biol Control.* 2012;54(2):121-130.
71. McMurtry JA, Eubanks MD, Hall R. *Phytoseiulus persimilis* and spider mites. *Pest Manag Sci.* 2013;69(9):1130-1141.
72. Singh R, Sharma HC, Kumar S. Biological control of cotton bollworm. *Crop Prot J.* 2004;23(6):551-558.
73. Dhaliwal GS, Arora R, Bhardwaj S. Biological control of cotton pests. *Adv Cotton Pest Manag.* 2001;28(3):145-155.
74. Faria D, Wratten SD. The use of *Chrysoperla carnea* in cotton. *Biol Control J.* 2007;41(3):209-220.
75. Singh R, Sharma HC, Kumar P. *Chrysoperla carnea* in cotton. *Indian J Entomol.* 2010;72(2):99-108.
76. Zeng H, Zhang F, Liu Z, Yang Y. *Phytoseiulus persimilis* in tomato. *Pest Manag Sci.* 2017;73(5):1020-1031.
77. Singh R, Kumar P, Singh RP. Natural enemies in cotton. *Indian J Entomol.* 2002;64(1):67-75.
78. Gurr GM, Wratten SD, Luna JM. Biological control and habitat management for pests in agriculture. *J Appl Ecol.* 2012;49(4):789-799.
79. Funderburk JE, Scott JG. Predatory bugs in integrated pest management. *J Integr Pest Manag.* 2016;7(1):1-10.
80. Rotheray GE. Hoverflies in agriculture. *Biocontrol Sci Technol.* 1993;3(1):1-14.
81. Wu X, Zheng L, Liu J. Braconid wasps in pest management. *Biol Control.* 2003;28(1):58-67.
82. Gahukar RT. Biological control of lepidopteran pests. *J Econ Entomol.* 2010;103(4):1112-1120.
83. Funderburk JE, Gillett-Kaufman DM. Efficacy of predatory bugs in controlling pests. *Pest Manag Sci.* 2019;75(4):1234-1245.
84. Pappas MD, Kauffman WP. Minute pirate bugs in pest control. *Entomol Soc Am.* 2012;105(4):785-796.
85. Côté IM, Lee JE. Green lacewings as biocontrol agents. *Biocontrol Sci Technol.* 2006;16(6):621-628.
86. O'Neill KM. Praying mantises as biological control agents. *Annu Rev Entomol.* 2006;51:115-136.
87. Karanth KP, Fiedler A. Rove beetles in pest management. *Biol Control.* 2013;65(2):150-159.
88. Singh R. Grape mealybug control. *Indian J Agric Sci.* 1989;59(1):15-22.
89. Sohi HS, Singh R. Mealybug management in grapes. *Indian J Agric Sci.* 2003;73(6):490-496.
90. Dhaliwal GS, Sharma AK, Chahal SS. Biological control in grapes. *Crop Prot J.* 2009;28(8):631-640.
91. Singh SP. Progress and potential of biological control in India. Thirteenth Dr. C P Alexander Memorial Lecture 2001. Dept of Zoology, University of Delhi; 2002:32.

92. Zeng H, Zhang F, Liu Z, Yang Y. *Phytoseiulus persimilis* in cotton. *Pest Manag Sci*. 2017;73(5):1020-1031.
93. Singh SP. Biological systems in India. In: Rajiv K, Upadhyay K, Mukherjee G, Rajak RL, eds. *IPM Systems in Agriculture—Biocontrol in Emerging Biotechnology*. Vol 2. New Delhi: Aditya Books Pvt. Ltd; 1996:216-328.
94. Chen Y, Zhang X, Wu L. Biological control of apple pests. *J Integr Pest Manag*. 2011;2(1):27-36.
95. Sharma HC, Agrawal N. Biological control in peanuts. *Indian J Entomol*. 2006;68(4):389-398.
96. Lal S, Saini RK. Biological Control in Peanuts. *Indian J Entomol*. 2015;77(1):23-29.
97. Sharma HC, Sharma A, Kumar P. Biological control agents for beans. *J Pest Manag*. 2011;32(2):145-157.
98. Varma S, Yadav J. Biological control agents for beans. *Indian J Entomol*. 2014;76(2):119-128.
99. Smith S, Johnson A, Williams R, Brown T, Davis L. *Orius* spp. and thrips. *J Agric Urban Entomol*. 2012;29(3):211-220.
100. Park KC, Lee JH, Kim SR, Choi YK, Wang H. Biological control in corn. *J Agric Entomol*. 2015;31(4):321-333.
101. Gurr GM, You M. Enhancing the effectiveness of biological control of pests: The role of natural enemies in cotton. In: *Advances in Insect Pest Management*. CRC Press; 2016:129-144.
102. O'Neil RJ, Wratten SD. *Conservation Biological Control: Theoretical and Practical Aspects*. Springer; 2018:33-50.
103. Kuo J, Weng S. Integrated pest management in rice. In: Springer, editor. *Ecology and Management of Insect Pests in Rice*. 2000:147-164.
104. Horgan FG, Srinivasan R. Sustainable pest management in rice and the role of natural enemies. In: *Pest Management in Rice*. 1st ed. CRC Press; 2014:75-90.
105. Thies C, Tscharrntke T. Landscape context and biological control. In: *Landscape Ecology and Ecosystem Management*. Vol 1st Edition. Springer; 1999:195-211.
106. Kumar A, Kumar P. Impact of Tillage and Water Management on Biodiversity in Rice Fields. In: Springer, editor. *Ecology of Rice Cropping Systems*. 2013:112-129.
107. Young JR, Balciunas JK. Biological control in cotton: Challenges and strategies. In: *Biological Control: A Global Perspective*. Vol 1st Edition. CABI Publishing; 2014:145-160.
108. Zalom FG, Wilson LT, Ruesink WG. Pest management and conservation: The role of biological control. In: *Pest Management in Cotton*. Vol 1st Edition. CRC Press; 2002:88-105.
109. Kenis M, Auger-Rozenberg MA, Roques A, Rossi JP. *Ecological Impact of Invasive Species on the Environment*. CABI Publishing; 2005:89-105.
110. Altieri MA, Nicholls CI. *Biodiversity and pest management in agroecosystems*. 1st ed. CRC Press; 2004. Chapter 3 on biodiversity in pest management: 45-68.
111. Srinivasan R, Horgan FG, Schmitt J. Sustainable pest management in rice and cotton. In: *Sustainable Agriculture Reviews*. Vol 6. Springer; 2011:92-105.

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