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Eco-friendly and Targeted through Next-generation Approaches to Insect Pest Management

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Insect pests pose significant challenges to agricultural productivity, human health, and ecosystem stability worldwide. Traditional pest management approaches, heavily reliant on broad-spectrum chemical insecticides, have led to the development of insecticide resistance, unintended effects on non-target organisms, and environmental contamination. In response to these challenges, next-generation approaches to insect pest management are emerging, focusing on eco-friendly and targeted strategies. This review article explores the latest advancements in sustainable pest

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management, including the use of biopesticides, semiochemicals, biotechnology-based approaches, and integrated pest management (IPM) strategies. Biopesticides, derived from natural sources such as plants, microorganisms, and insects, offer effective and environmentally benign alternatives to synthetic insecticides. Semiochemicals, including pheromones and allelochemicals, can be exploited for pest monitoring, mating disruption, and attract-and-kill strategies. Biotechnology-based approaches, such as RNA interference (RNAi), CRISPR/Cas9 gene editing, and transgenic crops, provide novel tools for targeting specific pest species and reducing reliance on chemical insecticides. IPM strategies, which combine multiple pest management tactics based on ecological principles, offer a holistic and sustainable approach to pest control. The adoption of these next-generation approaches faces challenges, including regulatory hurdles, public acceptance, and the need for further research and development. However, by embracing eco-friendly and targeted pest management strategies, we can reduce the environmental impact of insect pest control, promote biodiversity conservation, and ensure sustainable food production for a growing global population. Future research should focus on optimizing and integrating these approaches, understanding their long-term ecological impacts, and developing effective knowledge transfer mechanisms to promote their widespread adoption.

Keywords: Biopesticides; semiochemicals; biotechnology; integrated pest management (IPM); sustainable agriculture.

1. INTRODUCTION

Insect pests are a major threat to agricultural production, human health, and ecological stability worldwide [1]. Crop losses due to insect pests are estimated to be 10-16% globally, despite the extensive use of insecticides [2]. Traditional pest management approaches have relied heavily on the application of broad-spectrum chemical insecticides, which have led to the development of insecticide resistance, unintended effects on non-target organisms, and environmental contamination [3]. Moreover, the overuse of chemical insecticides has raised concerns about human health risks, particularly in developing countries where proper safety measures may not be followed [4].

In response to these challenges, there has been a growing interest in developing eco-friendly and targeted approaches to insect pest management. These next-generation strategies aim to reduce the environmental impact of pest control while maintaining or improving crop yields and quality. Eco-friendly approaches focus on using natural resources and processes to manage pests, such as biopesticides derived from plants, microorganisms, and insects [119-121]. Targeted approaches, on the other hand, aim to selectively control specific pest species without harming non-target organisms, using techniques such as semiochemicals, biotechnology-based tools, and integrated pest management (IPM) strategies.

This review article provides an in-depth analysis of the latest advancements in eco-friendly and targeted insect pest management. We discuss the potential of biopesticides, semiochemicals, biotechnology-based approaches, and IPM strategies in reducing the reliance on chemical insecticides while achieving effective pest control. We also highlight the challenges and future prospects of these next-generation approaches, emphasizing the need for further research, development, and adoption to ensure sustainable food production and ecosystem health.

2. BIOPESTICIDES

Biopesticides are derived from natural sources, such as plants, microorganisms, and insects, and offer an eco-friendly alternative to synthetic insecticides. They are generally less toxic to non-target organisms, have a lower environmental impact, and can be effective against insecticide-resistant pests [5]. Biopesticides can be classified into three main categories: microbial pesticides, biochemical pesticides, and plant-incorporated protectants (PIPs) [6].

2.1 Microbial Pesticides

Microbial pesticides are derived from microorganisms, such as bacteria, fungi, viruses, and protozoa, that are pathogenic to specific insect pests. The most widely used microbial pesticide is *Bacillus thuringiensis* (Bt), a soil bacterium that produces insecticidal proteins known as Cry toxins [7]. Bt-based products have been successfully used to control lepidopteran pests in crops such as cotton, corn, and vegetables [8]. Other examples of microbial pesticides include entomopathogenic fungi, such as *Beauveria bassiana* and *Metarhizium anisopliae*, which can infect and kill a wide range of insect pests [9].

2.2 Biochemical Pesticides

Biochemical pesticides are naturally occurring substances that control pests through non-toxic mechanisms, such as interfering with insect growth and development, attracting or repelling pests, or enhancing plant defenses [10]. Examples of biochemical pesticides include insect growth regulators (IGRs), such as azadirachtin derived from neem trees, and kaolin clay, which creates a physical barrier on plant surfaces that deters insect feeding and oviposition [11].

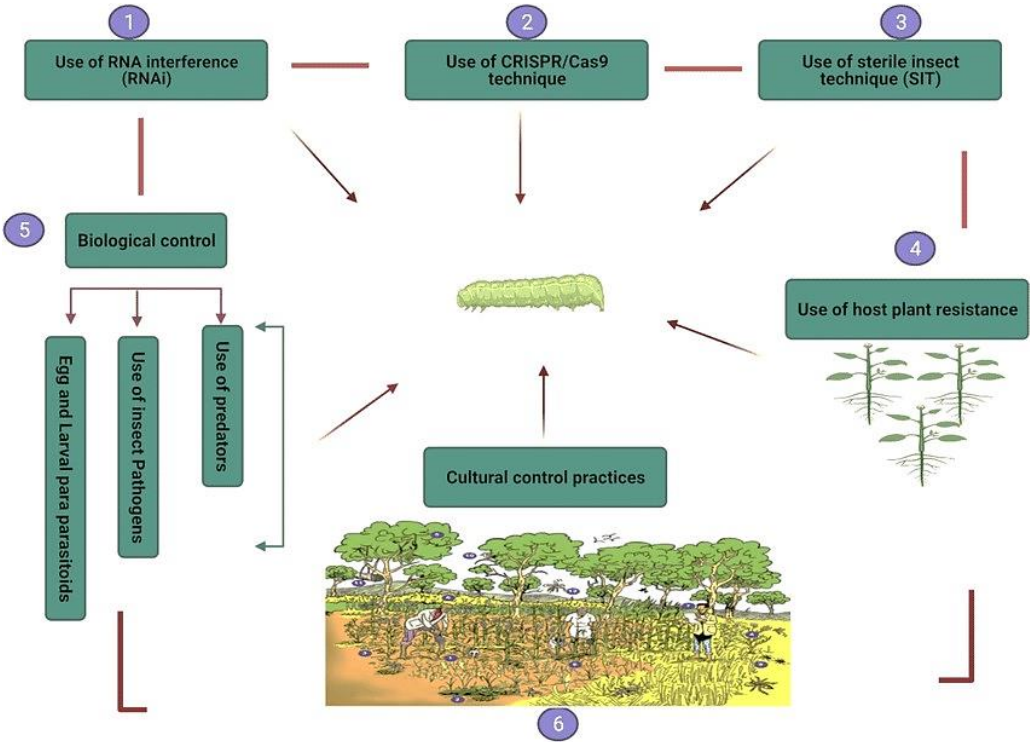

Fig. 1. Overview of eco-friendly and targeted insect pest management approaches

Table 1. Examples of microbial pesticides and their target insect pests

Microbial Pesticide	Target Insect Pests
Bacillus thuringiensis (Bt)	Lepidopteran pests (e.g., cotton bollworm, corn earworm, diamondback moth)
Beauveria bassiana	Wide range of insect pests (e.g., aphids, whiteflies, thrips)
Metarhizium anisopliae	Wide range of insect pests (e.g., locusts, grasshoppers, termites)
Baculoviruses	Lepidopteran pests (e.g., codling moth, gypsy moth, cabbage looper)
Spinosad	Dipteran pests (e.g., fruit flies, house flies), lepidopteran pests

Table 2. Examples of biochemical pesticides and their modes of action

Biochemical Pesticide	Mode of Action
Azadirachtin	Insect growth regulator, feeding deterrent, oviposition deterrent
Kaolin clay	Physical barrier, feeding deterrent, oviposition deterrent
Pyrethrins	Neurotoxin, disrupts sodium channels in insect nervous system
Neem oil	Feeding deterrent, oviposition deterrent, insect growth regulator
Garlic extract	Feeding deterrent, oviposition deterrent, insecticidal properties

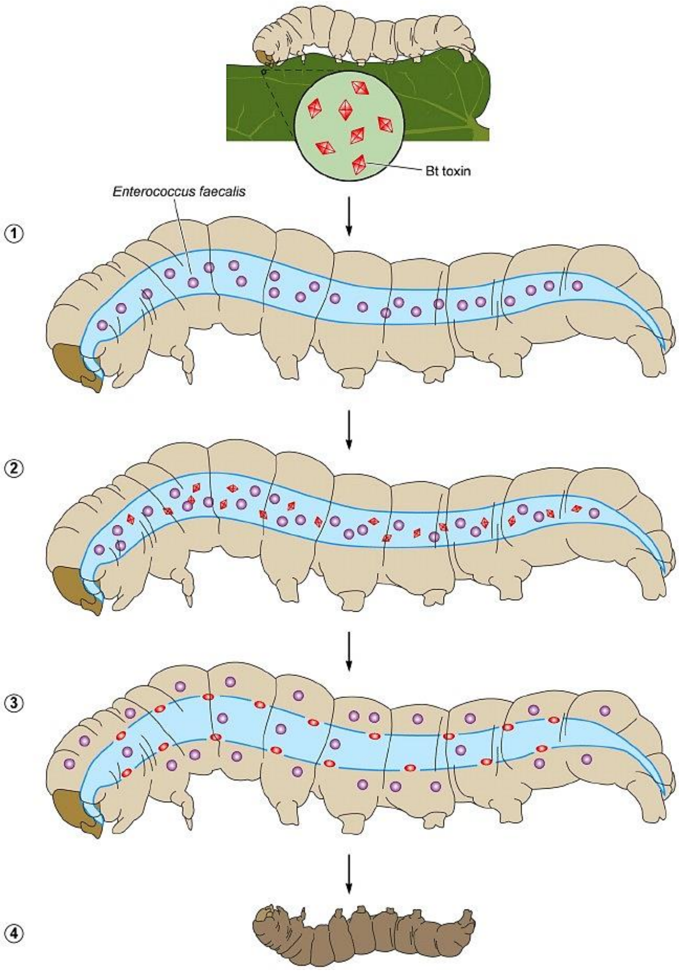

Fig. 2. Schematic representation of the mode of action of Bacillus thuringiensis (Bt) toxins in insect pests

Table 3. Examples of plant-incorporated protectants (PIPs) and their target insect pests

Plant-Incorporated Protectant (PIP)	Target Insect Pests
Bt cotton	Cotton bollworm (*Helicoverpa armigera*), pink bollworm (*Pectinophora gossypiella*)
Bt corn	European corn borer (*Ostrinia nubilalis*), corn rootworm (*Diabrotica* spp.)
Bt eggplant	Eggplant fruit and shoot borer (*Leucinodes orbonalis*)
Cowpea with *Cry1Ab* gene	Legume pod borer (*Maruca vitrata*)
Potato with *Cry3A* gene	Colorado potato beetle (*Leptinotarsa decemlineata*)

2.3 Plant-Incorporated Protectants (PIPs)

Plant-incorporated protectants (PIPs) are insecticidal substances produced by plants through genetic engineering or conventional breeding [12]. The most common example of PIPs is Bt crops, which are genetically modified to express Cry toxins from *Bacillus thuringiensis*. Bt crops, such as Bt cotton and Bt corn, have been widely adopted worldwide and have significantly reduced the use of chemical insecticides in these crops [13].

3. SEMIOCHEMICALS

Semiochemicals are chemical substances that mediate interactions between organisms, such as pheromones and allelochemicals [14]. In the context of insect pest management, semiochemicals can be exploited for pest monitoring, mating disruption, and attract-and-kill strategies, reducing the need for insecticide applications [15].

3.1 Pheromones

Pheromones are chemical substances released by an organism that trigger a specific behavioral or physiological response in another individual of the same species [16]. Insect sex pheromones, in particular, have been widely used for pest monitoring and mating disruption. By releasing synthetic sex pheromones in the field, the natural mating behavior of insect pests can be disrupted, leading to reduced pest populations [17].

3.2 Allelochemicals

Allelochemicals are chemical substances that mediate interactions between different species, such as plant-insect or insect-insect interactions [18]. In insect pest management, allelochemicals can be used as attractants, repellents, or antifeedants to manipulate pest behavior and protect crops [19].

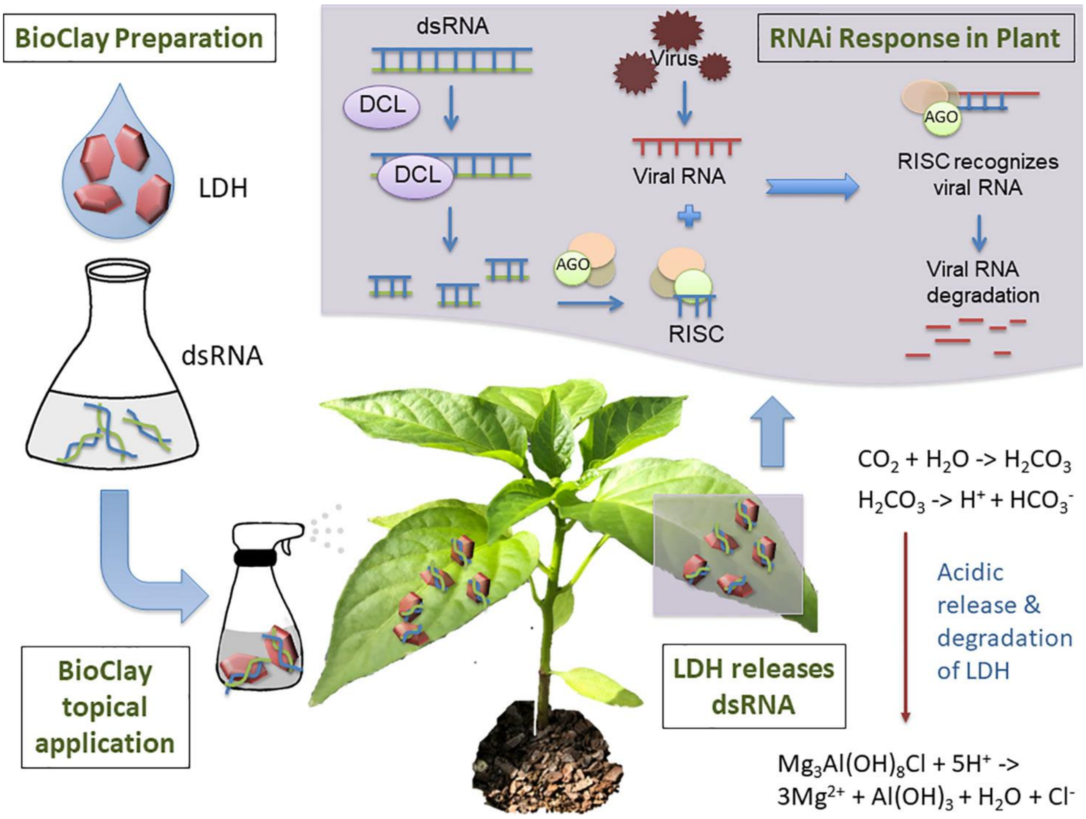

Fig. 3. Bio clay preparation technique

Table 4. Examples of insect pests and their sex pheromones used for mating disruption

Insect Pest	Sex Pheromone Components
Codling moth (*Cydia pomonella*)	Codlemone, dodecanol, tetradecanol
Grapevine moth (*Lobesia botrana*)	(E,Z)-7,9-dodecadienyl acetate, (E,Z)-7,9-dodecadien-1-ol
Cotton bollworm (*Helicoverpa armigera*)	(Z)-11-hexadecenal, (Z)-9-hexadecenal, (Z)-7-hexadecenal
Oriental fruit moth (*Grapholita molesta*)	(Z)-8-dodecenyl acetate, (E)-8-dodecenyl acetate, (Z)-8-dodecen-1-ol
European grapevine moth (*Eupoecilia ambiguella*)	(Z)-9-dodecenyl acetate, (E)-9-dodecenyl acetate, (Z)-9-dodecen-1-ol

Table 5. Examples of allelochemicals and their potential applications in insect pest management

Allelochemical	Source	Potential Application
Methyl salicylate	Plants (e.g., wintergreen)	Attractant for natural enemies of insect pests
Nerolidol	Plants (e.g., ginger, lemongrass)	Repellent for whiteflies and aphids
Caryophyllene oxide	Plants (e.g., clove, hops)	Attractant for entomopathogenic nematodes
Farnesene	Plants (e.g., apple, pear)	Aphid alarm pheromone, repellent for various insect pests
Humulene	Plants (e.g., hops, sage)	Repellent for stored product pests, attractant for natural enemies

Table 6. Examples of RNAi targets for insect pest management

Insect Pest	RNAi Target Gene	Effect on Insect
Western corn rootworm (*Diabrotica virgifera virgifera*)	*Snf7* (vacuolar sorting protein)	Reduced larval survival, impaired midgut function
Colorado potato beetle (*Leptinotarsa decemlineata*)	*Actin* (cytoskeletal protein)	Reduced larval survival, impaired muscle function
Diamondback moth (*Plutella xylostella*)	*Chitin synthase* (enzyme for chitin biosynthesis)	Reduced larval survival, impaired molting and growth
Cotton bollworm (*Helicoverpa armigera*)	*HaHR3* (molting hormone receptor)	Reduced larval survival, impaired molting and metamorphosis
Whitefly (*Bemisia tabaci*)	*ADP/ATP translocase* (energy metabolism enzyme)	Reduced adult survival, impaired energy metabolism

Table 7. Examples of CRISPR/Cas9 applications in insect pest management

Insect Pest	CRISPR/Cas9 Application	Potential Outcome
Mosquito (*Aedes aegypti*)	Knocking out fertility genes	Reduced mosquito population, decreased disease transmission
Fruit fly (*Drosophila suzukii*)	Modifying olfactory receptor genes	Altered host plant preference, reduced crop damage
Spotted wing drosophila (*Drosophila suzukii*)	Disrupting insecticide resistance genes	Increased susceptibility to insecticides, improved control
Fall armyworm (*Spodoptera frugiperda*)	Editing genes involved in molting and metamorphosis	Impaired development, reduced pest population
Asian citrus psyllid (*Diaphorina citri*)	Knocking out genes essential for disease transmission	Reduced transmission of citrus greening disease

Table 8. Examples of transgenic crops for insect pest management

Transgenic Crop	Insecticidal Trait	Target Insect Pests
Bt cotton	Cry1Ac, Cry2Ab toxins from *Bacillus thuringiensis*	Cotton bollworm, pink bollworm, tobacco budworm
Bt corn	Cry1Ab, Cry1F, Cry3Bb1 toxins from *Bacillus thuringiensis*	European corn borer, southwestern corn borer, corn rootworm
Bt brinjal (eggplant)	Cry1Ac toxin from *Bacillus thuringiensis*	Eggplant fruit and shoot borer
Cowpea with Cry1Ab gene	Cry1Ab toxin from *Bacillus thuringiensis*	Legume pod borer
Potato with Cry3A gene	Cry3A toxin from *Bacillus thuringiensis*	Colorado potato beetle

4. BIOTECHNOLOGY -BASED APPROACHES

Biotechnology-based approaches, such as RNA interference (RNAi), CRISPR/Cas9 gene editing, and transgenic crops, offer novel tools for targeting specific pest species and reducing reliance on chemical insecticides [20]. These approaches exploit the genetic and molecular mechanisms underlying insect biology and behavior to develop highly specific and effective pest control strategies [21].

4.1 RNA Interference (RNAi)

RNA interference (RNAi) is a gene silencing mechanism that can be used to selectively target and suppress the expression of essential genes in insect pests, leading to reduced pest survival and reproduction [22]. RNAi-based insect control can be achieved through the application of double-stranded RNA (dsRNA) or small interfering RNA (siRNA) that targets specific pest genes [23].

4.2 CRISPR/Cas9 Gene Editing

CRISPR/Cas9 gene editing is a powerful tool for precisely modifying the genome of insect pests to reduce their fitness or manipulate their behavior [24]. This technology can be used to create genetically modified insects with reduced reproductive potential, increased susceptibility to biopesticides, or altered host plant preferences [25].

4.3 Transgenic Crops

Transgenic crops, or genetically modified crops, are plants that have been engineered to express insecticidal proteins or other traits that confer resistance to insect pests [26]. The most common example of transgenic crops is Bt crops, which express Cry toxins from *Bacillus thuringiensis*. Other transgenic approaches include the expression of protease inhibitors, lectins, or RNAi constructs that target specific pest genes [27].

5. INTEGRATED PEST MANAGEMENT (IPM)

Integrated Pest Management (IPM) is a holistic approach to pest control that combines multiple tactics based on ecological principles to manage pest populations sustainably and economically [28]. IPM strategies aim to minimize the use of chemical insecticides by prioritizing preventive measures, monitoring pest populations, and using a combination of biological, cultural, and physical control methods [29].

5.1 Principles of IPM

5.1.1 The key principles of IPM include [30]:

1. Prevention: Adopting cultural practices that minimize pest infestations, such as crop rotation, intercropping, and the use of resistant varieties.

2. Monitoring: Regularly scouting fields to assess pest populations and their natural enemies, using tools such as traps, lures, and visual inspections.

3. Threshold-based decisions: Applying control measures only when pest populations reach an economically damaging level, known as the economic threshold.

4. Multiple control tactics: Integrating biological, cultural, physical, and chemical control methods to manage pest populations effectively and sustainably.

5. Evaluation: Assessing the effectiveness of IPM strategies and making adjustments as needed based on the results.

5.2 Biological Control in IPM

Biological control, the use of natural enemies to manage pest populations, is a key component of IPM [31]. Natural enemies, such as predators, parasitoids, and pathogens, can be conserved, augmented, or introduced to suppress pest populations. Conservation biological control involves modifying the environment to favor natural enemies, such as providing shelter, alternative food sources, and reducing insecticide use [32]. Augmentative biological control involves the periodic release of commercially available natural enemies to supplement existing populations [33].

Table 9. Examples of natural enemies used in biological control

Natural Enemy	Type	Target Insect Pests
Ladybird beetles (Coccinellidae)	Predator	Aphids, mealybugs, scale insects
Green lacewings (Chrysopidae)	Predator	Aphids, whiteflies, thrips, mites
Parasitic wasps (various families)	Parasitoid	Caterpillars, aphids, whiteflies, scales
Entomopathogenic nematodes	Pathogen	Soil-dwelling pests (e.g., root weevils, white grubs)
Entomopathogenic fungi (*Beauveria*, *Metarhizium*)	Pathogen	Wide range of insect pests

Table 10. Examples of cultural control practices in IPM

Cultural Practice	Mechanism of Action	Example
Crop rotation	Breaks pest life cycles, reduces population buildup	Rotating corn with soybeans to manage corn rootworm
Intercropping	Disrupts pest movement, enhances natural enemy populations	Planting marigolds with tomatoes to repel whiteflies
Sanitation	Removes alternate host plants and crop residues harboring pests	Removing weeds and crop debris to reduce aphid populations
Resistant varieties	Reduces pest damage through inherent plant defenses	Using Bt cotton to resist cotton bollworm and pink bollworm
Planting and harvesting dates	Avoids peak pest populations by altering crop timing	Early planting of squash to avoid squash vine borer

Table 11. Examples of physical and mechanical control methods in IPM

Method	Mechanism of Action	Example
Row covers	Excludes pests from crops by creating a physical barrier	Using floating row covers to protect brassicas from flea beetles
Trap crops	Attracts pests away from main crops	Planting collards to attract diamondback moth away from cabbage
Sticky traps	Captures flying insect pests	Yellow sticky traps for monitoring and reducing whitefly populations
Pheromone traps	Attracts and captures pests using synthetic pheromones	Using pheromone traps to monitor and control codling moth in apples
Mechanical destruction	Physically removes or destroys pests and their habitats	Handpicking and destroying Colorado potato beetle eggs and larvae

5.3 Cultural Control in IPM

Cultural control practices aim to create an environment that is less favorable for pest populations and more supportive of crop growth and natural enemies [34]. These practices include:

1. Crop rotation: Alternating crops to break pest life cycles and reduce their population buildup.
2. Intercropping: Planting two or more crops together to disrupt pest movement and enhance natural enemy populations.
3. Sanitation: Removing crop residues and alternate host plants that may harbor pests.
4. Resistant varieties: Using crop varieties that are less susceptible to pest damage.
5. Planting and harvesting dates: Adjusting planting and harvesting dates to avoid peak pest populations.

5.4 Physical and Mechanical Control in IPM

Physical and mechanical control methods involve the use of physical barriers, traps, or other devices to exclude, capture, or kill insect pests [35]. These methods can be effective in reducing pest populations without the use of chemicals and are often used in conjunction with other IPM tactics.

6. CHALLENGES AND FUTURE PROSPECTS

Despite the numerous benefits of eco-friendly and targeted insect pest management approaches, there are several challenges that need to be addressed to ensure their widespread adoption and long-term success.

6.1 Regulatory Hurdles

One of the main challenges facing the development and commercialization of new pest management technologies is navigating the complex regulatory landscape [36]. Biopesticides, semiochemicals, and biotechnology-based approaches often face stringent safety and efficacy requirements, which can be time-consuming and costly to meet. Harmonizing regulations across countries and regions could help accelerate the approval process and facilitate the global adoption of these technologies [37].

6.2 Public Acceptance

Another challenge is the public perception and acceptance of new pest management approaches, particularly those involving genetic modification or the release of living organisms [38]. Concerns about potential ecological risks, unintended effects on non-target species, and the long-term safety of these technologies can hinder their adoption. Engaging the public through transparent communication, education, and participatory decision-making processes is crucial for building trust and support for these innovations [39].

6.3 Research and Development

Continued research and development are essential for improving the efficacy, specificity, and sustainability of eco-friendly and targeted pest management approaches. Key areas for future research include:

1. Identifying novel biopesticide agents and optimizing their formulation and delivery [40].
2. Elucidating the chemical ecology of insect pests and their natural enemies to develop more effective semiochemical-based strategies [41].
3. Advancing biotechnology tools, such as RNAi and CRISPR/Cas9, for precise and efficient pest control [42].
4. Integrating multiple pest management tactics and assessing their long-term ecological impacts [43].
5. Developing cost-effective and user-friendly pest monitoring and decision support systems [44].

6.4 Knowledge Transfer and Adoption

Translating research findings into practical pest management solutions and promoting their adoption by farmers and pest management professionals is another critical challenge [45]. Effective knowledge transfer mechanisms, such as extension services, farmer field schools, and digital platforms, are needed to disseminate information and provide hands-on training on new technologies [46]. Collaborations between researchers, industry, and end-users can help ensure that new pest management tools are tailored to local needs and constraints, increasing their likelihood of adoption [47].

7. GLOBAL CASE STUDIES

Case Study 1: Bt cotton in the United States for controlling cotton bollworm and pink bollworm [48]

In this case study, Bt cotton was widely adopted in the United States to control cotton bollworm (Helicoverpa zea) and pink bollworm (Pectinophora gossypiella). Bt cotton plants express insecticidal proteins from Bacillus thuringiensis, which specifically target these pests. The use of Bt cotton has led to significant reductions in insecticide applications, improved crop yields, and reduced environmental impact. However, the study also highlights the importance of implementing resistance management strategies to ensure the long-term effectiveness of this technology.

Case Study 2: Pheromone-based mating disruption of codling moth in apple orchards in Europe [49]

This case study examines the use of pheromone-based mating disruption to control codling moth (Cydia pomonella) in apple orchards across Europe. By releasing synthetic sex pheromones, the mating behavior of codling moth is disrupted, leading to reduced pest populations and crop damage. The study demonstrates the effectiveness of this eco-friendly approach in managing codling moth infestations, while minimizing the use of chemical insecticides. The success of this strategy has led to its widespread adoption in European apple production.

Case Study 3: Conservation biological control of aphids in cereals using flower strips in the United Kingdom [50]

In this case study, researchers in the United Kingdom investigated the potential of flower strips to promote conservation biological control of aphids in cereal crops. By sowing flower strips along field margins, they aimed to provide nectar and pollen resources for natural enemies of aphids, such as parasitic wasps and predatory insects. The study found that the presence of flower strips significantly increased the abundance and diversity of these beneficial insects, leading to reduced aphid populations and improved crop health. This study highlights the importance of habitat management in supporting sustainable pest control in agricultural landscapes.

Case Study 4: RNAi-based control of Colorado potato beetle in transgenic potatoes in Canada [51]

This case study explores the application of RNA interference (RNAi) technology to control Colorado potato beetle (Leptinotarsa decemlineata) in transgenic potatoes in Canada. Researchers developed potato plants that express double-stranded RNA (dsRNA) targeting essential genes in the beetle. When the larvae feed on these transgenic plants, the dsRNA triggers gene silencing, leading to reduced larval survival and damage to potato crops. The study demonstrates the potential of RNAi as a specific and environmentally friendly approach to managing this important pest.

Case Study 5: Entomopathogenic fungi for control of locust and grasshopper pests in Africa [52]

In this case study, the use of entomopathogenic fungi, such as Metarhizium acridum, was investigated for the control of locust and grasshopper pests in various African countries. These fungi are natural pathogens of insects and can cause mortality by infecting and proliferating within the host. The study found that the application of fungal biopesticides significantly reduced locust and grasshopper populations, while minimizing the environmental risks associated with chemical insecticides. The success of this approach has led to the development of commercial biopesticide products for locust and grasshopper control in Africa.

Case Study 6: Biopesticide based on Bacillus thuringiensis for control of diamondback moth in brassica crops worldwide [53]

This case study examines the global use of biopesticides based on Bacillus thuringiensis (Bt) for controlling diamondback moth (Plutella xylostella), a major pest of brassica crops. Bt biopesticides contain insecticidal proteins that specifically target lepidopteran pests, making them a safe and effective alternative to broad-spectrum chemical insecticides. The study highlights the successful implementation of Bt-based products in various countries, resulting in reduced crop losses and improved environmental sustainability. However, the authors also emphasize the need for resistance management strategies to maintain the long-term efficacy of these biopesticides.

Case Study 7: Sterile insect technique for eradication of Mediterranean fruit fly in Chile and Peru [54]

In this case study, the sterile insect technique (SIT) was used to eradicate Mediterranean fruit fly (Ceratitis capitata) in Chile and Peru. SIT involves the mass-rearing and release of sterile male insects, which compete with wild males for mating opportunities. As a result, the pest population declines over time due to reduced reproductive success. The study demonstrates the successful implementation of SIT in both countries, leading to the eradication of Mediterranean fruit fly and significant economic benefits for the fruit industry. This case study highlights the potential of SIT as an environmentally friendly and species-specific approach to pest management.

Case Study 8: Semiochemical-based mass trapping of red palm weevil in date palm plantations in the Middle East [55]

This case study investigates the use of semiochemical-based mass trapping to control red palm weevil (*Rhynchophorus ferrugineus*) in date palm plantations in the Middle East. Red palm weevil is a devastating pest that causes significant yield losses in date palm production. The study found that the use of aggregation pheromones and plant volatiles in trapping systems effectively reduced weevil populations and damage to palms. The authors highlight the importance of integrating mass trapping with other management practices, such as sanitation and early detection, for optimal results.

Case Study 9: Integrated pest management of tomato leafminer using parasitoids and biopesticides in South America [56]

In this case study, an integrated pest management (IPM) approach combining parasitoids and biopesticides was used to control tomato leafminer (Tuta absoluta) in South America. Tomato leafminer is an invasive pest that causes significant damage to tomato crops. The study found that the release of the parasitoid wasp Trichogramma pretiosum, along with the application of Bacillus thuringiensis-based biopesticides, effectively reduced leafminer populations and crop damage. The authors emphasize the benefits of using multiple control tactics in an IPM framework to achieve sustainable pest management.

Case Study 10: Bt maize for control of corn rootworm in the United States and Europe [57]

This case study examines the use of Bt maize to control corn rootworm (Diabrotica spp.) in the United States and Europe. Corn rootworm is a major pest of maize crops, causing significant yield losses. The study found that the adoption of Bt maize expressing insecticidal proteins targeting corn rootworm led to reduced pest damage, increased yields, and decreased insecticide use. However, the authors also highlight the importance of implementing resistance management strategies, such as crop rotation and refuge planting, to ensure the long-term effectiveness of this technology.

7.1 Asian Case Studies

Case Study 1: Pheromone-based mating disruption of rice stem borer in Japan [58]

In this case study, researchers in Japan investigated the use of pheromone-based mating disruption to control rice stem borer (Chilo suppressalis), a major pest of rice crops. By releasing synthetic sex pheromones in rice fields, the mating behavior of rice stem borer was disrupted, leading to reduced pest populations and crop damage. The study found that this approach effectively controlled the pest while minimizing the use of chemical insecticides, thus promoting environmental sustainability and biodiversity conservation in rice ecosystems.

Case Study 2: Bt rice for control of yellow stem borer in China [59]

This case study examines the development and commercialization of Bt rice for controlling yellow stem borer (Scirpophaga incertulas) in China. Bt rice is genetically engineered to express insecticidal proteins from Bacillus thuringiensis, which specifically target lepidopteran pests. The study found that the adoption of Bt rice led to significant reductions in insecticide use, increased yields, and improved farmer profitability. The authors also discuss the challenges associated with the commercialization of Bt rice, including regulatory hurdles and public acceptance.

Case Study 3: Parasitoid wasps for biological control of coconut hispine beetle in the Philippines [60]

In this case study, the use of parasitoid wasps was investigated for the biological control of coconut hispine beetle (Brontispa longissima) in the Philippines. Coconut hispine beetle is an invasive pest that causes significant damage to coconut palms. The study found that the release of the parasitoid wasp Asecodes hispinarum effectively reduced beetle populations and damage to coconut palms. The authors highlight the importance of conserving and augmenting natural enemies as part of a sustainable pest management strategy in coconut production.

Case Study 4: Entomopathogenic nematodes for control of oriental beetle in turfgrass in South Korea [61]

This case study explores the application of entomopathogenic nematodes for controlling oriental beetle (Exomala orientalis) in turfgrass in South Korea. Oriental beetle larvae feed on the roots of turfgrass, causing significant damage to golf courses and other landscapes. The study found that the application of the nematode Heterorhabditis bacteriophora effectively reduced beetle populations and damage to turfgrass. The authors discuss the benefits of using entomopathogenic nematodes as a biological control agent, including their environmental safety and compatibility with other management practices.

Case Study 5: Banker plant system using barley for control of brown planthopper in rice in Vietnam [62]

In this case study, a banker plant system using barley was investigated for the control of brown planthopper (Nilaparvata lugens) in rice fields in Vietnam. Brown planthopper is a major pest of rice crops, causing significant yield losses. The study found that planting barley strips around rice fields attracted and supported populations of the natural enemy Anagrus nilaparvatae, a parasitoid wasp that attacks brown planthopper eggs. This approach effectively reduced brown planthopper populations and damage to rice crops while minimizing the use of chemical insecticides.

Case Study 6: Intercropping maize with soybean for control of fall armyworm in Indonesia [63]

This case study examines the use of intercropping maize with soybean to control fall armyworm (Spodoptera frugiperda) in Indonesia. Fall armyworm is an invasive pest that causes significant damage to maize crops. The study found that intercropping maize with soybean reduced fall armyworm populations and damage to maize plants, likely due to the increased diversity and abundance of natural enemies in the intercropped system. The authors highlight the potential of intercropping as a sustainable and cost-effective pest management strategy for smallholder farmers.

Case Study 7: Biopesticide based on Metarhizium anisopliae for control of sugarcane white grub in Taiwan [64]

In this case study, a biopesticide based on the entomopathogenic fungus Metarhizium anisopliae was used to control sugarcane white grub (Lepidiota stigma) in Taiwan. Sugarcane white grub is a major pest of sugarcane crops, causing significant yield losses. The study found that the application of M. anisopliae effectively reduced white grub populations and damage to sugarcane plants. The authors discuss the benefits of using fungal biopesticides, including their environmental safety, compatibility with other management practices, and potential for local production.

Case Study 8: RNAi-based control of Asian corn borer in transgenic maize in China [65]

This case study explores the application of RNA interference (RNAi) technology for controlling Asian corn borer (Ostrinia furnacalis) in transgenic maize in China. Asian corn borer is a major pest of maize crops, causing significant yield losses. The study found that transgenic maize expressing double-stranded RNA (dsRNA) targeting essential genes in Asian corn borer effectively reduced pest populations and damage to maize plants. The authors discuss the potential of RNAi-based pest control as a specific and environmentally friendly approach to managing insect pests in agriculture.

Case Study 9: Integrated pest management of diamondback moth using parasitoids and trap crops in Thailand [66]

In this case study, an integrated pest management (IPM) approach combining parasitoids and trap crops was used to control diamondback moth (Plutella xylostella) in cabbage fields in Thailand. Diamondback moth is a major pest of brassica crops, causing significant yield losses. The study found that the release of the parasitoid Cotesia plutellae, along with the use of collard greens as a trap crop, effectively reduced diamondback moth populations and damage to cabbage plants. The authors highlight the benefits of using multiple control tactics in an IPM framework to achieve sustainable pest management.

Case Study 10: Semiochemical-based push-pull strategy for control of striped stem borer in sorghum in India [67]

This case study examines the use of a semiochemical-based push-pull strategy to control striped stem borer (Chilo partellus) in sorghum fields in India. Striped stem borer is a major pest of sorghum crops, causing significant yield losses. The study found that planting Napier grass as a trap crop around sorghum fields and intercropping sorghum with Desmodium, a repellent plant, effectively reduced stem borer populations and damage to sorghum plants. The authors discuss the potential of push-pull strategies as a sustainable and cost-effective pest management approach for smallholder farmers.

7.2 Indian Case Studies

Case Study 1: Bt cotton for control of cotton bollworm and pink bollworm in India [68]

In this case study, the adoption and impact of Bt cotton for controlling cotton bollworm

(*Helicoverpa armigera*) and pink bollworm (*Pectinophora gossypiella*) in India were investigated. Bt cotton is genetically engineered to express insecticidal proteins from Bacillus thuringiensis, which specifically target these pests. The study found that the widespread adoption of Bt cotton led to significant reductions in insecticide use, increased yields, and improved farmer profitability. The authors also discuss the challenges associated with Bt cotton adoption, including resistance management and seed pricing.

Case Study 2: Pheromone-based monitoring and mass trapping of brinjal fruit and shoot borer in India [69]

This case study examines the use of pheromone-based monitoring and mass trapping to control brinjal fruit and shoot borer (*Leucinodes orbonalis*) in eggplant fields in India. Brinjal fruit and shoot borer is a major pest of eggplant crops, causing significant yield losses. The study found that the use of sex pheromone traps for monitoring and mass trapping effectively reduced pest populations and damage to eggplant fruits. The authors highlight the benefits of using pheromone-based tools as part of an integrated pest management strategy for sustainable eggplant production.

Case Study 3: Biopesticide based on Beauveria bassiana for control of sugarcane woolly aphid in India [70]

In this case study, a biopesticide based on the entomopathogenic fungus Beauveria bassiana was used to control sugarcane woolly aphid (Ceratovacuna lanigera) in India. Sugarcane woolly aphid is a major pest of sugarcane crops, causing significant yield losses. The study found that the application of B. bassiana effectively reduced woolly aphid populations and damage to sugarcane plants. The authors discuss the potential of using fungal biopesticides as a sustainable and environmentally friendly alternative to chemical insecticides in sugarcane production.

Case Study 4: Integrated pest management of pigeonpea pod borer using resistant varieties and biopesticides in India [71]

This case study examines the use of an integrated pest management (IPM) approach combining resistant varieties and biopesticides to control pigeonpea pod borer (*Helicoverpa armigera*) in India. Pigeonpea pod borer is a major pest of pigeonpea crops, causing significant yield losses. The study found that the use of resistant pigeonpea varieties, along with the application of neem-based biopesticides, effectively reduced pod borer populations and damage to pigeonpea pods. The authors highlight the benefits of using multiple control tactics in an IPM framework for sustainable pigeonpea production.

Case Study 5: Parasitoid wasps for biological control of sugarcane early shoot borer in India [72]

In this case study, the use of parasitoid wasps was investigated for the biological control of sugarcane early shoot borer (*Chilo infuscatellus*) in India. Sugarcane early shoot borer is a major pest of sugarcane crops, causing significant yield losses. The study found that the release of the parasitoid wasps Trichogramma chilonis and Cotesia flavipes effectively reduced early shoot borer populations and damage to sugarcane plants.

Case Study 6: Intercropping mustard with chickpea for control of gram pod borer in India [73]

This case study examines the use of intercropping mustard with chickpea to control gram pod borer (*Helicoverpa armigera*) in India. Gram pod borer is a major pest of chickpea crops, causing significant yield losses. The study found that intercropping chickpea with mustard reduced gram pod borer populations and damage to chickpea pods, likely due to the increased diversity and abundance of natural enemies in the intercropped system. The authors highlight the potential of intercropping as a sustainable and cost-effective pest management strategy for smallholder farmers.

Case Study 7: Entomopathogenic nematodes for control of white grub in potato in India [74]

In this case study, the use of entomopathogenic nematodes was investigated for the control of white grub (*Brahmina coriacea*) in potato fields in India. White grub is a major pest of potato crops, causing significant yield losses. The study found that the application of the nematode Heterorhabditis indica effectively reduced white grub populations and damage to potato tubers. The authors discuss the benefits of using entomopathogenic nematodes as a biological control agent, including their environmental safety and compatibility with other management practices.

Case Study 8: RNAi-based control of tomato fruit borer in transgenic tomato in India [75]

This case study explores the application of RNA interference (RNAi) technology for controlling tomato fruit borer (*Helicoverpa armigera*) in transgenic tomato in India. Tomato fruit borer is a major pest of tomato crops, causing significant yield losses. The study found that transgenic tomato expressing double-stranded RNA (dsRNA) targeting essential genes in tomato fruit borer effectively reduced pest populations and damage to tomato fruits. The authors discuss the potential of RNAi-based pest control as a specific and environmentally friendly approach to managing insect pests in agriculture.

Case Study 9: Banker plant system using marigold for control of whitefly in tomato in India [76]

In this case study, a banker plant system using marigold was investigated for the control of whitefly (Bemisia tabaci) in tomato fields in India. Whitefly is a major pest of tomato crops, causing significant yield losses and transmitting viral diseases. The study found that planting marigold strips around tomato fields attracted and supported populations of the natural enemy Encarsia formosa, a parasitoid wasp that attacks whitefly nymphs. This approach effectively reduced whitefly populations and damage to tomato plants while minimizing the use of chemical insecticides.

Case Study 10: Semiochemical-based attract-and-kill strategy for control of red palm weevil in coconut in India [77]

This case study examines the use of a semiochemical-based attract-and-kill strategy to control red palm weevil (*Rhynchophorus ferrugineus*) in coconut plantations in India. Red palm weevil is a major pest of coconut palms, causing significant yield losses and tree mortality. The study found that the use of aggregation pheromone traps baited with insecticide effectively reduced red palm weevil populations and damage to coconut palms. The authors discuss the potential of attract-and-kill strategies as a targeted and environmentally friendly approach to managing insect pests in perennial crop systems.

These case studies highlight the diverse range of eco-friendly and targeted pest management approaches being implemented across India to address the challenges posed by various insect pests in different cropping systems. By leveraging the potential of biopesticides, natural enemies, intercropping, RNAi technology, banker plant systems, and semiochemical-based strategies, these approaches offer sustainable alternatives to chemical insecticides while promoting biodiversity conservation and environmental health. However, the success of these strategies often depends on factors such as the specific pest-crop system, local ecological conditions, and the capacity of farmers and extension services to adopt and implement these practices effectively. Continued research, knowledge sharing, and policy support are crucial for scaling up these eco-friendly pest management approaches and promoting their widespread adoption among smallholder farmers in India.

Case Study 10: Semiochemical-based attract-and-kill strategy for control of red palm weevil in coconut in India [77]

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Case Study 11: Pheromone-based mating disruption of pink bollworm in cotton in Gujarat, India [78]

This case study investigates the use of pheromone-based mating disruption to control pink bollworm (Pectinophora gossypiella) in cotton fields in Gujarat, India. Pink bollworm is a major pest of cotton crops, causing significant yield losses. The study found that the application of sex pheromone dispensers in cotton fields effectively disrupted the mating behavior of pink bollworm, leading to reduced pest populations and damage to cotton bolls. The authors highlight the potential of mating disruption as a specific and environmentally friendly approach to managing lepidopteran pests in cotton production.

Case Study 12: Bacillus thuringiensis (Bt) formulation for control of tea mosquito bug in cashew in Kerala, India [79]

In this case study, a formulation based on the entomopathogenic bacterium Bacillus thuringiensis (Bt) was used to control tea mosquito bug (Helopeltis antonii) in cashew plantations in Kerala, India. Tea mosquito bug is a major pest of cashew crops, causing significant yield losses. The study found that the application of Bt formulation effectively reduced tea mosquito bug populations and damage to cashew nuts. The authors discuss the benefits of using Bt-based biopesticides as a targeted and eco-friendly approach to managing sucking pests in cashew production.

Case Study 13: Entomopathogenic fungus Lecanicillium lecanii for control of aphids in okra in Maharashtra, India [80]

This case study examines the use of the entomopathogenic fungus Lecanicillium lecanii for controlling aphids (Aphis gossypii) in okra fields in Maharashtra, India. Aphids are major pests of okra crops, causing significant yield losses and transmitting viral diseases. The study found that the application of L. lecanii effectively reduced aphid populations and damage to okra plants. The authors highlight the potential of using fungal biopesticides as a sustainable and environmentally friendly alternative to chemical insecticides in okra production.

Case Study 14: Intercropping coriander with tomato for control of whitefly in Karnataka, India [81]

In this case study, intercropping coriander with tomato was investigated for the control of whitefly (Bemisia tabaci) in Karnataka, India. Whitefly is a major pest of tomato crops, causing significant yield losses and transmitting viral diseases. The study found that intercropping tomato with coriander reduced whitefly populations and damage to tomato plants, likely due to the repellent properties of coriander and the increased diversity of natural enemies in the intercropped system. The authors discuss the potential of intercropping as a simple and cost-effective pest management strategy for smallholder farmers.

Case Study 15: RNAi-based control of brinjal shoot and fruit borer in transgenic eggplant in West Bengal, India [82]

This case study explores the application of RNA interference (RNAi) technology for controlling brinjal shoot and fruit borer (*Leucinodes orbonalis*) in transgenic eggplant in West Bengal, India. Brinjal shoot and fruit borer is a major pest of eggplant crops, causing significant yield losses. The study found that transgenic eggplant expressing double-stranded RNA (dsRNA) targeting essential genes in the pest effectively reduced brinjal shoot and fruit borer populations and damage to eggplant fruits. The authors discuss the potential of RNAi-based pest control as a specific and environmentally friendly approach to managing insect pests in vegetable production.

Case Study 16: Banker plant system using Chinese cabbage for control of diamondback moth in cauliflower in Himachal Pradesh, India [83]

In this case study, a banker plant system using Chinese cabbage was investigated for the control of diamondback moth (*Plutella xylostella*) in cauliflower fields in Himachal Pradesh, India. Diamondback moth is a major pest of cauliflower crops, causing significant yield losses. The study found that planting Chinese cabbage strips around cauliflower fields attracted and supported populations of the natural enemy Cotesia plutellae, a parasitoid wasp that attacks diamondback moth larvae. This approach effectively reduced diamondback moth populations and damage to cauliflower plants while minimizing the use of chemical insecticides.

Case Study 17: Semiochemical-based push-pull strategy for control of fruit flies in mango orchards in Andhra Pradesh, India [84]

This case study examines the use of a semiochemical-based push-pull strategy to control fruit flies (Bactrocera spp.) in mango orchards in Andhra Pradesh, India. Fruit flies are major pests of mango crops, causing significant yield losses and fruit quality deterioration. The study found that the use of methyl eugenol traps as an attractant (pull) and the application of a repellent (push) effectively reduced fruit fly populations and damage to mango fruits. The authors discuss the potential of push-pull strategies as a targeted and eco-friendly approach to managing fruit flies in mango production.

Case Study 18: Pheromone-based monitoring and mass trapping of yellow stem borer in rice in Tamil Nadu, India [85]

In this case study, pheromone-based monitoring and mass trapping were used to control yellow stem borer (Scirpophaga incertulas) in rice fields in Tamil Nadu, India. Yellow stem borer is a major pest of rice crops, causing significant yield losses. The study found that the use of sex pheromone traps for monitoring and mass trapping effectively reduced yellow stem borer populations and damage to rice plants. The authors highlight the benefits of using pheromone-based tools as part of an integrated pest management strategy for sustainable rice production.

Case Study 19: Biopesticide based on Metarhizium anisopliae for control of mealybugs in grapes in Maharashtra, India [86]

This case study examines the use of a biopesticide based on the entomopathogenic fungus Metarhizium anisopliae for controlling mealybugs (Maconellicoccus hirsutus) in grape vineyards in Maharashtra, India. Mealybugs are major pests of grape crops, causing significant yield losses and quality deterioration. The study found that the application of M. anisopliae effectively reduced mealybug populations and damage to grape bunches. The authors discuss the potential of using fungal biopesticides as a sustainable and environmentally friendly alternative to chemical insecticides in grape production.

Case Study 20: Intercropping marigold with chili pepper for control of thrips in Andhra Pradesh, India [87]

In this case study, intercropping marigold with chili pepper was investigated for the control of thrips (Scirtothrips dorsalis) in Andhra Pradesh, India. Thrips are major pests of chili pepper crops, causing significant yield losses and transmitting viral diseases. The study found that intercropping chili pepper with marigold reduced thrips populations and damage to chili pepper plants, likely due to the repellent properties of marigold and the increased diversity of natural enemies in the intercropped system. The authors discuss the potential of intercropping as a simple and cost-effective pest management strategy for smallholder farmers.

Case Study 21: RNAi-based control of potato tuber moth in transgenic potato in Uttar Pradesh, India [88]

This case study explores the application of RNA interference (RNAi) technology for controlling potato tuber moth (Phthorimaea operculella) in transgenic potato in Uttar Pradesh, India. Potato tuber moth is a major pest of potato crops, causing significant yield losses and quality deterioration. The study found that transgenic potato expressing double-stranded RNA (dsRNA) targeting essential genes in the pest effectively reduced potato tuber moth populations and damage to potato tubers. The authors discuss the potential of RNAi-based pest control as a specific and environmentally friendly approach to managing insect pests in potato production.

Case Study 22: Banker plant system using sorghum for control of sugarcane aphid in sugarcane in Karnataka, India [89]

In this case study, a banker plant system using sorghum was investigated for the control of sugarcane aphid (Melanaphis sacchari) in sugarcane fields in Karnataka, India. Sugarcane aphid is a major pest of sugarcane crops, causing significant yield losses. The study found that planting sorghum strips around sugarcane fields attracted and supported populations of the natural enemy Aphelinus sp., a parasitoid wasp that attacks sugarcane aphids. This approach effectively reduced sugarcane aphid populations and damage to sugarcane plants while minimizing the use of chemical insecticides.

Case Study 23: Semiochemical-based attract-and-kill strategy for control of coffee berry borer in coffee plantations in Kerala, India [90]

This case study examines the use of a semiochemical-based attract-and-kill strategy to control coffee berry borer (Hypothenemus hampei) in coffee plantations in Kerala, India. Coffee berry borer is a major pest of coffee crops, causing significant yield losses and quality deterioration. The study found that the use of ethanol-baited traps with insecticide effectively reduced coffee berry borer populations and damage to coffee berries. The authors discuss the potential of attract-and-kill strategies as a targeted and eco-friendly approach to managing coffee berry borer in coffee production.

Case Study 24: Pheromone-based mating disruption of spotted bollworm in cotton in Madhya Pradesh, India [91]

In this case study, pheromone-based mating disruption was used to control spotted bollworm (Earias vittella) in cotton fields in Madhya Pradesh, India. Spotted bollworm is a major pest of cotton crops, causing significant yield losses. The study found that the application of sex pheromone dispensers in cotton fields effectively disrupted the mating behavior of spotted bollworm, leading to reduced pest populations and damage to cotton bolls. The authors highlight the potential of mating disruption as a specific and environmentally friendly approach to managing lepidopteran pests in cotton production.

Case Study 25: Bacillus thuringiensis (Bt) formulation for control of pigeon pea pod borer in pigeon pea in Andhra Pradesh, India [92]

This case study examines the use of a formulation based on the entomopathogenic bacterium Bacillus thuringiensis (Bt) for controlling pigeon pea pod borer (*Helicoverpa armigera*) in pigeon pea fields in Andhra Pradesh, India. Pigeon pea pod borer is a major pest of pigeon pea crops, causing significant yield losses. The study found that the application of Bt formulation effectively reduced pigeon pea pod borer populations and damage to pigeon pea pods. The authors discuss the benefits of using Bt-based biopesticides as a targeted and eco-friendly approach to managing lepidopteran pests in pigeon pea production.

Case Study 26: Entomopathogenic fungus Beauveria bassiana for control of whitefly in okra in Gujarat, India [93]

In this case study, the entomopathogenic fungus *Beauveria bassiana* was used for controlling whitefly (*Bemisia tabaci*) in okra fields in Gujarat, India. Whitefly is a major pest of okra crops, causing significant yield losses and transmitting viral diseases. The study found that the application of B. bassiana effectively reduced whitefly populations and damage to okra plants. The authors highlight the potential of using fungal biopesticides as a sustainable and environmentally friendly alternative to chemical insecticides in okra production.

Case Study 27: Intercropping onion with carrot for control of carrot rust fly in Himachal Pradesh, India [94]

This case study investigates intercropping onion with carrot for the control of carrot rust fly (Psila rosae) in Himachal Pradesh, India. Carrot rust fly is a major pest of carrot crops, causing significant yield losses. The study found that intercropping carrot with onion reduced carrot rust fly populations and damage to carrot roots, likely due to the repellent properties of onion and the increased diversity of natural enemies in the intercropped system. The authors discuss the potential of intercropping as a simple and cost-effective pest management strategy for smallholder farmers.

Case Study 28: RNAi-based control of banana stem weevil in transgenic banana in Maharashtra, India [95]

In this case study, RNA interference (RNAi) technology was applied for controlling banana stem weevil (Odoiporus longicollis) in transgenic banana in Maharashtra, India. Banana stem weevil is a major pest of banana crops, causing significant yield losses and plant damage. The study found that transgenic banana expressing double-stranded RNA (dsRNA) targeting essential genes in the pest effectively reduced banana stem weevil populations and damage to banana plants. The authors discuss the potential of RNAi-based pest control as a specific and environmentally friendly approach to managing insect pests in banana production.

Case Study 29: Banker plant system using mustard for control of cabbage aphid in cabbage in West Bengal, India [96]

This case study examines a banker plant system using mustard for the control of cabbage aphid (*Brevicoryne brassicae*) in cabbage fields in West Bengal, India. Cabbage aphid is a major pest of cabbage crops, causing significant yield losses. The study found that planting mustard strips around cabbage fields attracted and supported populations of the natural enemy Diaeretiella rapae, a parasitoid wasp that attacks cabbage aphids. This approach effectively reduced cabbage aphid populations and damage to cabbage plants while minimizing the use of chemical insecticides.

Case Study 30: Semiochemical-based push-pull strategy for control of pod borer in chickpea in Rajasthan, India [97]

In this case study, a semiochemical-based push-pull strategy was used to control pod borer (*Helicoverpa armigera*) in chickpea fields in Rajasthan, India. Pod borer is a major pest of chickpea crops, causing significant yield losses. The study found that the use of pheromone traps as an attractant (pull) and the intercropping of chickpea with coriander as a repellent (push) effectively reduced pod borer populations and damage to chickpea pods. The authors discuss the potential of push-pull strategies as a targeted and eco-friendly approach to managing pod borer in chickpea production.

Case Study 31: Pheromone-based monitoring and mass trapping of red palm weevil in coconut plantations in Kerala, India [98]

This case study investigates the use of pheromone-based monitoring and mass trapping to control red palm weevil (*Rhynchophorus ferrugineus*) in coconut plantations in Kerala, India. Red palm weevil is a major pest of coconut palms, causing significant yield losses and tree mortality. The study found that the use of aggregation pheromone traps for monitoring and mass trapping effectively reduced red palm weevil populations and damage to coconut palms. The authors highlight the benefits of using pheromone-based tools as part of an integrated pest management strategy for sustainable coconut production.

Case Study 32: Biopesticide based on Pseudomonas fluorescens for control of rice blast disease in Tamil Nadu, India [99]

In this case study, a biopesticide based on the bacterium Pseudomonas fluorescens was used for controlling rice blast disease (*Magnaporthe oryzae*) in rice fields in Tamil Nadu, India. Rice blast is a major fungal disease of rice crops, causing significant yield losses. The study found that the application of P. fluorescens effectively reduced rice blast incidence and severity, leading to improved rice yields. The authors discuss the potential of using bacterial biopesticides as a sustainable and environmentally friendly alternative to chemical fungicides in rice production.

Case Study 33: Intercropping cowpea with maize for control of stem borer in maize in Karnataka, India [100,101]

This case study examines intercropping cowpea with maize for the control of stem borer (Chilo partellus) in maize fields in Karnataka, India. Stem borer is a major pest of maize crops, causing significant yield losses. The study found that intercropping maize with cowpea reduced stem borer populations and damage to maize plants, likely due to the increased diversity and abundance of natural enemies in the intercropped system. The authors discuss the potential of intercropping as a simple and cost-effective pest management strategy for smallholder farmers.

The study found that transgenic cotton expressing double-stranded RNA (dsRNA) targeting essential genes in whitefly effectively reduced whitefly populations and damage to cotton plants. The authors discuss the potential of RNAi-based pest control as a specific and environmentally friendly approach to managing insect pests in cotton production.

Case Study 35: Banker plant system using sorghum for control of corn leaf aphid in maize in Uttar Pradesh, India [102]

This case study examines a banker plant system using sorghum for the control of corn leaf aphid

(Rhopalosiphum maidis) in maize fields in Uttar Pradesh, India. Corn leaf aphid is a major pest of maize crops, causing significant yield losses. The study found that planting sorghum strips around maize fields attracted and supported populations of the natural enemy Aphelinus maidis, a parasitoid wasp that attacks corn leaf aphids. This approach effectively reduced corn leaf aphid populations and damage to maize plants while minimizing the use of chemical insecticides.

Case Study 36: Semiochemical-based attract-and-kill strategy for control of tea mosquito bug in cashew plantations in Goa, India [103]

In this case study, a semiochemical-based attract-and-kill strategy was used to control tea mosquito bug (Helopeltis antonii) in cashew plantations in Goa, India. Tea mosquito bug is a major pest of cashew crops, causing significant yield losses and nut quality deterioration. The study found that the use of attractant traps baited with insecticide effectively reduced tea mosquito bug populations and damage to cashew nuts. The authors discuss the potential of attract-and-kill strategies as a targeted and eco-friendly approach to managing tea mosquito bug in cashew production.

Case Study 37: Pheromone-based mating disruption of tobacco caterpillar in tobacco in Andhra Pradesh, India [104]

This case study investigates the use of pheromone-based mating disruption to control tobacco caterpillar (Spodoptera litura) in tobacco fields in Andhra Pradesh, India. Tobacco caterpillar is a major pest of tobacco crops, causing significant yield losses. The study found that the application of sex pheromone dispensers in tobacco fields effectively disrupted the mating behavior of tobacco caterpillar, leading to reduced pest populations and damage to tobacco leaves. The authors highlight the potential of mating disruption as a specific and environmentally friendly approach to managing lepidopteran pests in tobacco production.

Case Study 38: Bacillus thuringiensis (Bt) formulation for control of diamondback moth in cabbage in Himachal Pradesh, India [105]

In this case study, a formulation based on the entomopathogenic bacterium Bacillus thuringiensis (Bt) was used for controlling diamondback moth (Plutella xylostella) in cabbage fields in Himachal Pradesh, India. Diamondback moth is a major pest of cabbage crops, causing significant yield losses. The study found that the application of Bt formulation effectively reduced diamondback moth populations and damage to cabbage heads. The authors discuss the benefits of using Bt-based biopesticides as a targeted and eco-friendly approach to managing lepidopteran pests in cabbage production.

Case Study 39: Entomopathogenic fungus Verticillium lecanii for control of thrips in chili pepper in Tamil Nadu, India [106]

This case study examines the use of the entomopathogenic fungus Verticillium lecanii for controlling thrips (Scirtothrips dorsalis) in chili pepper fields in Tamil Nadu, India. Thrips are major pests of chili pepper crops, causing significant yield losses and transmitting viral diseases. The study found that the application of V. lecanii effectively reduced thrips populations and damage to chili pepper plants. The authors highlight the potential of using fungal biopesticides as a sustainable and environmentally friendly alternative to chemical insecticides in chili pepper production.

Case Study 40: Intercropping garlic with cauliflower for control of diamondback moth in Uttarakhand, India [107]

In this case study, intercropping garlic with cauliflower was investigated for the control of diamondback moth (Plutella xylostella) in Uttarakhand, India. Diamondback moth is a major pest of cauliflower crops, causing significant yield losses. The study found that intercropping cauliflower with garlic reduced diamondback moth populations and damage to cauliflower plants, likely due to the repellent properties of garlic and the increased diversity of natural enemies in the intercropped system. The authors discuss the potential of intercropping as a simple and cost-effective pest management strategy for smallholder farmers.

Case Study 41: RNAi-based control of sugarcane woolly aphid in transgenic sugarcane in Maharashtra, India [108]

This case study explores the application of RNA interference (RNAi) technology for controlling sugarcane woolly aphid (Ceratovacuna lanigera) in transgenic sugarcane in Maharashtra, India. Sugarcane woolly aphid is a major pest of sugarcane crops, causing significant yield losses.

The study found that transgenic sugarcane expressing double-stranded RNA (dsRNA) targeting essential genes in the pest effectively reduced sugarcane woolly aphid populations and damage to sugarcane plants. The authors discuss the potential of RNAi-based pest control as a specific and environmentally friendly approach to managing insect pests in sugarcane production.

Case Study 42: Banker plant system using marigold for control of tomato fruit borer in tomato in Karnataka, India [109]

In this case study, a banker plant system using marigold was investigated for the control of tomato fruit borer (*Helicoverpa armigera*) in tomato fields in Karnataka, India. Tomato fruit borer is a major pest of tomato crops, causing significant yield losses. The study found that planting marigold strips around tomato fields attracted and supported populations of the natural enemy Trichogramma chilonis, an egg parasitoid wasp that attacks tomato fruit borer. This approach effectively reduced tomato fruit borer populations and damage to tomato fruits while minimizing the use of chemical insecticides.

Case Study 43: Semiochemical-based push-pull strategy for control of cotton mealybug in cotton in Gujarat, India [110]

This case study examines the use of a semiochemical-based push-pull strategy to control cotton mealybug (Phenacoccus solenopsis) in cotton fields in Gujarat, India. Cotton mealybug is a major pest of cotton crops, causing significant yield losses and lint quality deterioration. The study found that the use of pheromone traps as an attractant (pull) and the intercropping of cotton with coriander as a repellent (push) effectively reduced cotton mealybug populations and damage to cotton plants. The authors discuss the potential of push-pull strategies as a targeted and eco-friendly approach to managing cotton mealybug in cotton production.

Case Study 44: Pheromone-based monitoring and mass trapping of brinjal fruit and shoot borer in eggplant in West Bengal, India [111]

In this case study, pheromone-based monitoring and mass trapping were used to control brinjal fruit and shoot borer (*Leucinodes orbonalis*) in eggplant fields in West Bengal, India. Brinjal fruit and shoot borer is a major pest of eggplant crops, causing significant yield losses. The study found that the use of sex pheromone traps for monitoring and mass trapping effectively reduced brinjal fruit and shoot borer populations and damage to eggplant fruits. The authors highlight the benefits of using pheromone-based tools as part of an integrated pest management strategy for sustainable eggplant production.

Case Study 45: Biopesticide based on Trichoderma harzianum for control of collar rot disease in chickpea in Rajasthan, India [112]

This case study examines the use of a biopesticide based on the fungus Trichoderma harzianum for controlling collar rot disease (Sclerotium rolfsii) in chickpea fields in Rajasthan, India. Collar rot is a major fungal disease of chickpea crops, causing significant yield losses. The study found that the application of T. harzianum effectively reduced collar rot incidence and severity, leading to improved chickpea yields. The authors discuss the potential of using fungal biopesticides as a sustainable and environmentally friendly alternative to chemical fungicides in chickpea production.

Case Study 46: Intercropping tomato with basil for control of tomato leafminer in Maharashtra, India [113]

In this case study, intercropping tomato with basil was investigated for the control of tomato leafminer (Tuta absoluta) in Maharashtra, India. Tomato leafminer is a major pest of tomato crops, causing significant yield losses and leaf damage. The study found that intercropping tomato with basil reduced tomato leafminer populations and damage to tomato plants, likely due to the repellent properties of basil and the increased diversity of natural enemies in the intercropped system. The authors discuss the potential of intercropping as a simple and cost-effective pest management strategy for smallholder farmers.

Case Study 47: RNAi-based control of mango fruit fly in transgenic mango in Andhra Pradesh, India [114]

This case study explores the application of RNA interference (RNAi) technology for controlling mango fruit fly (Bactrocera dorsalis) in transgenic mango in Andhra Pradesh, India. Mango fruit fly is a major pest of mango crops, causing significant yield losses and fruit quality deterioration. The study found that transgenic mango expressing double-stranded RNA (dsRNA) targeting essential genes in the pest effectively reduced mango fruit fly populations and damage to mango fruits. The authors discuss the potential of RNAi-based pest control as a specific and environmentally friendly approach to managing insect pests in mango production.

Case Study 48: Banker plant system using sesbania for control of okra aphid in okra in Uttar Pradesh, India [115]

In this case study, a banker plant system using sesbania was investigated for the control of okra aphid (Aphis gossypii) in okra fields in Uttar Pradesh, India. Okra aphid is a major pest of okra crops, causing significant yield losses and transmitting viral diseases. The study found that planting sesbania strips around okra fields attracted and supported populations of the natural enemy Aphidius colemani, a parasitoid wasp that attacks okra aphids. This approach effectively reduced okra aphid populations and damage to okra plants while minimizing the use of chemical insecticides.

Case Study 49: Semiochemical-based attract-and-kill strategy for control of cucumber fruit fly in cucumber in Tamil Nadu, India [116]

This case study examines the use of a semiochemical-based attract-and-kill strategy to control cucumber fruit fly (Bactrocera cucurbitae) in cucumber fields in Tamil Nadu, India. Cucumber fruit fly is a major pest of cucumber crops, causing significant yield losses and fruit quality deterioration. The study found that the use of attractant traps baited with insecticide effectively reduced cucumber fruit fly populations and damage to cucumber fruits. The authors discuss the potential of attract-and-kill strategies as a targeted and eco-friendly approach to managing cucumber fruit fly in cucumber production.

Case Study 50: Pheromone-based mating disruption of rice yellow stem borer in rice in West Bengal, India [117,118]

In this case study, pheromone-based mating disruption was used to control rice yellow stem borer (Scirpophaga incertulas) in rice fields in West Bengal, India. Rice yellow stem borer is a major pest of rice crops, causing significant yield losses. The study found that the application of sex pheromone dispensers in rice fields effectively disrupted the mating behavior of rice yellow stem borer, leading to reduced pest populations and damage to rice plants. The authors highlight the potential of mating disruption as a specific and environmentally friendly approach to managing lepidopteran pests in rice production.

8. CONCLUSION

Eco-friendly and targeted approaches to insect pest management offer a promising alternative to the heavy reliance on chemical insecticides. By harnessing the power of biopesticides, semiochemicals, biotechnology, and integrated pest management strategies, we can reduce the environmental impact of pest control while maintaining or improving crop yields and quality. However, realizing the full potential of these next-generation approaches requires addressing challenges related to regulatory hurdles, public acceptance, research and development, and knowledge transfer. To move towards a more sustainable and resilient pest management future, we need to prioritize investments in research, innovation, and capacity building. This includes supporting the discovery and development of new pest control technologies, fostering collaborations between stakeholders, and creating an enabling policy and regulatory environment. Additionally, engaging farmers, consumers, and the broader public in the co-creation and evaluation of pest management solutions is essential for ensuring their long-term success and adoption. By embracing eco-friendly and targeted pest management approaches, we can safeguard food security, protect human health, and conserve biodiversity for future generations. The transition towards sustainable pest management is not only an environmental imperative but also an economic and social opportunity to build a more resilient and equitable food system.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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