Review Article

A review on Advances in Biocontrol Techniques for Managing Insect Pests in Sustainable IndiaAgriculture.

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Abstract

Biocontrol techniques represent a vital avenue in the quest for sustainable agricultural practices. This approach, integrating ecological intelligence with modern scientific advancements, is seeing increasing adoption in various regions, notably in India. Drawing inspiration from nature's own mechanisms, biocontrol employs specific organisms or their biological derivatives to manage and mitigate pests, thereby decreasing the dependency on chemical agents. Through an in-depth exploration of biocontrol applications, this review ~~study~~ places a special emphasis on India's initiatives and contrasts them with global endeavors. Noteworthy examples include the innovative use of parasitic wasps to combat the papaya mealybug menace in Tamil Nadu, the strategic application of fungi like Trichoderma for disease control in Maharashtra, and the successful introduction of parasitoid wasps to manage olive flies in regions like California. Rooted in foundational ecological principles, these methodologies exhibit potential benefits that span improved crop yields, economic viability, and most importantly, reduced environmental adversities. Effective deployment and scaling of these techniques require an integrated approach, emphasizing collaboration among researchers, farming communities, and industry stakeholders. By presenting a detailed analysis of these synergistic efforts, this review accentuates the transformative potential of biocontrol. As the global community faces the dual challenges of an expanding population and the unpredictable impacts of climate change, the promise of biocontrol looms large, offering a sustainable pathway for India~~the~~ agriculture of the future.

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Keywords: ***Biocontrol, Sustainable, Agriculture, Pests, Ecology***

Introduction

In the realm of agriculture, the pursuit of sustainability has become increasingly significant over the years. Sustainable agriculture can be best described as the amalgamation of ecological well-being, economic profitability, and social fairness, thereby ensuring that we can feed the present without compromising the ability of future generations to meet their own needs [1]. Historically, a singular focus on augmenting yield and productivity led to the adoption of agricultural practices that, albeit effective in the short term, posed serious repercussions for the environment, most notably in the form of soil degradation, loss of biodiversity, and water pollution [2].The centrality of sustainable agriculture stems from its ability to address these challenges. It propounds the implementation of farming techniques that are not just environmentally amicable but also economically feasible, ensuring that agriculture remains a lucrative venture. By preserving soil, ensuring biodiversity, and maintaining ecosystem health, sustainable agriculture becomes an answer to the dual challenge of feeding a burgeoning global population while safeguarding the planet [3].As the global community slowly gravitates towards sustainable agricultural practices, one of the key challenges encountered is the management of insect pests. These pests, often diminutive in size, can wreak havoc on agricultural yields, leading to staggering losses. In some instances, such losses have been reported to be as high as 40% of the total crop production [4]. Beyond the immediate economic ramifications, these pests are also carriers of various diseases, diminishing the quality of the harvested produce and threatening food security, particularly in regions that are already susceptible [5].For years, the knee-jerk response to the menace of insect pests was the indiscriminate application of chemical pesticides. While initially successful, over-reliance on these chemicals culminated in a series of problems. The pests began developing resistance, the chemicals had unintended consequences on non-target species, and the broader environment suffered from prolonged exposure to these toxins [6].In light of these challenges, the global agricultural community began exploring a mosaic of pest management techniques. A prominent approach that emerged was Integrated Pest Management (IPM), which promotes a holistic and environmentally sound methodology to handle pests [7]. Central to IPM is the principle of using a combination of tactics, ranging from adjusting farming practices to render the environment inhospitable for pests [8], employing barriers and traps, leveraging the role of natural enemies like predators, parasitoids, and pathogens to judiciously using eco-friendly chemicals like pheromones and botanical insecticides [9].In essence, as the world inches closer to realizing the dream of sustainable agriculture, the path is riddled with challenges. Among them, managing insect pests stands out, not just for the immediate threat they pose but for the broader implications they have on food security and environmental health. With the right strategies, informed by research and innovation, it is possible to not just mitigate these challenges but turn them into opportunities for a greener, more sustainable future.

The Concept of Biocontrol

Biocontrol, or biological control, has rapidly garnered attention as a key pillar in the broader paradigm of sustainable agricultural practices. It presents an eco-friendly alternative to chemical pesticides, focusing on the utilization of natural mechanisms and agents to suppress pests. This approach not only aligns with the principles of sustainable agriculture but also promises a reduction in the environmental and health hazards typically associated with synthetic chemicals. Biocontrol can be succinctly defined as the use of living organisms to control the population of another organism, which is considered a pest [10]. This essentially means leveraging the natural predation mechanisms in ecosystems, using one organism to suppress or manage the population of another. The agents used for such purposes—predators, parasites, pathogens, and competitors—are often termed as 'biocontrol agents' [11]. This concept is rooted in the ecological principle of natural balance. In nature, populations of pests are often regulated by a variety of biological factors including their natural enemies. By introducing or enhancing the role of these natural enemies in agricultural settings, it's possible to control pest populations without resorting to chemicals [12]. The idea of biological control isn't entirely novel. Ancient Chinese manuscripts indicate the use of ants to control pests in citrus orchards as early as 400 BC [13]. However, the modern iteration of biocontrol can be traced back to the 19th century. One of the pioneering instances of biological control was witnessed in the late 1800s when the cottony cushion scale, a pest devastating the citrus industry in California, was successfully managed by introducing its natural enemy, the vedalia beetle, from Australia [14]. This success story sparked interest in the scientific community, leading to the exploration and introduction of various natural enemies to control numerous pests worldwide. Over the decades, the field of biocontrol has evolved immensely. From merely importing and releasing natural enemies, scientists began exploring techniques to mass-produce and release these biocontrol agents, enhancing their efficacy and ensuring they can be used at a larger scale [15]. Moreover, the advent of molecular biology and genetic engineering has opened up new avenues, allowing researchers to potentially develop genetically modified organisms (GMOs) that can act as more efficient biocontrol agents [16].

Table 1. Examples of the implication of semiochemicals enabling greater efficacy of biological control agents[17]**.**

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Biological Control Agent	**Insect Pest**	**Host Plant**
Parasitoids		
i. Trichogramma (Riley) spp.	Heliothiszea and Anticarsiagemmatalis	Glycine max and Trifoliumincarnatum
ii. Aphidiuservi	Rhopalosiphumpadi	Viciafaba
iii. Oomyzusgallerucae	Xanthogalerucaluteola	Ulmus minor
iv. Trissolcus spp.	Euschistusheros	Glycine max
v. Telenomuspodisi, Trisscolusteretis	Euschistusheros	Resistant Glycine max cultivars
Predators		
i. Thanasimusdubius	Ipspini	Pinusstrobus
ii. Rhizophagusgrandis	Dendroctonusmicans	-
iii. Coccinellaseptempunctata	Rhopalosiphumpadi	Viciafaba
iv. Temnochilachlorodia, Enocleruslecontei	Ipspini	Pinusstrobus

v. Medeterasetiventris, Thanasimusformicarius and Thanasimusfemoralis	Ipstypographus	Piceaabies
vi. Podisusmaculiventris	Manducasexta	Solanumlycopersicum
Entomopathogenic Fungus		
i. Trichotheciumroseum	Oryzaephilussurinamensis, O. mercator, Cryptolestesferrugineus, Ahasverusadvena, Cathartusquadricollis	-
ii. Zoophthoraradicans	Plutellaxylostella	Brassica chinensis var. pekinensis
iii. Beauveriabassiana	Cylasformicarius	-
iv. Verticilliumlecanii	Phorodonhumuli	Prunus domestica
v. Beauveriabassiana	Plautiacrossotastali	Orchards
vi. Zoophthoraradicans	Plutellaxylostella	Brassica oleracea
vii. Beauveriabassiana	Ipstypographus	-
viii. Beauveriabassiana	Cosmopolites sordidus	-
ix. Metarhizium anisopliae	Amblyommavariegatum	-
x. Metarhizium anisopliae	Frankliniellaoccidentalis	Phaseolus vulgaris var. Samantha
xi. Metarhiziumbrunneum	Agriotesobscurus	-
xii. Metarhiziumbrunneum and Metarhiziumanisopliae	Megalurothripssjostedti	Vigna unguiculata
Entomopathogenic Nematodes		
i. Heterorhabditisbacteriophora	Galleria mellonella	-
ii. Steinernemafeltiae	Galleria mellonella	-
iii. Steinernemacarpocapsae,	Galleria mellonella	-

Steinernemafeltiae, Heterorhabditisbacteriophora		
iv. Steinernemafeltiae and S Steinernemacarpocapsae	Tenebrio molitor	-
Entomopathogenic Virus		
i. Baculoviruses	Heliothisvirescens	-
ii. Baculoviruses	Cydiapomonella, Adoxophyesorana	-
Protozoa		
i. Mattesiatrogodermae	Trogodermaglabrum	-

The significance of biocontrol in sustainable agriculture

The shift towards sustainable agriculture necessitates the exploration of methods that are ecologically benign, economically viable, and socially acceptable.

1. **Ecological Benefits**: By reducing the reliance on chemical pesticides, biocontrol helps in mitigating the negative impacts on non-target species and the broader environment. This not only preserves biodiversity but also enhances the resilience of ecosystems [18.]

2. **Economic Implications**: In the long run, biocontrol can prove to be cost-effective. With the right infrastructure for mass-producing biocontrol agents, farmers can potentially reduce expenses related to purchasing and applying chemical pesticides. Additionally, by producing crops that are free from chemical residues, farmers can access premium markets that offer better prices [19].

3. **Health and Social Benefits**: Chemical pesticides have often been linked with various health issues, ranging from immediate poisoning to long-term diseases like cancer. By adopting biocontrol, the exposure of farmers and consumers to these chemicals can be minimized, ensuring safer food and a healthier environment [20].

Different Biocontrol Techniques and Their Advances

Biological control, or biocontrol, is a dynamic field that has continuously evolved over the years, offering innovative solutions to managing pests without heavily relying on chemical interventions. This strategy typically revolves around the utilization of living organisms, such as predators, parasitoids, pathogens, and other agents, to suppress or control pest populations.Predators have always been nature's way of maintaining balance. In biocontrol, predators are organisms that actively hunt and consume pests. Examples like ladybugs have gained popularity in agricultural setups due to their appetite for aphids and other soft-bodied pests [21]. Spiders, lacewings, and predatory mites are also recognized for their contribution to managing pests like mites, whiteflies, and thrips [22]. Modern ecological research has facilitated techniques that enhance these predators' presence in fields. For instance, habitat management, such as planting flower strips, has been known to improve their longevity and effectiveness [23].

While predators consume multiple prey throughout their lives, parasitoids have a unique relationship with their host. They lay eggs in or on their target organism, and upon hatching, the larvae feed on the host, leading to its eventual demise. The beauty of parasitoids in biocontrol is their specificity, allowing targeted pest management. Parasitic wasps, especially from the Trichogrammatidae family, are utilized against moth and butterfly pests [24]. Similarly, tachinid flies serve as a biocontrol agent for various pest caterpillars [25]. The application and efficiency of parasitoids have seen improvements due to advancements in understanding their host preferences and strategic deployment. Molecular tools have furthered our insight into their genetics, optimizing their role in pest management [26].

Pathogens, including certain bacteria, viruses, and fungi, hold potential in curbing pest populations. Bacteria such as *Bacillus thuringiensis* (Bt) have shown efficacy against multiple insect pests [27]. Viruses, including nucleopolyhedroviruses, target pest caterpillars [28]. Fungi, specifically species from genera like *Metarhizium* and *Beauveria*, have been identified as potential biocontrol agents against a variety of insect pests [30]. The application of these pathogens provides a targeted approach, ensuring minimal collateral damage to non-target organisms. However, the challenge lies in ensuring their efficacy across varied environmental conditions. Modern biotechnologies have played a pivotal role in enhancing their effectiveness and ensuring they remain resilient against environmental variables [30].

Entomopathogenic nematodes (EPNs) are another category of biocontrol agents that have garnered interest in recent years. These tiny worms infect and kill insects. Their mode of action involves carrying symbiotic bacteria. When these nematodes invade a host insect, the bacteria proliferate, leading to the insect's rapid death. EPNs offer a non-toxic, environmentally friendly solution to managing a wide range of soil-borne insect pests.

Lastly, chemical signals, namely semiochemicals, which include pheromones and allelochemicals, have been employed in pest management. Pheromones, which are chemical signals released by organisms to affect the behavior of their kind, have been used in traps to monitor or manage pest populations. They have also been instrumental in mating disruption techniques, wherein the released pheromones confuse pests and prevent successful mating. Allelochemicals, on the other hand, are chemicals produced by one species that affect the behavior or physiology of another species. These compounds hold potential in biocontrol by making the environment less conducive to pests or attracting their natural enemies.

Integrated Pest Management (IPM) and Biocontrol

In the complex world of agriculture, where pests persistently challenge production, Integrated Pest Management (IPM) stands as a beacon of hope. This holistic approach to pest management integrates cultural, biological, and chemical methods based on scientific principles, environmental considerations, and economic practicalities. By seeking to minimize pest damage rather than attempting to eradicate pests entirely, IPM offers a balanced, sustainable solution to one of agriculture's most pressing issues.Integrated Pest Management (IPM) is not just a method but a philosophy. It stresses the need for a comprehensive understanding of the ecological relationships within a given environment [31]. Originating in the mid-20th century in response to the adverse effects of indiscriminate pesticide use, IPM combines multiple techniques to manage pests, keeping their population at levels below those causing economic harm [32]. Central to this approach is the knowledge of pest biology, understanding the environmental factors influencing pest population dynamics, and the use of thresholds to determine when intervention is necessary. This system doesn't rely on a single solution but emphasizes a combination of practices tailored to each specific situation [33].

Biocontrol Techniques in IPM

Within the ambit of IPM, biocontrol holds a pivotal position. The emphasis of IPM on minimal environmental disruption and sustainable solutions naturally aligns with the principles of biocontrol. By relying on natural enemies of pests - predators, parasitoids, pathogens, and other beneficial organisms - biocontrol offers a way to regulate pest populations without the heavy-handed approach of synthetic chemicals [34].The beauty of integrating biocontrol within IPM lies in its adaptability and precision. Depending on the specific pest problem, ecological conditions, and the crop in question, different biocontrol agents can be introduced or their populations can be augmented. This could mean releasing parasitoid wasps to control moth pests in a vineyard, employing nematodes against soil-borne pests in vegetable crops, or fostering habitats to support native predators like ladybugs in grain fields [35]. Biocontrol complements other IPM strategies. For instance, cultural practices like crop rotation might deter certain pests, but those that persist can then be managed using appropriate biocontrol agents. Similarly, monitoring techniques, another pillar of IPM, can inform the timely release of biocontrol agents, ensuring their maximum impact [36].

Challenges and Limitations of Biocontrol Techniques

While biocontrol is hailed as a beacon of sustainable agriculture, it's not without its set of challenges. These limitations, stemming from ecological complexities to unintended consequences, are integral in understanding and refining the application of biocontrol for future endeavors.

Potential Downsides or Risks of Biocontrol

Biocontrol, although advantageous in many respects, can sometimes backfire or have unintended consequences. One of the significant concerns is the non-target effects, where the introduced biocontrol agents might affect species other than their intended pest targets. A classic example is the introduction of the cane toad in Australia to control the sugar cane beetle. The toads, having no natural predators in the region, proliferated and posed threats to native species, leading to unforeseen ecological issues [37].Another challenge arises from the complex interactions within ecosystems. A biocontrol agent might successfully control a pest, but this could inadvertently lead to the explosion of another pest species, filling the ecological vacuum left by the controlled pest. This phenomenon, termed "secondary pest outbreak," is a potential pitfall of biocontrol [38].Additionally, while biocontrol agents are introduced with the intent of establishing and proliferating, they don't always adapt well to the new environment. Factors like competition with native species, predation, or unfavorable environmental conditions can limit their establishment and effectiveness [39].

Environmental Concerns

While biocontrol offers an environmentally friendlier alternative to chemical pesticides, it isn't entirely devoid of ecological concerns. For instance, there's the risk of biocontrol agents becoming invasive, disrupting native ecosystems. In some cases, the biocontrol agent might compete with native species for resources or directly predate upon them, leading to shifts in biodiversity [40]. The practice of mass-releasing biocontrol agents can sometimes interfere with local ecological relationships. For example, the local predators might start preying more on the released biocontrol agents than on the pests, diluting the effectiveness of the biocontrol strategy [41].

Resistance Development in Pests

Just as pests can develop resistance to chemical pesticides, they can evolve to counteract the threats posed by biocontrol agents. Over time, if a pest population is continually exposed to a biocontrol agent, individuals that possess traits allowing them to evade or resist these agents might have a selective advantage. This could lead to the emergence of pest populations that are less susceptible to the biocontrol agents in question [42].For example, certain pests have developed behavioral adaptations to avoid parasitoids. In some cases, the mere presence of a parasitoid can lead to changes in the feeding, mating, or oviposition behavior of pests, reducing the chances of successful parasitization [43]. Similarly, pests can develop physiological resistances to pathogens introduced for biocontrol, rendering the pathogens less effective over time [44].This resistance development underscores the need for a diversified approach. Relying solely on one biocontrol agent can, over time, diminish its effectiveness. A multipronged strategy, employing a variety of biocontrol agents and methods, can mitigate this risk and ensure sustainable pest control.

Future Directions and Potential

Biocontrol stands at an exciting crossroads where tradition meets innovation. As humanity grapples with food security in the face of a burgeoning population and the exigencies of climate change, biocontrol provides a sustainable approach to pest management. The future of biocontrol promises an amalgamation of classical techniques with the power of cutting-edge science, potentially revolutionizing sustainable agriculture.Biotechnology offers a trove of possibilities for biocontrol. Genetic engineering can augment the efficacy of existing biocontrol agents or facilitate the creation of new ones. For instance, the bacterium *Bacillus thuringiensis* (Bt) has been used for decades as a biopesticide. Genetic engineering has made it possible to introduce genes from Bt into crops, allowing them to produce their own insecticidal proteins and ward off pests [45]. Molecular biology techniques can assist in understanding the genetics and biology of biocontrol agents, making it possible to select strains with greater virulence or better environmental adaptability [46]. There's also the burgeoning field of synthetic biology, which might, in the future, allow scientists to design biocontrol agents tailored for specific pests or environmental conditions. Biotechnological tools can aid in monitoring biocontrol agents. DNA barcoding and genome sequencing can help track and identify strains released into the environment, assess their proliferation, and gauge their interaction with native species [47].

Potential New Biocontrol Agents on the Horizon

Research continually unearths new potential biocontrol agents. Microbes, especially those found in extreme or unique habitats, hold promise. For instance, fungi from deep-sea environments or bacteria from desert ecosystems might possess unique biochemical pathways that can be leveraged for pest control [48]. The realm of RNA interference (RNAi) offers exciting possibilities. This method involves using double-stranded RNA molecules to silence specific genes in pests, thereby causing their death or reducing their virulence. This technology offers specificity, as the designed RNA molecules can target genes exclusive to particular pests, ensuring minimal non-target effects [49].Another area gaining traction is the use of endophytes – microbes that live within plants without causing them harm. Some of these endophytes produce compounds toxic to pests, making plants resistant to certain insects or pathogens. Harnessing these endophytes can provide a new arsenal for biocontrol [50].

Collaboration between Research, Farmers, and Industry for Better Pest Management

For biocontrol to realize its full potential, a holistic approach involving researchers, farmers, and the industry is crucial. Scientists bring to the table the tools and techniques, but the invaluable experience of farmers—who battle pests on the frontline—is essential for crafting pragmatic solutions.Farmers can offer insights into the local pest challenges, the efficacy of different biocontrol agents, and practical constraints. On-the-ground feedback can guide research directions and ensure that the developed solutions are not just theoretically sound but also practically implementable.The industry plays a pivotal role in scaling up these solutions. Through collaborations, innovations in the lab can be transformed into commercially viable products. This requires investments in infrastructure for mass production, formulation, and distribution of biocontrol agents.Further, farmer training and awareness programs, facilitated by both research institutions and industry, can ensure the proper deployment of biocontrol agents, maximizing their efficacy [51].

Case Studies

Biocontrol, with its myriad ecological, economic, and social benefits, has taken root in multiple regions worldwide. India, with its rich agricultural history and diverse ecosystems, has been an active participant in this shift towards sustainable pest management. This juxtaposition of Indian initiatives with international endeavors provides a comprehensive picture of biocontrol's potential and adaptability.

India:

Managing the Papaya Mealybug in Tamil Nadu: In the early 2000s, the papaya mealybug wreaked havoc in Tamil Nadu, attacking not just papaya, but also other crops like eggplant and mulberry. Chemical interventions proved ineffective, prompting the Tamil Nadu Agricultural University to collaborate with international agencies. They introduced a parasitic wasp, *Acerophaguspapayae*, from Puerto Rico. This biocontrol agent effectively curbed the mealybug infestation, saving significant economic losses and demonstrating the power of international cooperation in sustainable agriculture [52].

Trichoderma in Maharashtra: Fungal diseases are a significant concern for many crops in Maharashtra. The introduction of the fungus *Trichoderma* as a biocontrol agent provided an effective solution. *Trichoderma* strains, when applied to the soil, competed with plant-pathogenic fungi, reducing their impact. This biological control measure, coupled with farmer training, led to reduced fungal diseases and minimized the use of chemical fungicides, promoting sustainable farming practices [53].

Abroad:

Biological Control of Water Hyacinth in South Africa: Water hyacinth, an invasive plant species, was choking water bodies in South Africa, affecting both biodiversity and water access. Chemical and manual removal proved expensive and unsustainable. The solution came in the form of two biocontrol agents: the weevil *Neochetinaeichhorniae* and the mite *Orthogalumnaterebrantis*. Their introduction led to a significant reduction in water hyacinth coverage, restoring the health of aquatic ecosystems [54].

Wheat Stem Sawfly in North America: The wheat stem sawfly emerged as a significant pest in the wheat fields of North America. Chemical control was challenging due to the pest's behavior of burrowing inside the wheat stem. The solution came from the parasitic wasp *Braconcephi*. Field studies in Montana demonstrated that areas with the parasitoid presence had significantly reduced sawfly populations, leading to better crop yields and reduced dependency on chemical interventions [55].

Managing Olive Flies in California: California's olive industry faced significant challenges from the olive fruit fly. Traditional chemical control measures were not only environmentally detrimental but also had limited effectiveness due to the fly's behavior. Biocontrol emerged as a solution with the introduction of the parasitoid wasp *Psyttaliahumilis*. Field trials demonstrated the wasp's efficacy in controlling the fly populations, offering a sustainable solution to a pressing agricultural challenge [56].

Conclusion

Biocontrol techniques, employed both in India and globally, underscore a paradigm shift towards sustainable agriculture. By harnessing nature's intrinsic mechanisms, such as predatory wasps in Tamil Nadu or fungi in Maharashtra, these strategies offer effective and environmentally benign solutions to pest challenges. The juxtaposition of Indian endeavors with international initiatives reveals a shared vision for harmonious agriculture that respects ecological balance. Collaborative efforts, integration of traditional knowledge with scientific advancements, and adaptability remain central to this quest. As the world grapples with burgeoning populations and climate change, biocontrol stands as a beacon, promising resilient, productive, and sustainable food systems for the future.

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