Review Article

A review on Role of Beneficial Insects in Sustainable Crop Production Systems

Abstract

Beneficial insects are vital components of sustainable crop production systems, providing key ecosystem services such as biological pest control, pollination, and soil health enhancement. This review explores the diverse roles of beneficial insects, including predators, parasitoids, pollinators, and soil engineers, in promoting sustainable agriculture. Predators and parasitoids regulate pest populations, reducing the need for chemical pesticides, while pollinators, such as bees and butterflies, enhance crop yields and quality through effective pollination. Soil-dwelling insects contribute to nutrient cycling and soil structure, improving plant health and productivity. Despite their numerous benefits, the effective integration of beneficial insects is challenged by knowledge gaps in ecological interactions, high implementation costs, and environmental pressures such as habitat loss and pesticide exposure. Strategies to overcome these challenges include habitat management (e.g., establishing flower strips and hedgerows), conservation biological control, and augmentative releases of natural enemies. Sustainable practices like crop rotation and intercropping can increase habitat heterogeneity, supporting beneficial insect diversity. Should focus on Integrated Pest and Pollinator Management (IPPM) to optimize both pest suppression and pollination services. Advancements in digital technologies, such as remote sensing and precision agriculture, can improve monitoring and deployment strategies for beneficial insects. Supportive policies and educational initiatives are necessary to encourage farmers to adopt insect-friendly practices.

Keywords:*Biological Control, Pollinators, Predatory Insects, Ecosystem Services, Habitat Management*

I. Introduction

A. Sustainable Agriculture

Sustainable agriculture is an approach to farming that seeks to balance productivity, environmental health, and socio-economic viability, ensuring the long-term sustainability of both agricultural and natural ecosystems [1]. It focuses on meeting the needs of the present without compromising the ability of future generations to meet their own needs, emphasizing principles such as resource conservation, soil health, and biodiversity. The global demand for sustainable practices is increasing due to rising concerns about climate change, soil degradation, water scarcity, and the negative impacts of conventional agricultural methods, which often rely heavily on chemical inputs and monocultures.Conventional agricultural systems are characterized by intensive use of chemical fertilizers and pesticides, monoculture practices, and high resource consumption, leading to significant environmental issues such as soil erosion, water pollution, and loss of biodiversity [2]. In contrast, sustainable agriculture promotes the use of ecological principles, including crop diversification, reduced chemical inputs, and integrated pest management (IPM), to create resilient agroecosystems that can sustain long-term productivity. By integrating practices such as crop rotation, conservation tillage, and organic farming, sustainable agriculture not only improves soil health and water use efficiency but also enhances biodiversity, making the entire system more resilient to environmental stressors.One critical aspect of sustainable agriculture is its emphasis on ecosystem services, which include pest regulation, pollination, soil fertility, and water management [3].

B. Role of Beneficial Insects

Beneficial insects play a crucial role in supporting sustainable agriculture by contributing to essential ecosystem services such as pest control, pollination, and soil health enhancement (Fig. 1) and (Table 1). Predatory insects, such as lady beetles (Coccinellidae) and lacewings (Chrysopidae), naturally control pest populations by preying on harmful insects like aphids and caterpillars, reducing the need for chemical pesticides [4]. Parasitoids, including wasps from the families Ichneumonidae and Braconidae, lay their eggs inside or on host insects, ultimately killing them and providing effective biological control. These natural enemies play a pivotal role in Integrated Pest Management (IPM) strategies, where their use minimizes pest outbreaks and enhances crop productivity without the detrimental effects associated with chemical inputs.In addition to pest control, pollinators such as bees (Apidae), butterflies (Lepidoptera), and flies (Syrphidae) are essential for the reproduction of many crops, contributing directly to the quality and quantity of agricultural produce [5]. Approximately 75% of global food crops depend, to varying degrees, on animal pollination, with insect pollinators providing significant economic value estimated at over $235 billion annually. The decline of pollinator populations due to habitat loss, pesticide use, and climate change poses a serious threat to agricultural sustainability and food security, highlighting the need for conservation and management of these insects. Soil-dwelling insects, such as beetles and ants, contribute to soil health by breaking down organic matter, enhancing nutrient cycling, and improving soil structure. These activities increase soil fertility, water retention, and root penetration, promoting healthy crop growth and reducing the need for synthetic fertilizers. By maintaining healthy soil ecosystems, beneficial insects support long-term soil productivity and resilience, which are critical components of sustainable farming systems [6].The integration of beneficial insects into crop production systems not only enhances ecological health but also offers economic benefits.

Table 1: Role of Beneficial Insects in Sustainable Crop Production Systems (Source: [4], [5], [6])

Beneficial Insect	**Role in Crop Production**	**Mechanism of Action**	**Crops Benefited**
Honeybees (*Apis mellifera*)	Pollination	Transfer of pollen from male to female flower parts, aiding fertilization	Fruit crops (apple, almond, strawberry), vegetable crops (cucumber, tomato)
Ladybird Beetles (*Coccinellidae*)	Biological control of aphids and other pests	Predation of soft-bodied insects like aphids, mealybugs, and mites	Wheat, cotton, maize, horticultural crops like peppers and tomatoes
Parasitic Wasps (*Trichogramma spp.*)	Biological control of caterpillar pests	Lays eggs inside pest eggs, leading to parasitism and death of the pest	Corn, sugarcane, vegetables (cabbage, broccoli)
Predatory Mites (*Phytoseiulus persimilis*)	Biological control of spider mites	Predation of spider mites and other small arthropod pests	Ornamental plants, greenhouse crops, strawberries
Ground Beetles (*Carabidae*)	Pest control in soil	Predation of soil-dwelling larvae, slugs, and insect eggs	Corn, potatoes, legumes, and other row crops
Hoverflies (*Syrphidae*)	Biological control of aphids	Larvae feed on aphids, while adults contribute to pollination	Leafy vegetables, fruit crops, oilseeds, and ornamentals
Green Lacewings (*Chrysoperla spp.*)	Biological control of aphids and	Larvae (known as aphid lions) prey on aphids,	Vegetable crops, fruit trees, and cereals

	whiteflies	whiteflies, and thrips	
Spiders (*Araneae*)	Generalist predators of insect pests	Capture and kill various insect pests through web trapping or active hunting	Rice, wheat, maize, cotton, and other field crops
Bumblebees (*Bombus spp.*)	Pollination of flowers, especially in greenhouse systems	Efficient pollination through buzz pollination, where vibrations release pollen	Greenhouse-grown crops like tomatoes, peppers, and blueberries
Ants (*Formicidae*)	Biological control and soil aeration	Predation of pests, enhancement of soil structure through tunneling	Agroforestry systems, orchards, and row crops
Tachinid Flies (*Tachinidae*)	Parasitoids of caterpillar pests	Lay eggs on caterpillars; larvae develop inside and kill the pest	Maize, cotton, fruit trees, and vegetable crops
Nematode-Feeding Insects (e.g., *Steinernema* species)	Biological control of soil nematodes	Parasitize nematodes that harm plant roots	Root crops, potatoes, tomatoes, sugarcane, and ornamentals

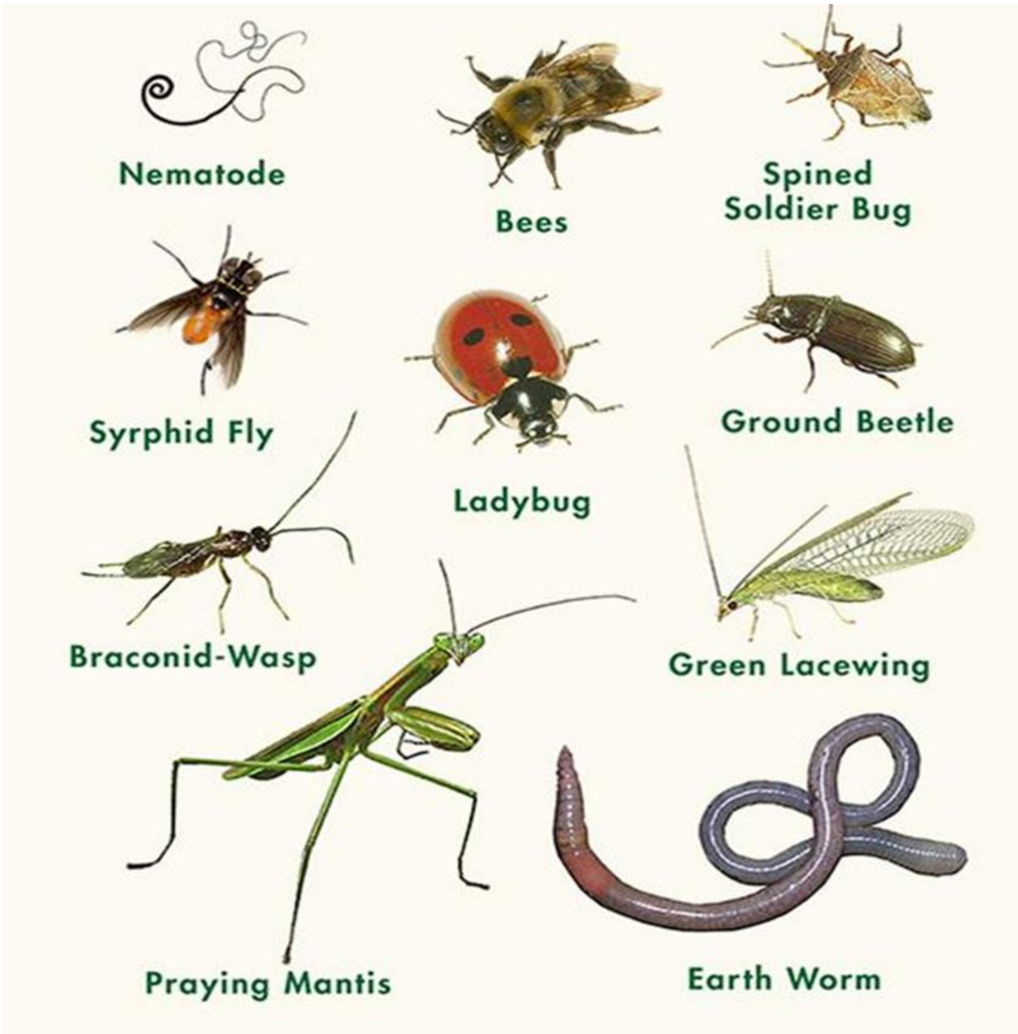

Fig.1: Beneficial Insects

C. Purpose and Scope

The purpose of this review is to highlight the multifaceted roles of beneficial insects in promoting sustainable crop production and to discuss the various strategies for enhancing their populations within agricultural systems. With the growing demand for sustainable practices, understanding the contributions of beneficial insects is crucial for developing agricultural systems that are both productive and environmentally friendly [7]. This review will provide an in-depth analysis of the types of beneficial insects, their specific roles in agroecosystems, and their impact on crop production, focusing on key ecosystem services such as biological pest control, pollination, and soil health.The scope of this paper includes an examination of the ecological and economic benefits of beneficial insects, the challenges associated with their conservation and utilization, and the strategies available to enhance their effectiveness in agricultural landscapes. It will cover the integration of beneficial insects into various sustainable farming practices, such as organic farming, agroforestry, and IPM, as well as future directions for research and policy development to support insect-friendly agricultural practices [8]. By synthesizing recent research and case studies, this review aims to provide comprehensive insights into the potential of beneficial insects to contribute to sustainable agriculture and to offer practical recommendations for farmers, researchers, and policymakers.

II. Types of Beneficial Insects

A. Predators

Predatory insects play a crucial role in natural and agricultural ecosystems by directly reducing pest populations. They actively hunt and consume a wide range of harmful insects, which helps regulate pest density and prevent pest outbreaks [9]. One of the most commonly known groups of predatory insects is the lady beetles (Coccinellidae), which primarily feed on soft-bodied pests such as aphids and scale insects. Similarly, lacewings (Chrysopidae) are effective generalist predators, consuming a variety of agricultural pests, including aphids, mites, and caterpillars, thus contributing to both pest suppression and increased crop yields.Ground beetles (Carabidae) represent another diverse group of predatory insects that are known for their capacity to control soil-dwelling pests like cutworms and root maggots. Ground beetles are particularly valued in integrated pest management (IPM) programs due to their high mobility and their ability to forage both above and below ground [10]. Another significant predator group includes spiders (Araneae), which can reduce pest densities by preying on various insect species across multiple life stages. Spiders are known to be opportunistic feeders, which makes them adaptable to diverse agricultural landscapes, and their presence is often associated with lower pest population levels in both conventional and organic systems.Hoverflies (Syrphidae), although primarily known as pollinators, also exhibit predatory behavior during their larval stage, feeding on aphids, thrips, and small caterpillars, making them effective biological control agents in diverse crop systems. Due to their dual role as both pollinators and predators, they contribute to multiple ecosystem services, enhancing both pest control and crop productivity [11].

B. Parasitoids

Parasitoids are insects whose larvae live as parasites that eventually kill their host. They are among the most effective biological control agents due to their specialized life cycles and host specificity. Parasitoids are primarily represented by various species of wasps and flies. Hymenopteran parasitoids, such as those from the families Ichneumonidae and Braconidae, are well-known for parasitizing a wide range of agricultural pests, including caterpillars, aphids, and beetles. For instance, the braconid wasp *Aphidiuscolemani* is a common parasitoid used in greenhouses to control aphid populations in vegetable crops [12].Tachinid flies (Tachinidae) are another important group of dipteran parasitoids that parasitize a variety of pest insects, including caterpillars and beetles. Tachinid flies are known for their capacity to locate host insects using chemical cues and their ability to parasitize pests in diverse agricultural settings. These parasitoids have been successfully incorporated into pest management programs for several high-value crops, resulting in reduced reliance on chemical insecticides and improved pest suppression.Parasitoids not only help reduce pest populations directly but also induce behavioral changes in their hosts, making them less effective at feeding and reproducing, which further enhances their role in pest management [13]. The high degree of host specificity displayed by many parasitoids makes them valuable allies in targeted pest control programs, minimizing the risk of harming non-target organisms and maintaining ecological balance.

C. Pollinators

Pollinators are vital for the reproduction of many flowering plants, including a large proportion of global food crops. They play a crucial role in enhancing crop quality and yield by facilitating the transfer of pollen, which is essential for fruit set and seed production. The most well-known pollinators are bees, particularly the European honeybee (*Apis mellifera*), which is used globally for the pollination of a wide range of crops such as almonds, apples, and berries [14]. Native bee species, including bumblebees (*Bombus* spp.) and solitary bees (e.g., *Osmia* spp.), are also significant contributors to crop pollination, often providing services that are complementary to those of honeybees.Butterflies and moths (Lepidoptera) are less efficient pollinators compared to bees, but they still play a role in the pollination of several crop and wild plant species, especially those with long-tubed flowers. Their presence contributes to the overall biodiversity and ecological resilience of agroecosystems. Similarly, flies (Diptera), particularly hoverflies (Syrphidae), have been recognized as effective pollinators of many crops, including carrots, onions, and various flowering herbs. Given their adaptability to a wide range of environments, flies can be especially important in landscapes where bee populations are declining [15].

D. Soil Engineers and Decomposers

Soil-dwelling insects, often referred to as soil engineers and decomposers, play a fundamental role in maintaining soil health and fertility by breaking down organic matter and facilitating nutrient cycling. They include beetles (Coleoptera), ants (Formicidae), and termites (Isoptera), all of which contribute to the decomposition of plant residues, the aeration of soil, and the enhancement of soil structure [16]. Dung beetles (Scarabaeidae) are particularly important for breaking down animal feces, which recycles nutrients back into the soil, enhances soil fertility, and reduces the spread of pests and diseases associated with livestock waste.Ants, due to their complex nesting and foraging behaviors, contribute to soil aeration and nutrient distribution, which improves water infiltration and root growth. Their activities help create soil microhabitats that promote microbial activity and the establishment of beneficial soil organisms [17]. Termites, though often considered pests in certain contexts, are key decomposers in many tropical and subtropical ecosystems, contributing significantly to the breakdown of tough plant materials such as cellulose, thereby enhancing soil organic matter content.The presence of soil-dwelling insects promotes a healthy soil ecosystem, which is essential for sustainable crop production. By improving soil structure and nutrient availability, these insects support plant growth and reduce the need for synthetic fertilizers, aligning with the goals of sustainable agriculture. Their role in enhancing soil health makes them critical components of agroecosystems, contributing to both short-term productivity and long-term sustainability [18].

III. Benefits of Beneficial Insects

A. Reduced Chemical Use

The presence of beneficial insects, such as predators, parasitoids, and pollinators, significantly reduces the reliance on chemical inputs in agriculture, particularly pesticides, which are commonly used for pest control. By preying on or parasitizing harmful pests, these insects naturally suppress pest populations, providing a sustainable alternative to chemical pest management strategies. For example, lady beetles (Coccinellidae), lacewings (Chrysopidae), and predatory beetles (Carabidae) have been shown to control populations of aphids, mites, and caterpillars, leading to a reduced need for insecticides. Similarly, parasitoid wasps such as *Aphidiuscolemani* are extensively used in greenhouses to manage aphid infestations, effectively reducing chemical applications and associated costs [19].The adoption of biological control through beneficial insects can significantly decrease the environmental and health impacts of conventional pesticide use. Pesticides can have unintended effects on non-target species, including beneficial insects, soil organisms, and human health. By implementing natural pest control strategies, farmers can reduce the negative side effects associated with pesticide overuse, such as pest resistance, loss of biodiversity, and contamination of water and soil resources. Studies show that in farms practicing biological control, pesticide use is typically reduced by 50–75% without compromising crop yields [20]. This reduction not only mitigates the risk of pesticide residues in food but also supports healthier agroecosystems that are more resilient to pest outbreaks. The presence of pollinators such as bees and butterflies can indirectly reduce the need for chemical inputs by promoting plant health and vigor, making plants less susceptible to diseases and pests. Enhanced pollination leads to more robust plant growth and improved resilience against biotic and abiotic stressors, further contributing to reduced dependency on chemical treatments. In vineyards, for instance, the introduction of flowering cover crops to attract pollinators and natural enemies has been shown to decrease the incidence of vine diseases and pest infestations, thereby lowering fungicide and insecticide applications [21].

B. Increased Yields and Quality

Beneficial insects, especially pollinators and natural enemies of pests, have a direct and measurable impact on crop yields and quality. Pollinators such as bees, butterflies, and hoverflies are responsible for the pollination of approximately 75% of globally important food crops, contributing significantly to the quantity and quality of fruits, vegetables, and nuts. Studies indicate that crops such as almonds, apples, and blueberries exhibit increased fruit set and improved quality when pollinated by a diverse community of wild and managed pollinators [22]. For instance, diverse pollinator communities have been associated with a 24% increase in fruit set in crops like watermelon and tomatoes, compared to reliance on a single pollinator species.Pollination by insects not only boosts yield but also enhances crop quality attributes such as fruit size, weight, and nutritional content [23]. For example, strawberries pollinated by a combination of honeybees and wild bees have been shown to have larger fruits with fewer deformities and a higher sugar content compared to those pollinated by honeybees alone. This improvement in quality can lead to higher market prices and greater economic returns for farmers. Additionally, the presence of beneficial insects such as predatory beetles and parasitoid wasps can reduce the damage caused by pests, leading to higher-quality produce with fewer blemishes and pest-induced deformities.The role of beneficial insects in biological pest control further contributes to yield stability and crop quality by preventing pest outbreaks that could otherwise devastate crops [24]. By keeping pest populations below economic thresholds, these insects help maintain consistent yields, even under conditions that would otherwise favor pest proliferation. This stability is particularly important in organic and low-input farming systems, where chemical interventions are limited. Soil-dwelling insects such as decomposers and soil engineers contribute to increased crop yields by enhancing soil fertility and promoting healthy root growth. The activities of dung beetles, ants, and other soil fauna improve nutrient availability and soil structure, which in turn supports healthier plant development and increased crop productivity. In maize fields, for example, the presence of soil-dwelling insects has been associated with a 10-15% increase in yields due to improved soil aeration and nutrient cycling [25].

C. Agroecosystem Stability

The presence of a diverse community of beneficial insects contributes to the overall stability and resilience of agroecosystems. By providing multiple ecosystem services, such as pest control, pollination, and soil health maintenance, beneficial insects enhance the complexity and functionality of agricultural landscapes, making them less vulnerable to disturbances such as pest outbreaks and environmental stressors. For example, farms with a high diversity of natural enemies, such as predatory beetles and parasitoid wasps, have been shown to experience fewer pest outbreaks and more consistent pest suppression compared to farms relying solely on chemical control [26].Diverse insect communities also contribute to agroecosystem stability by promoting functional redundancy, where multiple species perform similar roles within the ecosystem. This redundancy ensures that if one species is lost or its population declines, others can continue to provide critical ecosystem services, thereby maintaining system stability. In the context of climate change, which is expected to increase the frequency and intensity of environmental stressors, such as extreme weather events and pest outbreaks, the presence of diverse insect communities can buffer against these changes and help maintain agricultural productivity [27], [28].

IV. Strategies to Enhance Beneficial Insects

A. Habitat Management

Habitat management is a key strategy for enhancing the populations of beneficial insects by creating or restoring habitats that provide food, shelter, and breeding sites. It involves modifying agricultural landscapes to include diverse vegetation structures, such as hedgerows, flower strips, and cover crops, which increase habitat heterogeneity and resource availability. These habitats act as refuges for beneficial insects, such as predatory beetles, parasitoid wasps, and pollinators, providing them with alternative prey, nectar, pollen, and overwintering sites, thus supporting their survival and reproductive success.Field margins and hedgerows, for instance, serve as corridors that connect different habitats, facilitating movement and dispersal of beneficial insects across agricultural landscapes [29]. Studies show that farms with well-managed field margins have higher densities of natural enemies, which in turn results in better pest control and reduced reliance on chemical pesticides. For example, in vineyards, the establishment of flowering cover crops within rows has been shown to attract natural enemies, such as predatory mites and parasitic wasps, reducing the incidence of pests like grape leafhoppers and spider mites.Flower strips, which are composed of native flowering plants, provide a continuous supply of nectar and pollen, critical resources for pollinators and natural enemies throughout the growing season [30]. These strips are effective in increasing the abundance and diversity of beneficial insects, including hoverflies (Syrphidae), predatory beetles (Carabidae), and bees (Apidae). For example, incorporating wildflower strips along crop borders has been shown to enhance biological control of aphids in cereal fields by promoting higher populations of hoverflies and lady beetles, leading to reduced aphid infestations. Cover crops, such as clover and vetch, can be used as living mulches that improve soil health and provide habitat for ground-dwelling predators like spiders and ground beetles. These cover crops also contribute to weed suppression, moisture retention, and nitrogen fixation, creating a more favorable environment for crop growth while simultaneously supporting beneficial insect populations [31]. Effective habitat management requires careful planning and selection of plant species to ensure continuous availability of floral and structural resources that meet the needs of diverse beneficial insect communities.

B. Conservation Control

Conservation biological control focuses on preserving and enhancing the effectiveness of naturally occurring beneficial insects by modifying agricultural practices to minimize disturbances and provide a supportive environment. This approach involves reducing the use of broad-spectrum pesticides, implementing selective pesticide regimes, and adopting agricultural practices that conserve natural enemy populations. Pesticides, particularly insecticides, are a major threat to beneficial insects, as they can directly kill natural enemies or disrupt their behaviors and reproductive success [32]. Selective pesticide use, such as employing insect growth regulators or microbial pesticides, can minimize these negative effects, allowing beneficial insect populations to thrive while still controlling target pests.Conservation control also includes the provision of resources such as food and shelter to support beneficial insects during critical periods. For instance, providing supplemental nectar sources in the form of flowering plants or sugar sprays can enhance the survival and fecundity of parasitoid wasps, leading to improved biological control [33]. The use of artificial shelters, such as beetle banks and insect hotels, can provide overwintering sites for predatory beetles, spiders, and other natural enemies, thereby boosting their populations early in the growing season. These strategies are particularly useful in monoculture systems where habitat complexity is low, as they help mitigate the adverse effects of habitat simplification on beneficial insect communities.Another conservation control strategy is the practice of trap cropping, which involves planting a less valuable crop species that attracts pests away from the main crop. Trap crops can serve as reservoirs for beneficial insects by concentrating pest populations in a limited area, making it easier for natural enemies to locate and attack the pests [34]. This technique has been successfully used in various cropping systems, such as using alfalfa as a trap crop in cotton fields to manage lygus bugs, thereby enhancing the effectiveness of natural enemies and reducing the need for insecticides.

C. Augmentative Control

Augmentative biological control involves the supplemental release of natural enemies, either through inoculative or inundative methods, to control pest populations. Inoculative releases introduce small numbers of beneficial insects early in the season to establish a population that can provide long-term pest control, whereas inundative releases involve large-scale releases to achieve immediate suppression of a target pest. This approach is commonly used in greenhouse systems and high-value crops, where natural enemy populations may not establish or persist due to environmental conditions or seasonal limitations [35].Augmentative releases of predatory insects, such as lady beetles (*Hippodamia convergens*) and lacewings (*Chrysoperlacarnea*), have been used successfully in controlling aphids, thrips, and whiteflies in various horticultural crops. Similarly, parasitoids like *Trichogramma* spp. are widely released to control lepidopteran pests, including the European corn borer in maize and the codling moth in apple orchards. Inundative releases of *Trichogramma* wasps have shown to be effective in reducing the need for insecticides, with some studies reporting up to a 60% decrease in chemical applications.One of the main challenges of augmentative control is the high cost and variability in success rates, which can be influenced by factors such as weather, crop phenology, and the presence of hyperparasitoids [36]. To address these issues, recent advances in mass-rearing techniques, the development of resistant natural enemy strains, and improved release strategies have been implemented to enhance the effectiveness and affordability of augmentative biological control. For example, the use of banker plants in greenhouses, which serve as a habitat for alternative hosts or prey, has been shown to improve the establishment and persistence of released parasitoids and predators.

D. Crop Rotation and Intercropping

Crop rotation and intercropping are cultural practices that enhance the diversity and abundance of beneficial insects by creating a heterogeneous environment with varied plant resources. Crop rotation disrupts the life cycles of pest species by alternating host crops, making it more difficult for pests to locate suitable habitats and reducing their population buildup [37]. This disruption benefits natural enemies by creating a more stable environment with fewer pest outbreaks, allowing beneficial insects to establish and persist over time.Intercropping, the practice of growing two or more crop species together, provides a complex habitat that supports a wider range of natural enemies and enhances pest control through mechanisms such as habitat diversification and resource partitioning. For example, intercropping maize with legumes has been shown to attract higher numbers of predatory beetles and parasitoids, leading to reduced damage by stemborers and other pests [38]. Similarly, the use of flowering intercrops, such as mustard or buckwheat, in fruit orchards has been demonstrated to increase the abundance of pollinators and parasitoids, resulting in enhanced pollination and improved pest control.The benefits of crop rotation and intercropping are particularly pronounced in organic and low-input farming systems, where chemical control options are limited. By increasing plant diversity, these practices provide continuous resources for beneficial insects, such as nectar, pollen, and alternative prey, throughout the growing season. This enhances the stability of beneficial insect populations and contributes to more resilient and productive agricultural systems [39].

V. Challenges and Limitations

A. Knowledge Gaps

Despite the growing understanding of the role of beneficial insects in sustainable agriculture, significant knowledge gaps persist, limiting their effective utilization in crop production systems. One major gap is the limited understanding of the complex interactions between beneficial insects, pests, and crop plants within diversified agricultural landscapes. Beneficial insects operate within intricate ecological networks, and factors such as landscape composition, plant diversity, and non-crop habitats can influence their effectiveness as biological control agents or pollinators. The lack of comprehensive data on these multi-trophic interactions and how they vary across different environmental and management conditions hampers the ability to optimize the use of beneficial insects [40]. There is insufficient research on the behavioral ecology of many beneficial insects, particularly in large-scale monoculture systems. For instance, while the role of certain predators and parasitoids in small-scale experiments is well documented, their behavior and effectiveness in extensive agricultural landscapes remain poorly understood. The impact of agricultural practices, such as tillage and pesticide application, on the survival and dispersal of beneficial insects is also not fully quantified [41]. This gap in knowledge makes it difficult to develop practical guidelines for integrating beneficial insects into conventional farming systems effectively. The effectiveness of beneficial insects can be influenced by climate change, yet research on how shifting temperatures, altered precipitation patterns, and extreme weather events affect insect-mediated ecosystem services is still in its infancy. Understanding how climate change may alter the phenology, distribution, and interactions of beneficial insects with pests and plants is crucial for developing resilient pest management and pollination strategies. Addressing these knowledge gaps requires interdisciplinary research that integrates entomology, ecology, and agronomy to provide a holistic understanding of beneficial insects' roles in complex agroecosystems [42].

B. Economic Constraints

Economic constraints are a significant barrier to the widespread adoption of practices that promote beneficial insects. While the use of natural enemies and pollinators can reduce long-term production costs by minimizing chemical inputs and enhancing crop yields, the initial costs associated with implementing such strategies can be prohibitively high for many farmers. For example, the establishment of habitat management practices such as flower strips, beetle banks, or hedgerows requires upfront investment in planting, maintenance, and land that might otherwise be used for crop production [43]. Small-scale farmers, in particular, may lack the financial resources to implement these practices or to absorb potential short-term losses associated with transitioning to insect-friendly management systems.The cost of augmentative biological control, which involves purchasing and releasing natural enemies, can also be a limiting factor. Many commercially available biocontrol agents, such as predatory mites or parasitoid wasps, are expensive and may require repeated applications to achieve effective control. Additionally, the economic benefits of using these agents are often not immediate, which can deter farmers from adopting such strategies, especially in the absence of subsidies or financial incentives [44]. In cases where biocontrol agents fail to establish or provide inconsistent control due to environmental or management factors, the cost-effectiveness of these approaches becomes questionable. The economic valuation of ecosystem services provided by beneficial insects, such as natural pest control and pollination, is often underestimated. This underestimation leads to a lack of market-based incentives for farmers to invest in practices that conserve beneficial insects. Developing reliable economic models that quantify the benefits of these ecosystem services in terms of yield, quality, and reduced input costs is essential for promoting the adoption of sustainable agricultural practices that incorporate beneficial insects [45].

C. Environmental Factors

Environmental factors such as habitat fragmentation, land-use change, and pesticide exposure pose significant challenges to the conservation and effectiveness of beneficial insects. The conversion of natural habitats into agricultural land reduces the availability of resources and nesting sites for beneficial insects, leading to population declines and loss of biodiversity. Fragmented landscapes with limited habitat connectivity can hinder the dispersal and colonization of natural enemies and pollinators, reducing their ability to provide ecosystem services. For instance, research has shown that in highly fragmented agricultural landscapes, natural enemy populations are less effective at controlling pests due to reduced movement between habitat patches [46].Pesticide exposure is another major threat to beneficial insects. Even when used at sublethal levels, pesticides can negatively impact the behavior, reproduction, and longevity of pollinators and natural enemies, undermining their role in pest control and pollination. The widespread use of neonicotinoids, for example, has been linked to declines in bee populations and disruption of beneficial insect communities. Furthermore, the use of herbicides can reduce floral resources and habitat quality for pollinators and other beneficial insects, exacerbating their decline.Climate change also poses a significant environmental challenge by altering the distribution and life cycles of both pests and their natural enemies [47]. Shifts in temperature and precipitation patterns can disrupt the synchrony between crops, pests, and beneficial insects, potentially leading to mismatches that reduce the effectiveness of biological control and pollination. Addressing these environmental factors requires a landscape-scale approach that includes habitat restoration, pesticide regulation, and climate-adaptive management practices.

VI. Future

A. Integrated Pest and Pollinator Management

Integrated Pest and Pollinator Management (IPPM) is a holistic approach that combines pest management and pollinator conservation strategies to optimize crop production while maintaining ecological balance [48]. IPPM integrates various control methods, including biological control, habitat management, and selective pesticide use, to create an environment where both natural enemies and pollinators can coexist and thrive. This approach emphasizes the use of non-chemical pest control techniques, such as trap cropping and the promotion of natural enemy habitats, to reduce pesticide use and minimize harm to pollinators.One promising strategy within IPPM is the use of floral resource strips that provide both nectar and pollen for pollinators and alternative prey for natural enemies. Such strips enhance the abundance and diversity of beneficial insects, leading to improved pollination and more effective pest control. Additionally, IPPM advocates for the timing of pesticide applications to avoid periods of high pollinator activity and the use of selective pesticides that are less toxic to beneficial insects [49]. By integrating pest and pollinator management, IPPM provides a framework for achieving both yield stability and biodiversity conservation.

B. Innovative Technologies

The development of innovative technologies offers new opportunities to enhance the effectiveness of beneficial insects in agricultural systems. Advances in molecular biology, such as genetic engineering and CRISPR technology, could potentially be used to improve the traits of beneficial insects, making them more resistant to environmental stressors or more effective at locating and attacking pests. For example, the release of genetically modified parasitoids that are more efficient at targeting specific pests could revolutionize biological control practices.Digital tools, such as precision agriculture technologies, are also transforming the way beneficial insects are managed [50]. Remote sensing, geographic information systems (GIS), and machine learning can be used to monitor pest and beneficial insect populations in real-time, allowing for more targeted and efficient deployment of biological control agents. Drones equipped with multispectral cameras can identify areas of high pest pressure or locate beneficial insect habitats, enabling precision management that maximizes the impact of natural enemies.

C. Policy and Education

Effective policies and educational programs are essential for promoting the adoption of strategies that support beneficial insects. Policies that provide financial incentives for habitat conservation, such as subsidies for establishing flower strips or hedgerows, can encourage farmers to invest in practices that enhance beneficial insect populations [51]. Additionally, regulations that restrict the use of harmful pesticides, especially during critical periods of insect activity, can mitigate the negative impacts of chemical inputs on beneficial insects.Educational programs targeting farmers, extension agents, and the general public are crucial for raising awareness about the importance of beneficial insects and the best practices for their conservation. Training programs that demonstrate the economic and ecological benefits of integrating beneficial insects into crop production can facilitate wider adoption of sustainable practices. By combining policy support with effective education and outreach, it is possible to create a cultural shift towards farming practices that prioritize the conservation of beneficial insects and the ecosystem services they provide [52].

VII. Conclusion

Beneficial insects play a pivotal role in enhancing the sustainability of crop production systems by providing essential ecosystem services such as pest control, pollination, and soil health maintenance. However, their effective use is hindered by knowledge gaps, economic constraints, and environmental factors like habitat loss and pesticide exposure. Addressing these challenges requires a multi-faceted approach that includes habitat management, conservation control, augmentative releases, and diversification practices like crop rotation and intercropping. Future directions should focus on integrating pest and pollinator management, leveraging innovative technologies for monitoring and control, and implementing supportive policies and education to promote widespread adoption. By fostering conditions that support beneficial insects, it is possible to achieve more resilient and productive agricultural systems, contributing to both ecological health and sustainable food production.

Disclaimer (Artificial intelligence)

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

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