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Beyond Lethality: Exploring Sublethal Effects of Pesticides on Insect Behavior and Their Ecological Ramifications: A Review Analysis

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Abstract: Pesticides are widely used in modern agriculture to increase their yield, which has sparked worries about how they may affect insect biodiversity and ecosystem services. To thoroughly evaluate the impacts of pesticides on insect populations and the broader implications for ecosystem functioning, this review article reviews the body of available literature. The review emphasizes the effects of pesticides on insect biodiversity, both directly and indirectly, including alterations in population dynamics, genetic diversity, and species composition. It also looks at how beneficial insects like pollinators, predators, and parasitoids are affected, as well as how important those insects are for pollination and pest control in the natural world. The review also covers the trophic cascades, changes in community makeup, and disturbances in ecosystem processes that result from pesticide use. In addition, the evolution of pesticide resistance in insects is highlighted, highlighting the difficulties in developing pest management solutions. The need for policy and regulation to ensure sustainable pest control practices is also emphasized, along with alternative and mitigation techniques including integrated pest management and eco-friendly alternatives. This review, which synthesizes current knowledge, sheds light on the intricate relationships between pesticides, insect biodiversity, and ecosystem services and emphasizes the need for balanced strategies that limit damage to beneficial insects while preserving agricultural productivity and the environment.

Keywords: Biodiversity, Pollinators, Ecosystem services, Predators, Parasitoids

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1. Introduction

Pesticides have become an essential aspect of modern agricultural practices, aiding in the control of pests that can have a considerable impact on crop yield and quality. However, there have been questions raised over the unexpected effects of using pesticides on non-target animals, particularly insects, which are crucial to the health of ecosystems and offer crucial ecosystem services (Jepson, 2007; Goulson *et al*., 2015). For sustainable agricultural practices and environmental protection, it is essential to comprehend how pesticides affect insect biodiversity and ecosystem services.

According to Stork (2018), there are 5 to 10 million species of insects, making them the most diverse group of animals on the planet. Pollination, natural pest control, nitrogen cycling, and decomposition are just a few of the ecological functions they carry out (Losey and Vaughan, 2006). The reproduction of flowering plants, including many food crops, depends on pollinators like bees, butterflies, and flies (Potts *et al*., 2010). Agriculture pest populations can be reduced by parasitoids like predatory insects such as ladybirds and lacewings (Letourneau and Bothwell, 2008). Additionally, insects boost ecosystem productivity by aiding in the decomposition of organic matter and nutrient-cycling activities (Swift *et al*., 2004).

Pesticides have a broad impact on insect biodiversity. According to Pisa *et al.* (2015), direct toxicity from pesticide exposure can cause insect mortality and population reduction. Pesticides can also have sublethal effects on insects, which can further skew population dynamics and interspecies interactions by changing insect behavior, reproduction, development, and immunological function (Desneux *et al*., 2007; Rundlöf *et al.,* 2015). Further endangering ecosystem services are herbicides' off-target impacts on beneficial insects. According to Goulson *et al*. (2015), the loss of pollinators brought on by pesticide exposure, for instance, may endanger crop pollination and consequent food production. Similarly to this, natural enemies' vulnerability to pesticides, such as predators and parasitoids, can undermine biological control systems and exacerbate pest outbreaks (Romeis *et al*., 2008).

The detrimental effects of pesticides on insect biodiversity and ecosystem services have been shown in numerous studies. As an illustration, Goulson *et al*.'s (2015) meta-analysis showed that neonicotinoid insecticides can affect pollinators, resulting in decreased pollination and crop production. In a similar vein, research has revealed the negative effects of organophosphate and pyrethroid pesticides on natural enemies, resulting in reduced pest suppression and increasing pesticide dependence (Desneux *et al*., 2007; *Zhang et al*., 2017). Effective pest management tactics are further hampered by the emergence of insect pesticide resistance (Li *et al*., 2017).

Although the detrimental effects of pesticides on insects and ecosystem services are widely known, a growing body of research is looking into alternative pest management techniques and mitigation methods. To preserve insect biodiversity and lessen negative effects on the ecosystem,

Table 1: Effects of Pesticides on Insects and Ecosystem Services

Aspect	Effects
Insect Biodiversity	Direct toxicity causes mortality and population reduction. Sublethal effects on behavior, reproduction, development, and immunological function.
Pollination	Decreased pollination and crop production due to pesticide exposure.
Natural Pest Control	Negative effects on natural enemies (predators and parasitoids), reducing pest suppression.
Nutrient Cycling and Decomposition	Potential impact on ecosystem productivity and nutrient cycling activities.
Pesticide Resistance	The emergence of pesticide-resistant insect populations, hampering pest management strategies.

Integrated Pest Management (IPM) systems, which incorporate several pest control strategies while using few pesticides, have demonstrated encouraging results (Pretty, 2018). Additionally, the promotion of agroecological practices that increase habitat variety and the use of biopesticides generated from natural sources have been promoted as sustainable alternatives to conventional pesticide use (Isman, 2006; Batáry *et al*., 2015).

1.1. Important Ecosystem Services Provided by Insect Biodiversity

The most diverse group of creatures on Earth, insects make up a sizeable amount of the world's biodiversity (Stork, 2018). Through their numerous ecological interactions and supply of vital ecosystem services, they play significant roles in preserving the health and functionality of ecosystems. Promoting ecological balance and long-term environmental management requires an understanding of the value of insect variety and the services they provide.

1.1.1. Pollination Services: According to Potts *et al*. (2010), bees, butterflies, and flies are the primary pollinators that enable flowering plants, including many economically significant crops, to reproduce. They make it easier for pollen to spread, enabling fertilization and the subsequent development of fruit and seeds. Insect pollinators are crucial for ensuring the security of the world's food supply because about 75% of food crops depend, at least in part, on animal pollination (Klein *et al*., 2007). Insect pollination also helps to preserve biodiversity and wild plant communities (Ollerton *et al*., 2011).

1.1.2. Natural Pest Control: By serving as predators, parasitoids, and insect diseases, insects offer beneficial natural pest control services. Herbivorous insects are preyed upon by predatory insects like ladybirds, lacewings, and ground beetles, which help to control their populations and lessen crop damage (Letourneau and Bothwell, 2008). Pests are subject to biological control by parasitoids like wasps, which deposit their eggs inside or on the bodies of other insects and eventually kill them (Rosenheim *et al.*, 1995). The control of insect populations by these natural enemies helps to promote sustainable pest management by lowering the demand for chemical pesticides.

1.1.3. Nutrient Cycling and Decomposition: Insects play a key role in the breakdown of organic matter and the recycling of nutrients back into the ecosystem. They contribute to nutrient cycling and decomposition processes. Detritivores, such as termites and dung beetles (*Phanaeus vindex*), hasten the decomposition of dead plants and animals and the release of nutrients (Swift *et al*., 2004). Insects may change the decomposition through a variety of mechanisms, including direct ingestion and digestion, substrate alteration (such as fragmentation and tunnelling), and interactions with bacteria, fungi, and other saproxylic organisms (Ulyshen, 2016, Andringa *et al.,* 2019). Additionally, by stimulating the release of nutrients immobilised in fungal tissues and by speeding up N fixation, wood-dwelling insects can influence nitrogen (N) dynamics in decomposing wood (Ulyshen, 2015). This procedure is necessary for nutrient availability and soil fertility, which supports plant growth and ecosystem productivity.

1.1.4. Markers of Ecosystem Health: Insects are useful markers of environmental change and ecosystem health. Their interactions with other organisms, species makeup, and population dynamics can all provide insight into the general health of an ecosystem. For instance, decreases in particular insect species, such as bees and butterflies, may be a sign of pesticide exposure, habitat degradation, or other environmental stressors (Goulson *et al.*, 2015). Monitoring insect populations can assist in direct conservation efforts and reveal important information about the health of ecosystems.

1.2. Pesticides and their Utilization

Pesticides are chemicals created with the specific purpose of eradicating or controlling pests, such as weeds, insects, and plant diseases. They are essential to current farming and pest control techniques, helping to safeguard crops, boost yields, and guarantee food security. However, due to its possible effects on the environment, non-target creatures, and human health, pesticide use should be done with prudence (Blair, 2015).

1.2.1. Types of Pesticides Pesticides can be categorized into a variety of groups according to the pests they are meant to control and their chemical composition:

a. Insecticides: These chemicals are made to reduce or get rid of pest insects. Organophosphates, pyrethroids, neonicotinoids, and carbamates are a few examples of them (Sparks, 2013).

b. Herbicides: Unwanted weeds and plants are controlled or eliminated with herbicides. Depending on their capacity to target particular plant species, they can either be selective or non-selective (Grossmann and Sandmann, 2012).

c. Fungicides: To prevent or treat fungal diseases in crops, fungicides are used. Triazoles, strobilurins, and benzimidazoles are only a few examples of the various chemical families that they may contain

Table 2: Types of Pesticides

Category	Purpose	Examples
Insecticides	Control or eliminate pest insects	Organophosphates, Pyrethroids, Neonicotinoids, Carbamates
Herbicides	Control or eliminate weeds and plants	Selective: Glyphosate, 2,4-D, dicamba, Non-selective: Paraquat, Glufosinate
Fungicides	Prevent or treat fungal diseases in crops	Triazoles, Strobilurins, Benzimidazoles
Rodenticides	Manage rodent populations	Anticoagulant: Brodifacoum, Bromadiolone, Non-anticoagulant: Zinc phosphide, Bromethalin

(Haas *et al*., 2013).

d. Rodenticides: Rodenticides are used to manage rodent populations and stop the spread of disease or property damage. Both anticoagulant and non-anticoagulant substances may be present (Buckle, 2004).

1.2.2. Use of Pesticides: Depending on the target pest, crop type, and agricultural practices, pesticides are sprayed using a variety of ways and procedures. Typical usage techniques include:

a. Foliar Sprays: Pesticides are sprayed directly onto the foliage of plants, allowing the active ingredients to come into contact with the target pests (McGregor *et al*., 2002).

b. Seed Treatment: Pesticides are applied to seeds before planting, providing protection against pests during germination and early growth stages (Stevens and Price, 2000).

c. Soil Application: Pesticides are incorporated into the soil, either as granules or liquids, to control pests in the root zone or target soil-dwelling organisms (Agrios, 2005).

d. Fumigation: Gaseous pesticides, such as methyl bromide, are used to treat soil or enclosed spaces to control pests (Noling, 2002).

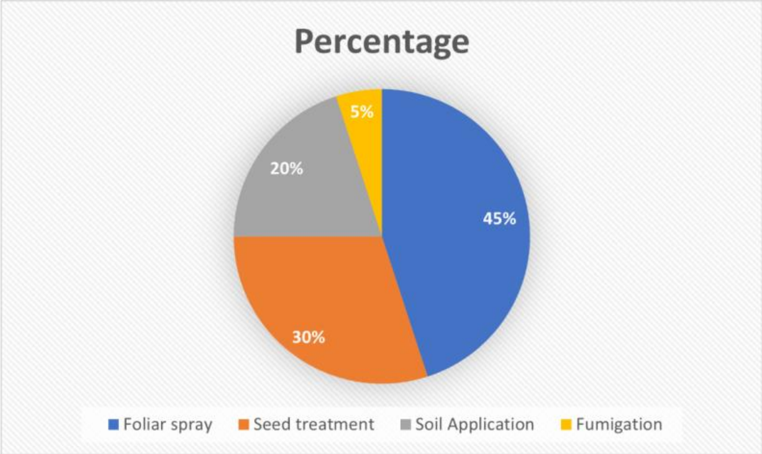

Fig 1: Methods of pesticide applications

1.2.3. Factors Influencing Pesticide Utilization: Several factors influence the utilization of pesticides, including:

a. Pest Pressure: The severity and type of pest infestations affect the decision to use pesticides and the choice of specific products (Zhang *et al.*, 2020).

b. Crop Type: Different crops may require specific pesticides or application techniques based on their susceptibility to pests and diseases (Matthiessen and Shackleton, 2005).

c. Regulatory Requirements: Pesticide usage is regulated by governmental authorities to ensure safety, proper handling, and environmental protection (European Commission, 2019).

d. Integrated Pest Management (IPM): The adoption of IPM practices, which combine multiple pest control strategies and minimize pesticide use, is encouraged to promote sustainable agriculture (Pretty, 2018).

1.2.4. Environmental and Health Considerations: Pesticides are useful for controlling pests, but their use raises questions about potential hazards to human health and the environment. According to research by Goulson *et al*. (2015) and Pimentel (2005), pesticides can contaminate soil, water, and non-target creatures, including beneficial insects and wildlife. According to Damalas and Eleftherohorinos (2011), prolonged exposure to several pesticides has been linked to harmful health effects in people, such as an increased risk of cancer, neurotoxicity, and reproductive abnormalities.

1.3. Pesticide Exposure and Effects on Insect Biodiversity

Pesticides are essential for keeping pests under control and safeguarding crop yields. Although pesticides are widely used, there are worries about their possible detrimental impacts on insect biodiversity, which is crucial for the health and functioning of ecosystems.

Insect Direct Toxicity: Through their acute toxicity, pesticides can have a direct impact on insect populations. By interfering with their neurological systems, insects are targeted and killed by insecticides including organophosphates, pyrethroids, and neonicotinoids (Desneux *et al.*, 2007). However, these chemicals can also damage non-target insect species, such as helpful insects like pollinators and natural pest adversaries (Pisa *et al.*, 2015).

1.3.1. Indirect Effects on Food Supplies: By limiting the availability of food supplies, pesticides might harm the biodiversity of insects. For example, nectar and pollen from flowering plants are the only sources of food for insect pollinators. Pollinators may consume pesticide residues found in these floral resources, which could diminish their foraging effectiveness, navigational skills, and reproductive success (Stanley *et al*., 2016). The dynamics of the ecosystem and insect populations may be affected in a cascading manner by this interruption in the availability of food sources.

1.3.2. Disruption of Insect Communication and Behaviour: Pesticides can disrupt insect behaviour and communication, which has detrimental effects on the insects' ability to survive and reproduce. For instance, neonicotinoid insecticides have been proven to reduce bees' capacity to navigate and return to their hives, which has an effect on their ability to forage and the survival of the colony (Henry *et al*., 2012). The mating habits and reproductive success of insects can also be impacted by sublethal pesticide exposure, potentially causing population decreases (Cresswell, 2011).

1.3.3. Habitat Loss and Fragmentation: Pesticides can exacerbate the reduction in insect biodiversity by causing habitat loss and fragmentation. Natural habitats including hedgerows, field margins, and wetlands that serve as key resources and havens for insects may be destroyed as a result of the usage of pesticides in agricultural landscapes (Kleijn *et al*., 2006). Insect populations can become isolated due to habitat fragmentation, which decreases genetic diversity and makes them more susceptible to outside stresses (Tscharntke *et al*., 2012).

1.3.4. Interactive Effects with Other Stressors: Pesticides can interact with other stressors, such as habitat degradation, climate change, and invasive species, amplifying the negative effects on insect biodiversity. For example, the combination of pesticide exposure and habitat loss can have synergistic effects on pollinator populations, leading to declines and local extinctions (Goulson *et al*., 2015). These interactive effects highlight the complex nature of pesticide impacts on insect biodiversity and the importance of considering multiple stressors in conservation efforts.

1.4. Ecological Consequences of Pesticide Use

Pesticide use has significant ecological consequences, as these chemicals can impact various components of ecosystems, including non-target organisms, food webs, and ecosystem services.

1.4.1. Non-target Organisms: Pesticides, especially insecticides, can harm non-target organisms, including beneficial insects, birds, mammals, and aquatic organisms. For example, neonicotinoid insecticides have been associated with declines in pollinators, such as bees and butterflies, which play a vital role in plant reproduction and ecosystem functioning (Rundlöf *et al.*, 2015). Similarly, the use of herbicides can result in the loss of plant diversity and affect herbivorous insects and other organisms that rely on specific plant species for food and habitat (Gaba *et al*., 2014).

1.4.2. Disruption of Food Webs: Pesticides can disrupt food webs by altering the abundance and composition of species at different trophic levels. The elimination of pest species through pesticide use can indirectly impact higher trophic levels, such as predators and their prey. For example, the decline of insect prey due to insecticide use can negatively affect insectivorous birds and other predators, leading to cascading effects on ecosystem dynamics (Mineau and Whiteside, 2013).

1.4.3. Effects on Aquatic Ecosystems: Pesticides can contaminate water bodies through runoff from agricultural fields and other application sites, leading to adverse effects on aquatic ecosystems. Aquatic organisms, including fish, amphibians, and invertebrates, are particularly vulnerable to pesticide exposure. Pesticides can impair their growth, reproduction, behavior, and survival (Stehle and Schulz, 2015). In addition, the persistence of some pesticides in water can have long-term effects on aquatic communities and disrupt ecosystem processes.

1.4.4. Soil Health and Microbial Communities: Pesticide use can affect soil health and microbial communities, which play crucial roles in nutrient cycling, decomposition, and plant-microbe interactions. The application of pesticides, especially fungicides and herbicides, can alter the diversity and activity of soil microorganisms, leading to changes in nutrient availability and soil functioning (Geiger *et al*., 2010). Prolonged pesticide use can result in soil degradation, reduced fertility, and increased vulnerability to erosion.

1.4.5. Impacts on Ecosystem Services: Pesticide use can have significant consequences for ecosystem services, which are the benefits that ecosystems provide to humans. For instance, the decline of pollinators due to pesticide exposure can negatively impact crop pollination and agricultural productivity (Bommarco *et* al., 2013). Similarly, the loss of natural enemies of pests, such as predatory insects and birds, can lead to increased pest outbreaks and the need for more pesticide applications.

1.5. Factors Influencing Pesticide Effects on Insects

The effects of pesticides on insects can vary depending on several factors that influence their toxicity, exposure, and susceptibility. Understanding these factors is crucial for assessing and mitigating the impacts of pesticide use on insect populations.

1.5.1. Pesticide Characteristics: The properties of the pesticide itself can influence its effects on insects. Factors such as chemical class, mode of action, persistence, and formulation can determine the toxicity and potential for environmental persistence of a pesticide (Goulson, 2013). For example, some insecticides may have specific target sites in insect physiology, making them more toxic to certain insect species while having minimal effects on others.

1.5.2. Dose and Concentration: The dose or concentration of the pesticide is a critical factor in determining its effects on insects. Higher pesticide doses or concentrations are more likely to cause acute toxicity and immediate mortality in insects (Desneux *et al.,* 2007). However, even sublethal doses can have significant impacts on insect behaviour, reproduction, and overall population dynamics (Rundlöf *et al*., 2015).

1.5.3. Exposure Duration and Timing: The duration and timing of pesticide exposure can influence its effects on insects. Longer exposure durations increase the likelihood of cumulative effects and chronic toxicity, whereas short-term exposures may primarily result in acute effects (Desneux *et al.,* 2007). Additionally, the stage of insect development at the time of exposure can affect susceptibility, as certain life stages may be more sensitive to pesticides than others.

1.5.4. Interaction with Environmental Factors: Environmental factors can interact with pesticides and influence their effects on insects. Temperature, humidity, light conditions, and habitat characteristics can modify the toxicity and degradation rates of pesticides, affecting their persistence and bioavailability in the environment (Liess and Beketov, 2011). Interactions with other stressors, such as pollution, climate change, and habitat loss, can further exacerbate the effects of pesticides on insect populations (Goulson, 2013).

1.5.5. Species-Specific Sensitivities: Insects exhibit variations in their sensitivities to different pesticides. Species-specific differences in physiology, behaviour, detoxification mechanisms, and susceptibility can affect their tolerance or vulnerability to specific pesticide classes (Desneux *et al*., 2007). Some insect species may have developed resistance to certain pesticides through genetic adaptations, making them less susceptible to their effects.

1.6 Strategies for Mitigating Pesticide Impacts

To minimize the negative impacts of pesticides on insect biodiversity and ecosystems, various strategies can be implemented. These strategies aim to reduce pesticide use, promote sustainable pest management practices, and safeguard non-target organisms.

1.6.1. Integrated Pest Management (IPM): Integrated Pest Management is an ecosystem-based approach that combines various pest control strategies to minimize pesticide use while effectively managing pests (Dent, 2018). IPM emphasizes the integration of cultural, biological, and chemical control methods, with an emphasis on prevention, monitoring, and targeted pesticide application. By considering the pest's life cycle, natural enemies, and ecological interactions, IPM reduces the reliance on broad-spectrum pesticides, promoting ecological balance and preserving beneficial insects (Van Lenteren, 2012).

1.6.2. Precision Agriculture: Precision agriculture utilizes technology and data to apply pesticides more accurately and efficiently, reducing the overall amount of chemicals used. Techniques such as GPS-guided equipment, remote sensing, and variable-rate application allow farmers to target specific areas in the field, reducing pesticide drift and optimizing pest control (Huang *et al*., 2019). This approach helps minimize non-target exposure and environmental contamination while improving cost-effectiveness and sustainability.

1.6.3. Buffer Zones and Habitat Conservation: Implementing buffer zones and conserving natural habitats in and around agricultural areas can mitigate pesticide impacts on non-target organisms. Buffer zones, such as strips of vegetation or wetlands, act as physical barriers that reduce pesticide runoff and provide refuge for beneficial insects and wildlife (Bianchi *et al*., 2017). Conserving natural habitats, including hedgerows, field margins, and forests, enhances biodiversity, promotes natural pest control, and provides alternative resources for insects, reducing the reliance on pesticides (Kleijn *et al.*, 2006).

1.6.4. Pesticide Alternatives and Innovative Technologies: The development and utilization of pesticide alternatives and innovative technologies can help reduce reliance on conventional chemical pesticides. These alternatives include biological control agents (e.g., predatory insects, parasites), pheromones for mating disruption, biopesticides derived from natural compounds (e.g., botanicals, microorganisms), and genetically modified crops with built-in pest resistance (Koul and Dhaliwal, 2018). Additionally, emerging technologies, such as precision sprayers and drone applications, can improve pesticide targeting, reducing environmental exposure.

1.6.5. Education and Training: Programmes that promote sustainable pesticide usage and raise knowledge of the potential effects on insect biodiversity are essential. Information on IPM techniques, pesticide selection, application methods, and safety precautions can help farmers, agricultural workers, and pest management experts better understand how pesticides interact with the environment and promote responsible pesticide use (Gaylor *et al*., 2019). Campaigns aimed at educating the public and increasing consumer awareness of pesticide reduction measures can also help them.

1.7. Future Perspectives and Research Needs

Despite efforts to mitigate the impacts of pesticides on insect biodiversity and ecosystems, there are still important research gaps and future directions that need to be addressed. Advancements in scientific knowledge and innovative approaches can further improve our understanding of pesticide effects and inform sustainable pest management practices.

1.7.1. Long-Term Effects and Sublethal Effects: There is a need for long-term studies to assess the cumulative and sublethal effects of pesticides on insect populations. Many studies focus on acute toxicity, but chronic exposures and sublethal effects can have significant consequences for population dynamics, behaviour, reproduction, and ecosystem functions (Stanley *et al*., 2016). Investigating the long-term impacts of pesticide exposure on different life stages and across generations is essential for understanding population-level effects.

1.7.2. Interactions with Multiple Stressors: In natural ecosystems, insects often face multiple stressors simultaneously, including pollution, habitat loss, climate change, and invasive species. Future research should investigate the interactive effects of pesticides with these stressors to better understand their combined impacts on insect populations and ecosystem functioning (Pisa *et al*., 2015). Studying how multiple stressors interact can help develop holistic management strategies that consider the complexity of real-world conditions.

1.7.3. Development of Safer Pesticides: The development of safer pesticides with reduced ecological impacts is a major area of research. Future efforts should focus on designing pesticides that are target-specific, biodegradable, and have minimal effects on non-target organisms (Pisa *et al*., 2015). Integrated approaches that combine chemical, biological, and cultural control methods can enhance pest management efficacy while minimizing environmental harm.

1.7.4. Landscape-Scale Studies: Conducting landscape-scale studies can provide valuable insights into the effects of pesticide use on insect biodiversity and ecosystem functioning. Research should investigate how landscape composition, connectivity, and land management practices influence the persistence and movement of pesticides and their impacts on insect populations (Tscharntke *et al.,* 2005). Such studies can inform landscape planning and conservation strategies to minimize pesticide exposure risks.

1.7.5. Socioeconomic and Policy Considerations: Future research should consider pesticide use's socioeconomic and policy dimensions and impacts. Assessing alternative pest management strategies' economic costs and benefits can help policymakers and farmers make informed decisions. Additionally, exploring the social and cultural factors that influence pesticide use and the adoption of sustainable practices can facilitate the development of context-specific solutions (Bommarco *et al*., 2013).

Conclusion

The insect biodiversity and ecological services are significantly disturbed due to pesticide residues. This review emphasises the detrimental effects of pesticides on insect populations, the disruption of ecological connections, and the degradation of vital functions like pollination and pest control. Unintentional harm is caused to non-target insects, including beneficial species. To lessen pesticide consumption and encourage sustainable practices, strategies including Integrated Pest Management, precision agriculture, buffer zones, and habitat preservation are suggested. There are still unanswered questions regarding long-term impacts, interactions with other stressors, safer substitutes, studies conducted at a landscape scale, and socioeconomic factors. Collaboration between researchers, decision-makers, farmers, and other stakeholders is essential. We may work towards sustainable pest control and protect insect biodiversity while preserving the provision of ecosystem services by using interdisciplinary approaches and taking the long-term effects of pesticide use into account. For a robust and healthy ecosystem, agricultural productivity and environmental sustainability must be balanced.

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