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PESTICIDES AND ECOSYSTEM HEALTH: UNRAVELING THE COMPLEX IMPACT ON BIODIVERSITY AND FUNCTIONALITY

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ABSTRACT

Pesticides are widely used in pest control for the protection of crops and for increasing yields, but their impact on ecosystem health is of concern. The present review explores the complex consequences of pesticide application on biodiversity as well as the functioning of the ecosystem. Though pesticides are effective for pest management, they are involved in decreasing the diversity of species, particularly non-target organisms. Disturbance of trophic interactions and food webs often has cascading ecological effects, compromising ecosystem stability. Furthermore, pesticides may interfere with major ecosystem processes such as water filtration, soil fertility, and pollination, compromising ecosystem resistance to extrinsic disturbances. Sublethal phenomena like changes in behavior and reproduction in organisms are unperceived but contribute substantially to ecosystem perturbation. The persistence in the environment of the byproducts of pesticides, bioaccumulation, and biomagnification enhance the environmental risks. Mitigation strategies like the use of integrated pest management (IPM), biological control, and environmentally safe substitutes are also discussed in this review. Additionally, the regulatory controls' role in minimizing harm due to pesticides is considered. Implications stress the need for more environmentally sustainable methods for pest control and environmental management to maintain ecosystem health. Increased scientific research is essential to gain full understanding of long-term impacts of pesticide use and to develop more sustainable and ecological agricultural systems.

Keywords: Pesticides, biodiversity, ecosystem functioning, trophic interactions, bioaccumulation, integrated pest management

INTRODUCTION

Pesticides are substances used to destroy or control harmful organisms, including insects, weeds, fungi, and rodents, which pose potential risks to crops, animals, and human health. The substances are frequently used in agriculture, forestry, and urban areas to protect crops from pests, promote productivity of crops, and preserve aesthetics in cities (Liu *et al*., 2025; Zare *et al*., 2005). Pesticides are a wide assortment of chemicals, including insecticides, herbicides, fungicides, and rodenticides, each targeting specific pest categories. Pesticides are crucial tools in food availability and high crop yield within agriculture, but their use is not without severe ecological consequences. In the case of urban settings, household pests and vector-borne diseases are managed through pesticides, but possible injury to the non-target fauna of the larger environment is no less significant (Zare *et al*., 2005; Blair *et al*., 2015).

The ability of an ecosystem to remain stable in the face of changes in the environment is what makes up ecosystem health. Biodiversity in this sense is crucial, as a high richness of species is needed for efficient ecosystem process functioning such as nutrient cycling, pollination, and pest control (Cardinale *et al*., 2012). Ecosystem services provided by biodiversity contribute to enhancing human well-being by ensuring the sustainability of agricultural production, water quality, and climate regulation. Pesticides, however, pose significant challenges to biodiversity since they disrupt these ecological processes. The use of pesticides can lead to a reduction in species diversity, disruption of food webs, and degradation of the capacity of ecosystems to resist environmental stresses, ultimately influencing the services provided by ecosystems (Horrigan *et al*., 2002; Khan *et al.*, 2022; Meryem *et al.*, 2022).

The aim of this review is to take into account the effects of pesticide exposure on biodiversity and ecosystem function. Focus will be placed on understanding how pesticides, both in their immediate toxic effect and in their longer-term ecological influence, impact the health of ecosystems. This review will present mechanisms by which pesticides disrupt species interactions, alter trophic structure, and impair ecosystem functioning. The problems posed by the accumulation and persistence of pesticides in ecosystems and subsequent bioaccumulation in food webs will also be addressed (Shah *et al.,* 2022; Haroon *et al.,* 2022; Zeb *et al.,* Parveen *et al.,* 2022). Through the incorporation of current research on pesticide-induced ecosystem alterations, this article attempts to provide a conceptual model for understanding the complexity of pesticide effects on environmental health and inform future policy and management choices (**Table 1**).

Types of Pesticides and Mechanisms of Action

Pesticides are divided based on the types of pests they are meant to control, with the most common divisions being insecticides, herbicides, fungicides, and rodenticides. Insecticides are designed to control insects by affecting their nervous system, usually by disrupting neurotransmission or inhibiting enzymes in neural function. Organophosphates and carbamates, for example, inhibit acetylcholinesterase, an important enzyme required for nerve function, paralyzing and killing insects (Kumar *et al.,* 2023). Herbicides, on the other hand, disrupt plant growth processes, often by preventing photosynthesis or hormone balance, leading to plant death. Selective herbicides, such as glyphosate, are designed to target particular plant species, while non-selective herbicides kill a broader range of plants (Thompson *et al.,* 2006). Fungicides destroy fungi and spores by inhibiting their growth, typically by interfering with cell membrane integrity or fungal respiration. Fungicides are members of several classes, such as sterol biosynthesis inhibitors (e.g., azoles) and respiration inhibitors (e.g., strobilurins), which operate through distinctive biochemical mechanisms (Kumar *et al*., 2024). Rodenticides control rodent populations, typically by interfering with rodent blood clotting or metabolism. Anticoagulants like warfarin suppress blood clotting, resulting in fatal bleeding (Lohr and Davis, 2018).

Pesticides may have a diverse chemical composition based on their action and target species. Most synthetic pesticides are organic carbon-based compounds with engineered chemical structures that interact with the biological processes of target pests. For example, organophosphates contain phosphorus and are highly toxic insectically, whereas pyrethroids are synthetic substances akin to a naturally occurring pesticide found in flowers of chrysanthemum (Horrigan *et al*., 2002). The persistence of pesticides in the environment depends to a great extent on the chemical structure of the pesticide, environmental conditions, and type of action. Some pesticides, for instance, glyphosate, possess short half-lives that enable them to quickly degrade in soil, while others, such as organochlorines, are long-lived in the environment for decades, accumulating in soil and aquatic food chains (Staley *et al.,* 2015; Kumar *et al.,* 2023). The persistence of these pesticides is at a greater risk of bioaccumulation in the food chain because the chemicals can be accumulated by living organisms and amplified as they continued through trophic levels. For example, DDT (dichlorodiphenyltrichloroethane) has been shown to bioaccumulate in animal fatty tissues, causing long-term ecological damage and disrupting species reproduction (Thompson *et al.,* 2006). Moreover, pesticides also infiltrate groundwater, contaminating drinking water and having the potential to affect human health from long-term exposure (Zhou *et al*., 2025; Fairbrother *et al*., 2016).

Table 1. Conceptual framework of pesticide impacts on ecosystem health.

Pesticide Type	Mechanism of Action	Impact on Species Diversity	Impact on Ecosystem Functions	Key Studies
Insecticides	Neurotoxic, disrupts nervous system of insects	Reduction in insect diversity, impact on pollinators	Impaired pollination, soil health	Relyea, 2005
Herbicides	Interferes with plant growth through photosynthesis inhibition	Decline in plant diversity, non-target plant species affected	Disruption of food chains, reduced plant cover	Sharma *et al.,* 2018
Fungicides	Inhibits fungal growth and reproduction	Non-target fungal species impacted, reduction in fungal biodiversity	Disruption of decomposers, nutrient cycling	Tsalidis, 2022
Rodenticides	Poisoning of rodents by anticoagulants	Reduction in rodent populations, may affect predator-prey relationships	Disruption of food web, affects predator species	Baudrot *et al.,* 2020; Lohr and Davis, 2018

The environmental risks entailed in the application of pesticides highlight the necessity of understanding how they persist and can bioaccumulate within the ecosystem. Practices such as integrated pest management (IPM) are aimed at reducing the application of chemical pesticides and their impact on the environment through the application of biological control agents, crop rotation, and other methods of sustainable agriculture (Chagnon *et al*., 2015). The practice seeks to balance pest control with environmental health, reducing pesticide-induced harm to biodiversity and ecosystem functioning (**Table 2**).

Table 2. Comparative analysis of environmental persistence, bioaccumulation, and toxicity of common pesticides.

Pesticide Type	Persistence in Soil (Days)	Bioaccumulation Potential (Bioaccumulation Factor)	Acute Toxicity to Aquatic Species (LC50, µg/L)	References
Insecticides	30–365	2.5–10 (organophosphates), 1–5 (pyrethroids)	0.1–5.0 (organophosphates), 5–50 (pyrethroids)	Kumar *et al.*, 2023; Relyea, 2005
Herbicides	7–180	0.5–3.0 (glyphosate), 0.1–1.0 (atrazine)	10–100 (glyphosate), 5–30 (atrazine)	Brühl and Zaller, 2019
Fungicides	14–180	1.0–3.5 (azoles), 0.2–1.5 (strobilurins)	1.0–50 (azoles), 5–50 (strobilurins)	Fairbrother *et al.*, 2015; Horrigan *et al.*, 2002
Rodenticides	7–90	5–20 (warfarin), 10–30 (bromadiolone)	0.1–5.0 (warfarin), 0.5–5.0 (bromadiolone)	Lohr and Davis, 2018; Chagnon *et al.*, 2015

Table 2 contrasts the environmental persistence, bioaccumulation potential, and acute toxicity of various pesticides, which are some of the main factors used to gauge their effects on the environment. It displays the range among the various classes of pesticides, such as insecticides, herbicides, fungicides, and rodenticides, in their potential to remain in the environment, build up in food chains, and affect aquatic life. These data are essential for assessing the risks of pesticide use, guiding more sustainable agriculture, and supporting policymakers in developing regulations that minimize environmental harm. Through the analysis of these key properties, we can more completely understand the long-term impact of pesticide exposure on ecosystem health and biodiversity.

Impacts of Pesticides on Biodiversity

Pesticides are widely used to control pests and promote crop yields, yet their use poses significant ecological impacts, particularly for biodiversity. Diversity and variability of forms of life comprise biodiversity that is central in providing stability, resilience, and functionality of the ecosystem. Non-target organisms or species of pests, as well as target species, can destabilize ecosystems so that species diversity in the long term reduces. Here, we report the impacts of pesticide exposure on species diversity, provide case studies from various ecosystems, and review how pesticide pollution alters habitats, which reduces their capacity to support diverse species.

- Impact on Species Diversity

Numerous studies have confirmed that pesticides can significantly reduce species diversity in terrestrial and aquatic ecosystems. The effects vary depending on the pesticide class, mode of application, and characteristics of the ecosystem. In aquatic ecosystems, the pesticides organophosphates and carbamates have been seen to decline species diversity among the aquatic animals as a result of impacts on survival and reproductive capacities (Kumar *et al.,* 2023). The herbicides, especially glyphosate, within terrestrial ecosystems have been related to the loss of herbivores in plants as a response to its effect at the lower trophic levels impacting the herbivores and their apex predators. Additionally, research has recorded a decline in pollinator diversity as a result of pesticide application, which directly threatens plant reproduction and ecosystem health according **Table 3 and Figure 1** (Relyea, 2005).

- Case Studies

A number of case studies indicate the destructive impact of pesticides on species populations and ecosystem function. For example, pesticide pollution has caused dramatic reductions in fish populations and food web disturbances in the Tajan River (Ebadi and Hisoriev, 2018b). In agroecosystems, herbicide overuse has resulted in the virtual extinction of many plant species that are vulnerable to chemical exposure (Chagnon *et al*., 2015). Similarly, studies from the Farahabad Region in Iran have suggested a reduction in aquatic biodiversity due to pesticide runoff from surrounding agricultural fields into sea water bodies (Ebadi *et al*., 2017). Such case studies emphasize the necessity of considering the broader ecological context of pesticide application, particularly for sensitive ecosystems (**Figure 2**).

Table 3. Impact of pesticides on species diversity in aquatic and terrestrial ecosystems.

Ecosystem Type	**Pesticide Type**	**Mode of Action**	**Impact on Species Diversity**	**Key Study Reference**
Aquatic Ecosystems	Organophosphates, Carbamates	Neurotoxic, affects nerve transmission	Significant decline in fish and aquatic insect populations; reduced predator-prey dynamics	Kumar *et al.*, 2023; Ebadi and Hisoriev, 2018b
Terrestrial Ecosystems	Glyphosate, Atrazine	Herbicidal, disrupts photosynthesis in plants	Loss of plant diversity, which cascades through the food web affecting herbivores, insect predators, and pollinators	Chagnon *et al.*, 2015
Coastal Aquatic Ecosystems	Chlorpyrifos, Pyrethroids	Disrupts endocrine system, immune function in marine species	Reduction in marine species diversity, alteration of food webs and ecosystems	Ebadi *et al.*, 2017; Brühl and Zaller, 2019
Freshwater Ecosystems	Atrazine, Malathion	Herbicidal, neurotoxic effect on amphibians	Decline in amphibian populations, reproductive failure, and biodiversity loss in freshwater habitats	Relyea, 2005

- Habitat Pollution

Agricultural pesticide runoff can severely disturb habitats so that they become less capable of supporting diverse species. In aquatic ecosystems, pesticide runoff contaminates water bodies, affecting water quality and aquatic life that depends on it. Studies have shown that persistent pesticides such as atrazine and glyphosate, when they wash into rivers and lakes, can interfere with the reproductive cycles of aquatic species, including amphibians, fish, and invertebrates (Kumar *et al.*, 2023). On land, pesticide drift and leaching into the soil can degrade ecosystems, which results in the decline of plant species that are vital for soil health and herbivores' feeding. In addition, non-target organisms, for example, useful insects like bees and predatory beetles, typically suffer from pesticide exposure, hence the reduction in population and reduced ecosystem services based on **Table 4**.

Table 4. Pesticide runoff and habitat alterations: effects on ecosystem functions and species populations.

Ecosystem Type	**Pesticide Type**	**Pathway of Exposure**	**Environmental Consequences**	**Effect on Habitat Functioning**	**Key Study Reference**
Agricultural Land	Herbicides (e.g., Glyphosate)	Runoff into rivers, leaching into soil	Degradation of soil health, loss of plant species	Reduction in soil fertility, loss of primary producers; impacts herbivore populations	Gauthier *et al.*, 2018
Riparian Zones	Insecticides (e.g., DDT)	Leaching into groundwater, runoff	Reduction of insect populations, affecting food webs	Loss of insect pollinators, which affects plant reproduction and crop yields	Brühl and Zaller, 2019; Ebadi *et al.*, 2017
Marine Coastal	Chlorpyrifos, Pyrethroids	Pesticide runoff from agricultural land into oceans	Disruption of marine biodiversity, particularly invertebrates	Reduced primary productivity, altered marine food webs	Ebadi and Hisoriev, 2018c; Kumar *et al.*, 2023
Wetland Ecosystems	Fungicides (e.g., Mancozeb)	Surface runoff into wetland areas	Reduction in amphibian and aquatic insect populations	Decline in amphibian populations, disruption in wetland plant diversity	Fairbrother *et al.*, 2016

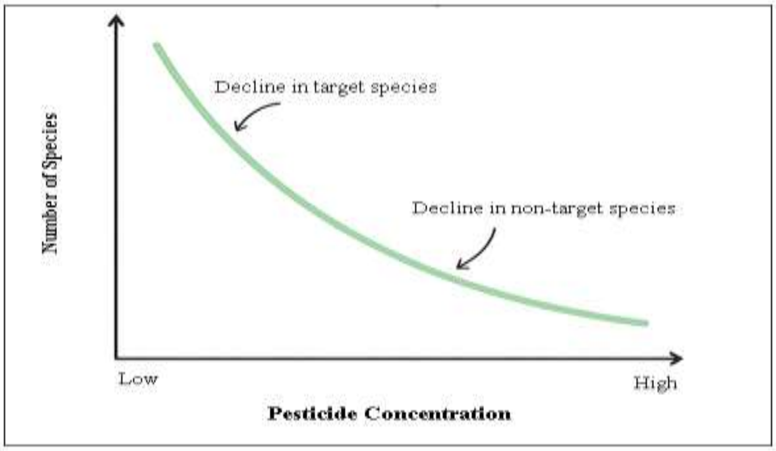

Fig. 1. Decline in species diversity with increasing pesticide concentration remediation.

Table 3 gives a broad overview of the ways different pesticides affect biodiversity on both aquatic and terrestrial ecosystems. The data indicates both the pesticide's mode of action and overall ecological impacts on species diversity and is of interest to inform pesticide application control in different ecosystems. Also Table 4 presents the broader environmental effects of pesticide runoff on different ecosystems. It identifies the pathways by which pesticides are introduced into the environment, their effects on habitat quality, and the ways habitat function is altered, reducing the ability of ecosystems to support a diversity of species. This is significant information in understanding how pesticide pollution in runoff influences biodiversity and habitat health.

Figure 1 illustrates the relationship between pesticide exposure and species diversity in various ecosystems. This is significant because species diversity is a primary measure of ecosystem health and resilience. Biodiversity loss—often the consequence of pesticide overuse or misuse—can destabilize food webs, disrupt pollination, and compromise natural pest control. These disturbances can lead to long-term environmental degradation, reducing ecosystems' capacity for recovery from stressors and providing vital services. Therefore, this effect is important to understand and visualize in order to inform sustainable agriculture and environmental practices.

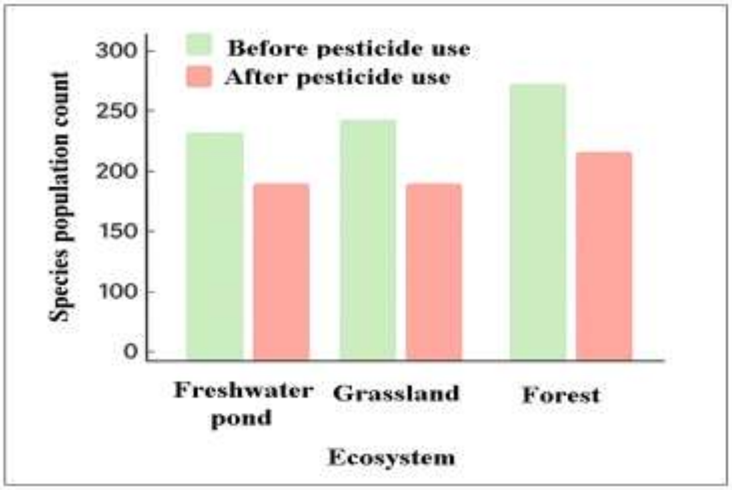

Fig. 2. Comparative species population before and after pesticide use in ecosystems.

Figure 2 depicts freshwater pond, grassland, and forest species populations before and after pesticide exposure and indicates the sharp declines—especially in sensitive aquatic ecosystems. These graphical data emphasize the need for ecosystem-specific pesticide control because the observed population declines are symptoms of a more profound ecological imbalance. These disruptions can undermine essential ecosystem services like pollination, water filtration, and pest control, thereby affecting agricultural production and climate resilience.

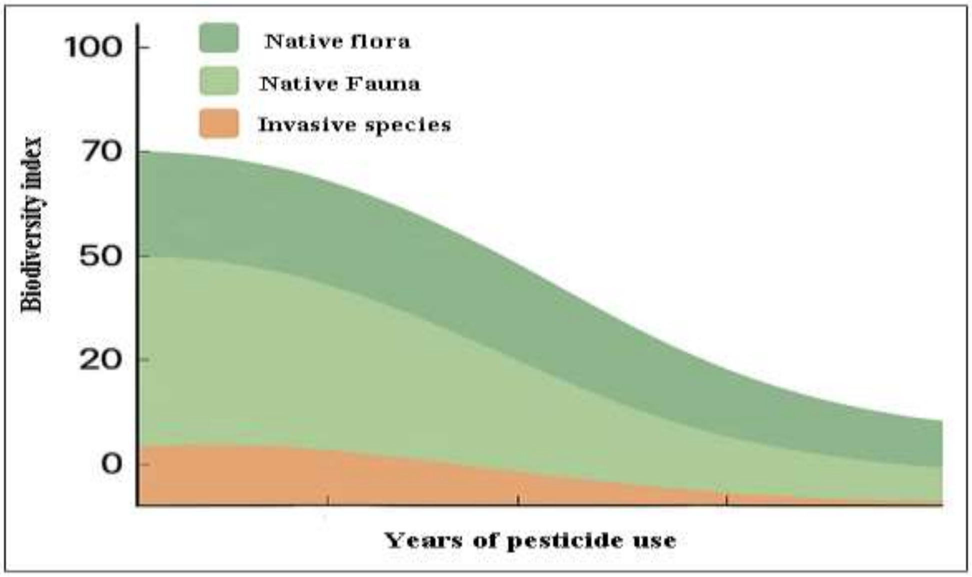

Fig. 3. Habitat Support Capacity and Biodiversity Trends During Pesticide Use Over Time.

Figure 3 indicates the decline in native wildlife and vegetation and rise in the presence of invasives annually since pesticide spraying began. This steady drop in overall biodiversity indicator reflects the loss of the environmental capacity to carry a diverse group of living species. This habitat disruption, made possible by pesticide pollution, has far-reaching, negative long-term consequences—placing ecosystem integrity at risk, increasing the incidence of invasive species, and making it more difficult and expensive to restore later.

Pesticide Impacts on Ecosystem Functionality

Pesticides are vital in modern agriculture for pest management, but they significantly disrupt critical ecosystem services at large-scale use. Critical ecosystem processes such as pollination, soil health, water purification, and natural pest control are all threatened by pesticide exposure (Gauthier *et al.*, 2018). Pollinators like bees are particularly susceptible to use of pesticides like neonicotinoids, which impair their navigation and foraging abilities and ultimately decrease pollination services indispensable for the successful reproduction of crops and wild flowers (Brühl and Zaller, 2019). Soil pesticide residues also affect microorganisms in soil and earthworms, soil fertility and nutrient cycling agents necessary for plant development and agricultural output. Besides, natural water purification, carried out by riparian and wetland ecosystems, is repressed when aquatic systems are polluted with pesticides, destabilizing biota that filter and purify water (Ebadi *et al*., 2017).

Pesticides also have profound effects on trophic interactions and food webs. Pesticides modify the abundance and diversity of species at different trophic levels, leading to cascading consequences on ecosystem stability (Thompson *et al.,* 2006). For instance, when herbivorous insects are exposed to pesticides, their number declines, which leads to the decline in the availability of food for insectivores. This perturbation can propagate down the food web, ultimately affecting predators at higher trophic levels (Gauthier *et al*., 2018). In accordance with research by Kumar *et al*. (2024), the decline in insect populations due to pesticide exposure led to fewer available foods for birds and amphibians, which in turn had diminished reproduction success and species losses. Moreover, exposure to pesticides can also help cause changes in species composition that favor pest species over their natural enemies, thus destabilizing food webs based on **Table 5** (Brühl and Zaller, 2019).

Ecosystem resilience, or a function of the ecosystem to recover from disturbance, is also greatly disturbed in exposed ecosystems. Although resilience indicates a function of the ecosystem to overcome disturbance, an ecosystem that is exposed to pesticides is mostly at risk of added stressors, such as climate change and invasive plants and animals (Ebadi and Hisoriev, 2018c). This weakness is most apparent in agricultural landscapes where ecosystems, which are already compromised by the use of pesticides, are struggling to cope with other stresses brought about by droughts, temperature variability, and invasion by alien species (Gauthier *et al*., 2018). Aquatic ecosystems with pesticide pollution, for example, are less resilient in a recovery from contaminants and climate stress, leading to biodiversity loss and ecosystem functions that are critical (Brühl and Zaller, 2019).

Table 5. Impact of pesticide exposure on ecosystem services and resilience.

Ecosystem Service	Impact of Pesticide Exposure	Key Study Reference
Pollination	Reduced pollinator populations due to pesticide toxicity, leading to lower crop yields and plant diversity	Brühl and Zaller, 2019
Soil Fertility	Disruption of soil microorganisms and earthworms, leading to reduced nutrient cycling and impaired plant growth	Gauthier *et al.*, 2018; Ebadi *et al.*, 2017
Water Purification	Pesticide contamination of water bodies, disrupting filtration by aquatic organisms and reducing water quality	Ebadi and Hisoriev, 2018b; Brühl and Zaller, 2019
Pest Regulation	Loss of natural predators and increased pest populations due to pesticide toxicity affecting predator species	Relyea, 2005; Kumar *et al.*, 2024
Ecosystem Resilience	Loss of resilience to additional stressors (climate change, invasive species) due to pesticide-induced disruptions in biodiversity	Gauthier *et al.*, 2018

Table 5 summarizes the effects of pesticide exposure on crucial ecosystem services and the resilience of ecosystems. It effectively conveys the manner in which pesticides disrupt the natural process of preserving ecological balance and how this has added consequences for ecosystem health and stability.

Mechanisms of Pesticide Impact on Ecosystem Processes

Pesticides exercise a negative influence on non-target organisms to elicit their toxic action through a variety of biological mechanisms, disrupting ecosystem processes at various levels. At the organismal level, pesticides interfere with the primary physiological activities such as respiration, digestion, and cellular activity, leading to toxicity and death (Yadav, 2010; Gauthier *et al*., 2018). These impacts often spill over to populations and communities beyond the organismal level. For example, when pesticides reduce the mortality rate of some species, it can trigger a cascade effect on entire ecosystems, disrupting food webs and species interactions (Brühl and Zaller, 2019). For instance, the application of neonicotinoid pesticides in agricultural fields has been shown to affect the foraging of pollinators like bees, which indirectly affects plant-pollinator interactions (Relyea, 2005). Not only do these disturbances affect the target pest populations but also affect other organisms which form a vital component of the stability and functionality of the ecosystem.

One of the most distressing aspects of pesticide exposure is bioaccumulation and biomagnification, particularly for persistent pesticides. Bioaccumulation refers to the gradual accumulation of pesticides within an organism's tissues over time, while biomagnification is the increased concentration of pesticides as one moves up the food web. Predators and scavengers at higher trophic levels receive increased levels of pesticides due to prey intake. The research by Kumar *et al*. (2024) revealed that the apex predators such as birds of prey and fish accumulate pesticide residues in concentrations much higher than those at lower levels, leading to reduced population sizes and ecosystem instability. For example, pesticide contamination in aquatic ecosystems results in higher pesticide levels in fish, which, upon consumption by human beings or other animals, could result in serious health and environmental risks (Gauthier *et al*., 2018). **Table 6** illustrates the process of biomagnification and bioaccumulation of pesticides along trophic levels within aquatic ecosystems. It illustrates the increase in the concentration of the pesticides up through the food chain, which needs to be comprehended in order to appreciate long-term ecological consequences and risks for top trophic organisms.

Sublethal pesticide impacts are another significant manner in which these pesticides impact ecosystems. Although sublethal impacts do not result in death, they can have a drastic impact on an organism's growth, reproduction, and behavior. For instance, exposure to certain pesticides has been associated with impaired reproductive success in amphibians and fish, leading to declining populations in the long term). Similarly, studies on bees have established that sublethal levels of pesticides influence their navigation and foraging behavior, which leads to compromised pollination services in ecosystems (Kumar *et al.*, 2023). Sublethal effects prove to be hard to detect because they do not directly cause death but, in the long term, accumulate to disorganize and disrupt functioning within ecosystems, particularly in those species that are vital to ecological balance (**Table 7**). This table highlights the sublethal effect of pesticides on various organisms, taking particular note of behavioral and reproductive abnormalities. Sublethal effects can have extreme long-term effects on ecosystem function despite not being lethal in themselves.

Pesticide exposure to ecosystem processes can be quantified by the effect of effects on population dynamics and community interactions. For example, pesticide exposure reduces species diversity since it has an uneven effect on sensitive species such as amphibians and arthropods, which are important in food webs and nutrient cycling (Relyea, 2005). This can lead to species alteration, reducing the functionality and stability of the ecosystem. In addition, loss of biodiversity has the tendency to lower the resilience of ecosystems, making them susceptible to other disturbances such as climate change or invasive species. Kumar *et al*. (2024) in their research stated that loss of biodiversity due to pesticides is one of the main causes of decreased resilience of ecosystems experiencing multiple stressors.

Mitigation Alternatives and Strategies

To minimize the environmental effects of pesticides, a number of pesticide management practices have been established. Integrated Pest Management (IPM) is a common practice that integrates various strategies, such as biological control, habitat manipulation, and the careful application of chemical pesticides (Kumar *et al.*, 2023). Through the application of pesticides only when needed and at the lowest effective rates, IPM minimizes pesticide exposure to ecosystems while still controlling pests. Precision agriculture involving the use of technologies such as drones, sensors, and GPS can also optimize the use of pesticides. Through this process, there is exact pesticide delivery to minimize runoff and off-target occurrences (Momeniha *et al*., 2025; Mgendi, 2024). In addition, methods of organic agriculture that entirely avoid the use of synthetic pesticides are becoming increasingly popular as ways of sustaining ecosystem health through having natural modes of pest control, such as the use of crop rotation and beneficial insects (Bengtsson *et al*., 2005). **Table 8** is critical to outline various approaches to pesticide management and enable a simple comparison of strategies like Integrated Pest Management (IPM), Precision Agriculture, Organic Farming, Biological Control, and Green Chemistry. It simplifies the advanced concepts, making it easier to make decisions towards sustainable pest management. Additionally, it is an invaluable resource for researchers and policymakers to assess the effectiveness and ecological impact of the approaches.

Biological control offers a measure alternative to pesticides that leverages the natural predators, parasites, or pathogens to restrict the population of pests. As an example, the release of natural enemies like ladybugs or parasitoid wasps can offer effective pest population reduction without adverse effects on the overall ecosystem (He *et al*., 2021). Green chemistry also has provided answers for environment-friendly alternatives of pesticides, focusing on the production of less toxic chemicals with quicker ability to degrade in the environment and low bioaccumulation capacity (Fenibo *et al.,* 2021). These approaches not only reduce chemical pesticide hazards but also provide long-term, sustainable remedies for pest control.

Table 6. Bioaccumulation and biomagnification of pesticides in aquatic ecosystems.

Trophic Level	Pesticide Concentration (ppb)	Example Organisms	Key Study Reference
Primary Producers	2.5	Algae, Aquatic Plants	Gauthier *et al.,* 2018
Primary Consumers	4.2	Zooplankton, Small Fish	Kumar *et al.,* 2024
Secondary Consumers	6.5	Larger Fish, Amphibians	Brühl and Zaller, 2019
Tertiary Consumers	12.3	Birds of Prey, Fish-eating Mammals	Thompson *et al.,* 2006

Table 7. Sublethal effects of pesticides on organisms.

Organism	Sublethal Effect	Pesticide Type	Key Study Reference
Bees	Impaired foraging behavior, reduced navigation	Neonicotinoids	Kumar *et al.,* 2023
Amphibians	Reduced reproductive success	Organophosphates	Gauthier *et al.*, 2018
Fish	Impaired growth, delayed development	Pyrethroids	Relyea, 2005
Earthworms	Reduced burrowing activity, decreased reproduction	Chlorpyrifos	Fairbrother *et al.*, 2016

Regulatory measures are necessary to control the application of pesticides and minimize environmental damage. Pesticide prohibitions have been imposed by various countries, such as the European Union prohibition on several neonicotinoids, because of apprehension regarding their impact on pollinators and other non-target species (Brühl and Zaller, 2019). In addition to pesticide bans, buffer zones around fields have also been established to protect sensitive areas, such as water bodies and wildlife habitats, from pesticide drift. Environmental monitoring is also required to track pesticide levels in ecosystems and evaluate the effectiveness of mitigation measures to ensure that pesticide use does not exceed safe levels for biodiversity and ecosystem health (Staley *et al.*, 2015; Ebadi *et al.*, 2025).

Table 8. Comparison of pesticide management strategies.

Management Strategy	Approach/Description	Example Study Reference
Integrated Pest Management (IPM)	Combines chemical, biological, and cultural methods to manage pests.	Cardinale *et al.*, 2012; Bengtsson *et al.*, 2005
Precision Agriculture	Uses technology for targeted pesticide application.	Mgendi, 2024
Organic Farming	Avoids synthetic pesticides, relying on natural pest control methods.	Bengtsson *et al.*, 2005
Biological Control	Uses natural predators or parasites to control pest populations.	He *et al.*, 2021
Green Chemistry	Focuses on developing environmentally-friendly pesticides.	Fenibo *et al.*, 2021

CONCLUSION

In summary, the complex interactions among pesticides, biodiversity, and ecosystem functioning reveal significant threats to ecological stability, including loss of species diversity, changed ecosystem services, and reduced resilience to environmental stress. Future research will need to tackle the long-term effects of pesticide exposure on ecosystems, particularly regarding sublethal effects, bioaccumulation, and trophic interactions. It will be required to create more ecologically friendly pest control practices, such as integrated pest management and ecologically friendly alternatives, in an effort to prevent these effects. An ecosystem-balanced method of pest control with emphasis on ecosystem conservation is crucial to sustaining the health and functionality of ecosystems and the crucial services they provide.

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REFERENCES

Bengtsson, J., J. Ahnström and A.C. Weibull (2005). The effects of organic agriculture on biodiversity and abundance: a meta-analysis. *Journal of Applied Ecology*, 42(2): 261–269.

Baudrot, V., J. Fernandez-de-Simon, M. Coeurdassier, G. Couval, P. Giraudoux, and X. Lambin (2020). Trophic transfer of pesticides: The fine line between predator–prey regulation and pesticide–pest regulation. *Journal of Applied Ecology,* 57(4): 806–818.

Blair, A., B. Ritz, C. Wesseling and L.B. Freeman (2015). Pesticides and human health. *Occupational and Environmental Medicine,* 72(2): 81–82.

Brühl, C.A. and J.G. Zaller (2019). Biodiversity decline as a consequence of an inappropriate environmental risk assessment of pesticides. *Frontiers in Environmental Science,* 7: 464007.

Cardinale, B.J., J.E. Duffy, A. Gonzalez, *et al*. (2012). Biodiversity loss and its impact on humanity. *Nature,* 486(7401): 59-67.

Chagnon, M., D. Kreutzweiser, E.A. Mitchell, C.A. Morrissey, D.A. Noome and J.P. Van der Sluijs (2015). Risks of large-scale use of systemic insecticides to ecosystem functioning and services. *Environmental Science and Pollution Research,* 22: 119–134.

Ebadi, A.G. and H. Hisoriev (2018a). *Cladophora glomerata* L. as indicator of chemical pollution in coastal areas of Farahabad Region, Iran. *Revista Publicando*, 5(14(2)): 183-191.

Ebadi, A.G. and H. Hisoriev (2018b). Physicochemical characterization of sediments from Tajan River Basin in the Northern Iran. *Toxicological and Environmental Chemistry*, 100(5–7): 540-549.

Ebadi, A.G. and H. Hisoriev (2018c). Metal pollution status of Tajan River – Northern Iran. *Toxicological and Environmental Chemistry,* 99(9–10): 1358-1367.

Ebadi, A.G., H. Hisoriev and K. Aliev (2017). Measurement of some chemical and biochemical parameters in Cladophora glomerata L. from Farahabad Region of Iran. *Bulgarian Chemical Communication*, 49: 540-544.

Ebadi, A.G., F. Boufahja, S.A. Basim and Z. Selamoglu (2025). Fish as bioindicators: Monitoring environmental mercury pollution with aquatic food webs – A mini review. *International Journal of Environmental Science and Green Technology,* 1(1): 56–65.

Fairbrother, A., B. Hartl, B.K. Hope, J.J. Jenkins, Y.W. Li and D.R. Moore (2016). Risk management decisions for pesticides and threatened and endangered species: The role of uncertainty analysis. *Human and Ecological Risk Assessment: An International Journal,* 22(2): 502–518.

Fenibo, E.O., G.N. Ijoma and T. Matambo (2021). Biopesticides in sustainable agriculture: A critical sustainable development driver governed by green chemistry principles. *Frontiers in Sustainable Food Systems,* 5: 619058.

Haroon, B., M. Irshad, A.G. Ebadi and P. An. (2022). Soil metal contamination and its mitigation. *Sustainable Plant Nutrition Under Contaminated Environments,* Springer International Publishing, pp. 17–40.

He, D.C., M.H. He, D.M. Amalin, W. Liu, D.G. Alvindia and J. Zhan (2021). Biological control of plant diseases: An evolutionary and eco-economic consideration. *Pathogens,* 10(10):1311.

Horrigan, L., R.S. Lawrence and P. Walker (2002). How sustainable agriculture can address the environmental and human health harms of industrial agriculture. *Environmental Health Perspectives*, 110(5): 445-456.

Khan, R., A. Noorpoor and A.G. Ebadi. (2022). Effects of air contamination on agriculture. *Sustainable Plant Nutrition Under Contaminated Environments*, Springer International Publishing, pp. 1–16.

Kumar, P., R. Kumar, K. Thakur, D. Mahajan, B. Brar, D. Sharma, S. Kumar and A.K. Sharma (2023). Impact of pesticides application on aquatic ecosystem and biodiversity: A review. *Biology Bulletin,* 50(6): 1362–1375.

Liu, J., Y. Xie, J. Ren, L. Han, C. Jing, G. Lu, J. Hou and W. Ji (2025). Occurrence characteristics, source analysis, and ecological risk of PFASs in different cultivated soil at an urban scale in Yangtze River Basin. *Emerging Contaminants,* 11(1): 100413.

Lohr, M.T. and R.A. Davis (2018). Anticoagulant rodenticide use, non-target impacts and regulation: a case study from Australia. *Science of the Total Environment,* 634: 1372–1384.

Meryem, S.S., A. Pervez and A.G. Ebadi. (2022). Role of quorum sensing in nutrient acquisition and synergistic plant-microbe association. *Sustainable Plant Nutrition Under Contaminated Environments*, Springer International Publishing, pp. 287–308.

Mgendi, G. (2024). Unlocking the potential of precision agriculture for sustainable farming. *Discover Agriculture,* 2(1): 87.

Momeniha, F., H. Janjani, M. Aghaei, M.H. Dehghani, A. Salimifard, S. Suhas and N. Mujawar Mubarak (2025). A systematic review of occurrence and concentrations of selected phthalic acid esters in waste processing and management facilities: Challenges and the future research perspectives. *Emerging Contaminants,* 11(1): 100407.

Parveen, A., M.A. Ashraf, I. Hussain, S. Perveen, R. Rasheed, A.G. Ebadi and S. Thind (2022). Potential of inorganic fertilizers for sustainable development in agriculture. *Sustainable Plant Nutrition Under Contaminated Environments*, Springer International Publishing, pp. 41–55.

Relyea, R.A. (2005). The impact of insecticides and herbicides on the biodiversity and productivity of aquatic communities. *Ecological Applications,* 15(2): 618–627.

Shah, A.M.U.H., A. Ditta, A. Parveen, S. Thind and A.G. Ebadi. (2022). Transcription factors that scavenge reactive oxygen species in rhizobacteria. *Sustainable Plant Nutrition Under Contaminated Environments*, Springer International Publishing, pp. 235–256.

Sharma, A., P. Jha and G.V. Reddy (2018). Multidimensional relationships of herbicides with insect-crop food webs. *Science of the Total Environment*, 643: 1522–1532.

Staley, Z.R., V.J. Harwood and J.R. Rohr (2015). A synthesis of the effects of pesticides on microbial persistence in aquatic ecosystems. *Critical Reviews in Toxicology,* 45(10): 813–836.

Thompson, D.G., K.R. Solomon, B.F. Wojtaszek, A.N. Edginton, G.R. Stephenson and R.A. Relyea (2006). The impact of insecticides and herbicides on the biodiversity and productivity of aquatic communities: [with response]. *Ecological Applications*, 16(5): 2022–2034.

Tsalidis, G.A. (2022). Human health and ecosystem quality benefits with life cycle assessment due to fungicides elimination in agriculture. *Sustainability,* 14(2): 846.

Yadav, S.K. (2010). Pesticide applications-threat to ecosystems. *Journal of Human Ecology,* 32(1): 37-45

Zare, S., A.G. Ebadi and M. Babaee (2005). Measurement and survey of organochlorine pesticides (OCPs) level in milk samples of agricultural workers (Mazandaran–Iran). *International Journal of Biology and Biotechnology*, 2(4): 967–970.

Zeb, B.S., M.T. Hayat, T. Zeb, F.Y. Khan, H.Z. Abbasi, I. Nawaz and A.G. Ebadi. (2022). Uptake of organic pollutants and the effects on plants. *Sustainable Plant Nutrition Under Contaminated Environments*, Springer International Publishing, pp. 209–234.

Zhou, W., M. Li and V. Achal. (2025). A comprehensive review on environmental and human health impacts of chemical pesticide usage. *Emerging Contaminants,* 11(1): 100410.

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