

# Environmental and Public Health Impacts of Pesticides: A Comprehensive Review Study

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**Abstract:** Pesticides play a crucial role in contemporary agricultural practices, serving to manage pests, weeds, and diseases that can diminish crop yields. The application of pesticides is crucial for augmenting agricultural productivity and ensuring food security; however, their overuse or misuse has engendered significant apprehension concerning environmental contamination and public health. Pesticide residues can spread through soil, water, air, and food. This can potentially harm the environment and reduce biodiversity. People exposed to pesticides can experience immediate poisoning, neurological problems, reproductive issues, and an increased risk of cancer. This review analyses the environmental and public health effects of pesticides, based on a thorough examination of existing research. The text dives into the mechanisms of pesticide toxicity, the pathways of exposure, and sustainable management strategies, such as integrated pest management and biological control. The investigation underscores a pressing need for safer ways to apply pesticides, along with tougher rules and a shift toward more environmentally friendly options. These measures are essential to mitigate environmental pollution and protect public health.

**Keywords:** Pesticides, Environmental pollution, Human health, Toxicity, Integrated pest management

## INTRODUCTION

Agriculture's significance in supporting the expanding global population is undeniable, functioning as a fundamental element for ensuring food security and fostering economic advancement. Nevertheless, agricultural productivity is continually challenged by a range of pests, encompassing insects, weeds, fungi, and rodents, all of which inflict damage on crops and diminish overall yields (Pawlak and Kołodziejczak 2020). Consequently, the use of pesticides has become a vital component of modern agricultural practices, designed to combat these significant challenges. Pesticides, whether chemical concoctions or biological agents, serve a singular purpose: to fend off, eradicate, or manage pests that threaten crops, stored provisions, and livestock. These applications have been crucial in increasing agricultural productivity, protecting crops from diseases, and ensuring a stable global food supply (Aktar, Sengupta, and Chowdhury 2009).

The application of pesticides saw a significant rise in the mid-20th century, especially following the Green Revolution, which brought forth high-yield crop varieties, advanced irrigation systems, and contemporary agricultural practices (Pretty and Bharucha 2014). Throughout this time, the widespread use of chemical pesticides emerged as a prominent strategy for managing pests and improving agricultural yields. Agricultural producers increasingly depended on these substances to mitigate crop losses and enhance productivity. Pesticides are now widely used in agricultural systems worldwide. Different types of pesticides, such as insecticides, herbicides, fungicides, and rodenticides, are commonly used in both agricultural and non-agricultural settings (Rajak et al. 2023).

Although pesticides are useful for protecting crops and increasing food production, their overuse and misuse have raised significant concerns about environmental health and public safety. Many pesticides, designed to harm living things, have the potential to affect non-target species (Oirdi et al. 2024). This includes beneficial insects, birds, aquatic organisms, and soil microorganisms. Furthermore, specific pesticides demonstrate considerable environmental persistence, allowing them to maintain activity over prolonged periods and accumulate within ecosystems (Lazarević-Pašti et al. 2025). This sustained presence heightens the potential for environmental contamination and destabilizes ecological equilibrium. Pesticides can infiltrate the environment via multiple routes. When pesticides are used in farming, tiny particles can become airborne. These particles then settle on the surrounding soil, water, and plants. Rainfall and irrigation can facilitate the movement of these chemicals from agricultural fields into nearby water systems, such as rivers, lakes, and aquifers, through runoff and leaching (Albaseer et al. 2025).

The infiltration of these substances into natural ecosystems can result in the pollution of soil, water, and the atmosphere, thereby affecting both terrestrial and aquatic environments. Furthermore, certain pesticides can accumulate within living organisms and propagate through the food web, a phenomenon known as bioaccumulation and biomagnification. As a result, this process can increase the concentration of harmful substances in organisms higher up the food chain, including humans (Nuruzzaman, Bahar, and Naidu 2025).

The use of pesticides in the environment has significant effects, impacting both biodiversity and the overall health of ecosystems. Beneficial organisms, encompassing pollinators, pest predators, and soil microorganisms, are indispensable for maintaining ecological equilibrium and augmenting agricultural yields. Conversely, the application of pesticides poses a threat to these populations, thereby contributing to a reduction in biodiversity and a disturbance of ecosystem processes (Elhamalawy, Bakr, and Eissa 2024). For example, pollinators, such as bees, are very sensitive to certain pesticides. As a result, their decline can negatively affect the pollination of crops and, in turn, food production. Beyond environmental consequences, exposure to pesticides presents significant dangers to human health. People can be exposed to pesticides in several ways. These include eating food with pesticide residues, drinking water that has been contaminated, breathing in pesticide sprays, and direct skin contact during agricultural work. Farmers and agricultural workers face significant risks due to their regular exposure to pesticides during handling and application (Shekhar et al. 2024).

Acute pesticide poisoning can precipitate the swift emergence of symptoms, encompassing headaches, vertigo, nausea, respiratory difficulties, and dermal irritation. In instances of heightened exposure, more severe consequences may manifest, potentially resulting in neurological damage or even death (Hailu et al. 2025). Furthermore, extended exposure to low concentrations of pesticides has been correlated with a spectrum of chronic health complications. Numerous scientific investigations have established correlations between exposure to pesticides and a spectrum of health issues, encompassing cancer, endocrine system disruption, reproductive difficulties, developmental irregularities, and neurological conditions like Parkinson's disease (Thundiyl 2008).

The health risks identified underscore the necessity for careful monitoring and regulation of pesticide use, with the goal of protecting the environment and human health. Over the past few decades, there has been a growing awareness of the harmful effects of pesticides. Consequently, experts, policymakers, and environmental organizations have begun to investigate safer and more sustainable alternatives (Beyuo et al. 2024). Integrated pest management (IPM), biological pest control, and the development of eco-friendly pesticides have all gained importance. These methods aim to reduce the use of chemical pesticides while still effectively controlling pests, and maintaining agricultural productivity. Given the widespread use of pesticides and the potential risks they pose, a thorough understanding of their effects on the environment and human health is essential (Zhou et al. 2024).

This review paper aims to analyze the current understanding of pesticide contamination in the environment and its effects on ecosystems and public health. It also examines management strategies that promote sustainability, reduce pesticide-related risks, support agricultural growth, and protect the environment. By combining existing research, this study seeks to clarify the challenges associated with pesticides and encourage the use of safer and more sustainable farming practices.

### Types of Pesticides

Pesticides are widely used in agriculture and public health to protect crops and control organisms that threaten food production and human health. These substances can be classified in different ways, depending on the organisms they target or their chemical structure. Understanding how pesticides are classified is essential for evaluating their effectiveness, how they behave in the environment, and their potential effects on human health (Tudi et al. 2021).

#### Based on the Target Organism

Pesticides are often categorized based on the organisms they are designed to control. Different pesticides are created to control specific pests that harm crops or spread diseases (Verdadero et al. 2025).

**Insecticides** are pesticides specifically formulated to control harmful insects that feed on crops or transmit diseases. They are widely used in agriculture to protect crops from pests such as aphids, beetles, caterpillars, and mosquitoes. While insecticides help reduce crop losses, they may also affect beneficial insects such as pollinators and natural predators (Souto et al. 2021).

**Herbicides** are chemicals used to control unwanted plants or weeds that compete with crops for nutrients, sunlight, and water. These pesticides are commonly applied in agricultural fields, lawns, and public spaces to maintain crop productivity and manage vegetation growth (Paul, Mazumder, and Naidu 2024).

**Fungicides** are used to prevent or eliminate fungal infections that cause plant diseases. Fungal pathogens can significantly reduce crop yields and quality. Fungicides help protect crops from diseases such as rust, mildew, and blight by inhibiting fungal growth and reproduction (Islam et al. 2024).

**Rodenticides** are designed to control rodents such as rats and mice that damage crops, stored food, and agricultural infrastructure. These pesticides are often used in both agricultural and urban environments to reduce rodent populations (Fisher et al. 2019).

### Based on Chemical Structure

Pesticides can also be classified according to their chemical composition. Different chemical groups vary in terms of toxicity, persistence, and environmental behaviour (Thapa et al. 2022).

**Organochlorines**, such as DDT, are highly persistent compounds that remain in the environment for long periods and tend to accumulate in the food chain. Due to their environmental persistence and toxicity, many organochlorines have been banned or restricted in several countries (Jayaraj, Megha, and Sreedev 2016).

**Organophosphates** are widely used insecticides that act by disrupting the nervous system of pests. Although effective, they are generally more toxic to humans and animals than many other pesticide groups (Saad et al. 2025).

**Carbamates** are chemically similar to organophosphates and also affect the nervous system of insects. However, they are typically less persistent in the environment (Mdeni et al. 2022).

**Pyrethroids** are synthetic chemicals derived from natural pyrethrins found in chrysanthemum flowers. They are commonly used due to their effectiveness and relatively lower toxicity to mammals compared to other pesticide classes (Ruberti 2024).

These different pesticide groups exhibit varying levels of toxicity, environmental persistence, and ecological impact, which must be carefully considered in pesticide management and regulation (Garud et al. 2024).

## ENVIRONMENTAL IMPACT OF PESTICIDES

### Soil Contamination

Soil is a crucial environmental component, and it accumulates pesticide residues after these chemicals are used in agriculture. After applying sprays or soil treatments, a significant amount of pesticides accumulates on the soil surface. These pesticides then undergo various physical, chemical, and biological changes (Yasir, Hossain, and Pratap-Singh 2025).

Pesticides are often designed to be chemically stable, which helps them work well against pests for a long time. However, this stability can lead to pesticide residues building up in the soil, which can cause lasting environmental damage. The persistence of pesticides in soil is contingent upon a multitude of factors, including the pesticide's chemical structure, the soil's composition, microbial activity, temperature, moisture content, and pH (Perpetuini et al. 2023).

Some pesticides are subject to swift degradation through microbial metabolism or chemical processes, whereas others demonstrate stability, persisting for months or even years. Persistent pesticide residues tend to strongly bind to soil particles and organic matter, thereby hindering their removal from the environment (Chowdhury et al. 2025). The progressive buildup of these substances could potentially disrupt the equilibrium inherent in soil ecosystems. Soil microorganisms, including bacteria, fungi, and actinomycetes, are essential for preserving soil vitality, facilitating nutrient cycling, decomposing organic material, and fostering the formation of soil structure. Nonetheless, the presence of pesticide residues can impede the growth and functionality of these microorganisms (Timmis and Ramos 2021).

Some pesticides have been observed to diminish microbial biomass and enzyme activity in soil, potentially interfering with vital biochemical processes. This disruption could reduce the availability of nutrients for plants and lower soil fertility. In addition to microorganisms, various beneficial soil organisms, such as earthworms, are notably affected by pesticide contamination (Arora and Sahni 2016). Earthworms are essential for improving soil aeration, helping water to seep in, and breaking down organic matter. When exposed to harmful pesticide residues, earthworms may experience reduced survival, reproductive difficulties, and behavioral changes. The reduction in earthworm populations may have detrimental effects on soil structure and can lead to decreased productivity in agricultural lands (Oleszczuk et al. 2014).

A significant environmental concern is the potential for pesticide residues to move from the soil to other parts of the ecosystem (Verma, 2025.). Volatilization, erosion, and leaching are some of the ways that pesticides can get from the soil to the air or groundwater. In certain instances, the continuous use of pesticides can lead to an accumulation of harmful substances in the soil, heightening the potential for prolonged environmental pollution (Acharya et al. 2025).

In summary, the presence of pesticides in soil can significantly affect biological activity, reduce fertility, and jeopardize the sustainability of agricultural ecosystems. Therefore, effective pesticide management practices, such as careful application, using less persistent chemicals, and adopting sustainable agricultural methods, are crucial for reducing soil pollution (Yahyah, Kameri-Mbote, and Kibugi 2024).

### Water Pollution

The application of pesticides engenders considerable environmental challenges, especially with respect to water pollution. Pesticides employed in agricultural practices are prone to contaminating nearby water sources through processes such as surface runoff, spray drift, and leaching (Verma 2025b). During rainfall or irrigation, pesticide residues on the soil surface

can be transported into diverse water bodies, encompassing rivers, lakes, streams, and reservoirs. Moreover, certain pesticides demonstrate substantial water solubility, facilitating their movement through soil profiles and resulting in the contamination of groundwater (Kalyabina et al. 2021).

The presence of pesticide residues within aquatic ecosystems poses considerable threats to aquatic life. Fish, algae, amphibians, and aquatic invertebrates demonstrate increased susceptibility to chemical contaminants; even trace amounts of pesticides can induce adverse consequences (Verma 2025a). Aquatic organisms can experience physiological changes, reproductive issues, and developmental problems due to pesticide exposure (Saha and Dutta 2024).

In severe cases, elevated levels of contamination can precipitate fish mortality and the decline of at-risk aquatic species. Prolonged exposure to water contaminated with pesticides has the potential to disrupt aquatic food webs and the overall balance of ecosystems. Pesticides that adversely affect algal and plankton populations can disrupt the primary productivity of aquatic ecosystems, a critical component of the food web's base. Likewise, detrimental effects on aquatic insects and small invertebrates can reduce the food availability for fish and other organisms situated at higher trophic levels (Mustafa, Al-Rudainy, and Salman 2024).

Moreover, the presence of pesticides in groundwater presents a significant environmental challenge, particularly in areas with intensive agricultural practices. The widespread reliance on groundwater for potable and agricultural purposes necessitates consideration of the potential hazards posed by pesticide residues, which can adversely affect both human well-being and environmental integrity. Therefore, carefully regulating and overseeing how pesticides are used near water sources is essential to reduce the ongoing pollution of aquatic ecosystems (Kashyap, Garg, and Arora 2024).

### **Impact on Non-Target Organisms**

Although pesticides are designed to control specific pests, they often affect many non-target organisms present in the environment. Non-target species include beneficial insects, birds, mammals, soil organisms, and aquatic life that play important roles in maintaining ecological balance. Exposure to pesticides can occur directly through contact with sprayed chemicals or indirectly through contaminated food, water, and habitats (Ahmad et al. 2024).

Pollinators such as bees, butterflies, and other insects are among the most vulnerable groups affected by pesticide exposure. These organisms are essential for the pollination of many crops and wild plants, contributing significantly to global food production and biodiversity. However, certain pesticides, particularly systemic insecticides, have been shown to impair the nervous system of bees, affecting their ability to navigate, forage, and communicate. Prolonged exposure can lead to reduced colony growth, weakened immunity, and decreased reproductive success (Sponsler et al. 2019).

Birds and other wildlife species may also be affected by pesticide contamination. Birds that feed on pesticide-treated insects or seeds can accumulate toxic chemicals in their bodies, which may cause behavioural changes, reproductive failure, or mortality. Similarly, natural predators such as lady beetles, spiders, and parasitic wasps—which help control pest populations naturally—can be harmed by pesticide exposure. The reduction of these beneficial predators may ultimately lead to increased pest outbreaks and greater dependence on chemical pesticides (Gibbons, Morrissey, and Mineau 2015).

### **Bioaccumulation and Biomagnification**

The phenomenon of bioaccumulation and biomagnification represents a critical environmental issue linked to the use of pesticides. Bioaccumulation is the process by which chemical substances gradually accumulate in the tissues of living organisms over time. Some pesticides, especially those that are persistent organic compounds, resist degradation through biological processes and tend to accumulate in the fatty tissues of living organisms (Ray and Shaju 2023).

The consumption of contaminated organisms by predators leads to the transfer of pesticide residues throughout the food chain. This phenomenon, referred to as biomagnification, leads to increasingly elevated levels of harmful substances at each subsequent trophic level. For instance, diminutive aquatic organisms that take in pesticide residues from water can be ingested by fish, which are subsequently preyed upon by larger predators like birds or mammals. At every level of the food chain, the accumulation of pesticides intensifies, resulting in more pronounced toxic effects on organisms higher up the chain (Acosta-Lizárraga et al. 2026).

As apex organisms in numerous ecosystems, humans exhibit a heightened susceptibility to the consequences of biomagnification. The intake of contaminated food items, including fish, meat, fruits, and vegetables, can result in the buildup of pesticide residues within the human body. Prolonged exposure to these substances could lead to a range of health issues, such as neurological disorders, disruption of endocrine functions, and a heightened risk of chronic diseases (Saidon et al. 2024).

Consequently, grasping the mechanisms of bioaccumulation and biomagnification is crucial for evaluating the enduring environmental and health hazards linked to pesticide application and for formulating more secure pest management approaches (Muñoz-Bautista et al. 2025).

**IMPACT OF PESTICIDES ON PUBLIC HEALTH**

The extensive application of pesticides within agricultural practices has engendered considerable apprehension concerning their potential ramifications for human well-being. Although pesticides are indispensable for safeguarding crops and managing disease vectors, their intrinsic toxicity can precipitate a range of detrimental health outcomes subsequent to human exposure. People can be exposed to pesticides through their jobs, environmental pollution, and consuming food or water that has been contaminated. Both short-term and long-term exposure have been linked to serious health problems, particularly among farmers, agricultural workers, and people living near agricultural areas (Suwanaruang 2024).

**Acute Health Effects**

Acute pesticide poisoning occurs when a person comes into contact with a significant quantity of pesticide all at once. Such exposure often happens because of accidental spills, improper handling, or using too much of the chemical. Agricultural workers face heightened risks. Their routine mixing, loading, and application of pesticides means they have frequent, direct exposure to these chemicals. Even short-lived exposure to these dangerous substances can lead to a range of immediate health issues. Headaches, feelings of dizziness, nausea, vomiting, and stomach pain are frequently reported. Pesticides frequently induce skin irritation and allergic responses upon direct contact. Exposure to the ocular region may precipitate redness, irritation, and, in some instances, transient visual impairments (Damalas and Koutroubas 2016). Furthermore, inhalation of pesticide vapors or aerosols can engender respiratory complications. Symptoms can include coughing, difficulty breathing, a feeling of tightness in the chest, and a sore throat. The severity of acute pesticide poisoning is contingent upon several variables, including the inherent toxicity of the chemical, the duration of exposure, and the route of entry into the body. In cases of extreme exposure, contact with highly toxic pesticides, particularly certain organophosphate and carbamate compounds, can disrupt normal neurological function (Upadhayay et al. 2020). This disruption may manifest as muscle weakness, convulsions, impaired coordination, and, in the most severe cases, respiratory failure or fatality. Consequently, prompt medical attention is often essential to prevent serious health consequences (Racca et al. 2020).

**Chronic Health Effects**

While the immediate consequences of acute pesticide poisoning are frequently evident, the public health implications stemming from extended exposure to low concentrations of pesticides are more complex and substantial. Sustained exposure can arise from regular contact with pesticide residues found in food, drinking water, soil, and the atmosphere. Consequently, even minimal exposure to these substances can accumulate within the human body over time, potentially resulting in chronic health issues (Pathak et al. 2022).

Numerous scientific studies have shown connections between long-term exposure to pesticides and a range of serious health problems. A significant area of research focuses on the possible link between pesticide exposure and different types of cancer. Certain pesticides are classified as probable or possible carcinogens, which suggests a potential increase in the risk of cancers such as leukaemia, lymphoma, and prostate cancer. Moreover, pesticides have demonstrated the capacity to impact the nervous system. Prolonged exposure to neurotoxic pesticides could potentially trigger neurological disorders, which may manifest as cognitive decline, memory impairments, and neurodegenerative diseases, including Parkinson's disease (Sarwar 2016).

The effects of these factors are especially concerning for people who are exposed to them for long periods in their jobs. Pesticides can potentially act as endocrine disruptors, which means they can interfere with the hormonal systems that control growth, metabolism, and reproduction. Such disruption can result in a range of adverse outcomes, including reproductive difficulties, infertility, hormonal imbalances, and developmental problems in children. Furthermore, pregnant women exposed to pesticides may face an elevated risk of miscarriage, congenital anomalies, or complications related to fetal development. Consequently, these observations underscore the potential for significant long-term health risks linked to ongoing exposure to pesticide residues (Mnif et al. 2011).

**Exposure Pathways**

Human exposure to pesticides can take place through various routes. A prevalent pathway involves the intake of tainted food and water sources. Fruits, vegetables, and other agricultural products can harbour pesticide residues if they are not adequately washed or if there is an over-application of pesticides during their cultivation (Liu et al. 2024).

The inhalation of pesticide sprays and airborne particles represents a notable exposure pathway, especially for those engaged in agriculture and residents in proximity to treated fields. During the application of pesticides, minute droplets may disperse through the atmosphere and be inhaled by individuals in close proximity. Skin contact serves as a significant pathway for exposure, particularly during the processes of pesticide mixing, application, and equipment cleaning (Boonupara et al. 2023).

Environmental residues present in soil, dust, and household surfaces can lead to indirect exposure, especially for children, who are particularly susceptible because of their developing immune systems and their frequent interactions with contaminated surfaces. Inadequate management of pesticides, insufficient storage practices, and the absence of suitable personal protective equipment significantly elevate the risk of human exposure (Buralli et al. 2025).

In summary, the possible health hazards linked to pesticide exposure highlight the necessity for enhanced safety measures, more stringent regulatory frameworks, and greater public consciousness. Implementing effective pesticide management strategies and advocating for safer alternatives are crucial measures for safeguarding human health and alleviating the worldwide impact of pesticide-related illnesses (Othman Said 2026).

### **GLOBAL CONCERNS AND RECENT FINDINGS**

In recent years, accumulating scientific evidence has underscored the escalating environmental and health issues linked to the extensive application of pesticides. A multitude of studies carried out in various regions globally suggest that pesticide contamination poses a considerable risk to ecosystems and biodiversity. A significant issue is the rising toxicity of pesticide mixtures found in the environment, which can negatively impact a range of non-target organisms. Studies indicate that insects, especially those that provide benefits like pollination, are significantly at risk from pesticide exposure. The reduction in pollinator populations, such as bees and butterflies, has been closely associated with the widespread application of specific chemical pesticides, which can negatively affect their navigation, reproduction, and overall survival (Punniyakotti et al. 2024).

Alongside insects, soil organisms, including earthworms, bacteria, and fungi, experience detrimental impacts due to pesticide contamination. The role of these organisms is essential for sustaining soil fertility, facilitating nutrient cycling, and ensuring overall soil health. The accumulation of pesticides in soil has the potential to disrupt microbial communities, leading to a decline in soil productivity over time (Saharan et al. 2025). In a similar vein, aquatic ecosystems face growing threats from pesticide runoff originating from agricultural fields. A significant number of investigations have documented the occurrence of pesticide residues in rivers, lakes, and groundwater, posing risks to fish, amphibians, and various aquatic species (Dhuldhaj, Singh, and Singh 2022).

A rising global issue is the identification of pesticide residues in food items, especially in fruits and vegetables. Investigations conducted across various nations have detected quantifiable amounts of pesticide residues in widely consumed food items. While numerous residues remain within established regulatory thresholds, ongoing exposure to minimal pesticide levels could potentially lead to long-term health concerns for consumers (Tadesse et al. 2025). The results highlight the necessity for enhanced regulations, better monitoring frameworks, and the advocacy of safer agricultural methods to mitigate pesticide contamination and safeguard environmental and human well-being (Mengistie, Ray, and Iyanda 2025).

### **SUSTAINABLE PEST MANAGEMENT STRATEGIES**

Sustainable pest management strategies have developed because of the growing environmental and health problems caused by using too many pesticides. These strategies focus on reducing dependence on chemical pesticides while ensuring effective pest management and sustaining agricultural output. Sustainable pest management emphasizes practices that are kind to the environment, aiming to minimize ecological harm, safeguard biodiversity, and promote enduring agricultural viability (Shang et al. 2024).

#### **Integrated Pest Management (IPM)**

Integrated Pest Management (IPM) stands out as a highly endorsed strategy for achieving sustainable pest control. IPM represents a comprehensive approach that combines various pest management techniques, such as biological, cultural, mechanical, and chemical methods. The main aim of integrated pest management is to regulate pest populations to economically viable levels, all while reducing risks to human health and the environment. This method uses pesticides in a targeted way, only applying them, when necessary, which reduces the use of chemicals. Integrated Pest Management (IPM) involves observing pest populations and using crops that are resistant to pests, varieties, and the implementation of crop rotation strategies to mitigate the risk of pest outbreaks (Karlsson Green, Stenberg, and Lankinen 2020).

#### **Biological Control**

Biological control offers a substantial strategy for reducing dependence on chemical pesticides. This technique employs natural adversaries, encompassing predators, parasites, and microorganisms, to regulate pest populations. Within agricultural settings, beneficial insects, like lady beetles, parasitic wasps, and spiders, are crucial for the natural management of pest populations. Furthermore, certain bacteria and fungi function as biological agents, specifically targeting and eradicating harmful pests. These biological control strategies offer environmental benefits by concentrating on particular pests, thus mitigating the effects on non-target organisms and ecosystems (Shao et al. 2026).

**Bioremediation**

Bioremediation offers an environmentally friendly method for reducing pesticide pollution in the environment. This process uses microorganisms, such as bacteria and fungi, to break down or neutralize pesticide residues found in soil and water. These microorganisms break down complex pesticide molecules into less harmful substances, which helps to reduce pollution in the environment. Bioremediation has become a popular method for restoring polluted environments and reducing the lasting effects of pesticide use (Kuppan et al. 2024).

**DEVELOPMENT OF SAFER PESTICIDES**

Growing concerns about the environmental and health effects of traditional pesticides have led to a focus on creating safer and more sustainable alternatives. Contemporary studies focus on developing pesticides that are environmentally friendly, exhibit lower toxicity to non-target species, and can decompose swiftly in natural settings. The development of these safer pesticides aims to ensure effective pest management while reducing adverse impacts on ecosystems and human health (Khursheed et al. 2022). A potentially beneficial strategy entails the creation of bio-based pesticides derived from natural sources, including plants, bacteria, and fungi. These biological pesticides are generally considered more environmentally sound, owing to their targeted action against specific pests and their swift degradation within soil and aquatic environments. Moreover, advancements in nanotechnology and green chemistry are significantly contributing to the development of more effective pesticides that demonstrate reduced environmental persistence. The evolution of safer pesticides represents a vital advancement in sustainable agriculture, as it mitigates ecological damage and protects public health, concurrently maintaining agricultural productivity (Ayilara et al. 2023).

**CONCLUSION**

Pesticides are crucial in modern agriculture, protecting crops and increasing food production. However, their widespread and often improper use has led to significant environmental pollution and health problems. Pesticide residues introduce pollutants into soil, water, and food webs, thereby affecting biodiversity and ecosystem equilibrium. Furthermore, pesticide exposure poses a range of health risks, manifesting both acutely and chronically. These health effects encompass neurological impairments, reproductive dysfunctions, and an elevated susceptibility to cancer. Therefore, implementing sustainable pest management strategies, including integrated pest management, biological control, and bioremediation, is crucial.

To ensure the safe and responsible use of pesticides, strong regulations, thorough farmer training, and increased public awareness are essential. Future research should focus on creating sustainable alternatives that improve agricultural productivity while also protecting the environment and public health.

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**Ravi Verma** Formal analysis, Investigation, Original draft, Writing - review & editing.

**CONFLICT OF INTEREST**

The authors have no conflicts of interest to declare that are relevant to the content of this article.

**DATA AVAILABILITY STATEMENT**

The data that support the findings of this study are available on request from the corresponding author.

**REFERENCES**

- [1]. Acharya, Licon Kumar, Pradosh Kumar Paramaguru, Kailashpati Tripathi, Tanmay Kumar Bhoi, Pinki Seth, and Ajanta Birah. 2025. "Pesticide Contamination in Groundwater: Processes, Risks, and Mitigation Strategies." *Discover Agriculture* 3 (1): 152. <https://doi.org/10.1007/s44279-025-00337-x>.
- [2]. Acosta-Lizárraga, L. Gilyary, Susana Rodríguez-Jurado, Magdalena E. Bergés-Tiznado, Humberto Aguirre-Becerra, Karen Esquivel Escalante, Claudia E. Pérez-García, and Ana A. Feregrino-Pérez. 2026. "Biomagnification of

- Potentially Toxic Elements and Metal-Based Nanomaterials in Food.” *Environments* 13 (2): 116. <https://doi.org/10.3390/environments13020116>.
- [3]. Ahmad, Md Faruque, Fakhruddin Ali Ahmad, Abdulrahman A. Alsayegh, Md. Zeyauallah, Abdullah M. AlShahrani, Khursheed Muzammil, Abdullah Ali Saati, et al. 2024. “RETRACTED: Pesticides Impacts on Human Health and the Environment with Their Mechanisms of Action and Possible Countermeasures.” *Heliyon* 10 (7): e29128. <https://doi.org/10.1016/j.heliyon.2024.e29128>.
- [4]. Aktar, Wasim, Dwaipayana Sengupta, and Ashim Chowdhury. 2009. “Impact of Pesticides Use in Agriculture: Their Benefits and Hazards.” *Interdisciplinary Toxicology* 2 (1): 1–12. <https://doi.org/10.2478/v10102-009-0001-7>.
- [5]. Albaseer, Saeed S., Veerle L.B. Jaspers, Luisa Orsini, Penny Vlahos, Hussein E. Al-Hazmi, and Henner Hollert. 2025. “Beyond the Field: How Pesticide Drift Endangers Biodiversity.” *Environmental Pollution* 366 (February 2025): 125526. <https://doi.org/10.1016/j.envpol.2024.125526>.
- [6]. Arora, Sanjay, and Divya Sahni. 2016. “Pesticides Effect on Soil Microbial Ecology and Enzyme Activity- An Overview.” *Journal of Applied and Natural Science* 8 (2): 1126–1132. <https://doi.org/10.31018/jans.v8i2.929>.
- [7]. Ayilara, Modupe S., Bartholomew S. Adeleke, Saheed A. Akinola, Chris A. Fayose, Uswat T. Adeyemi, Lanre A. Gbadegesin, Richard K. Omole, Remilekun M. Johnson, Qudus O. Uthman, and Olubukola O. Babalola. 2023. “Biopesticides as a Promising Alternative to Synthetic Pesticides: A Case for Microbial Pesticides, Phytopesticides, and Nanobiopesticides.” *Frontiers in Microbiology* 14 (February 2023). <https://doi.org/10.3389/fmicb.2023.1040901>.
- [8]. Beyuo, Janet, Lyndon N. A. Sackey, Cornelius Yeboah, Phebe Y. Kayoung, and Delphine Koudadje. 2024. “The Implications of Pesticide Residue in Food Crops on Human Health: A Critical Review.” *Discover Agriculture* 2 (1): 123. <https://doi.org/10.1007/s44279-024-00141-z>.
- [9]. Boonupara, Thirasant, Patchimaporn Udomkun, Eakalak Khan, and Puangrat Kajitvichyanukul. 2023. “Airborne Pesticides from Agricultural Practices: A Critical Review of Pathways, Influencing Factors, and Human Health Implications.” *Toxics* 11 (10): 858. <https://doi.org/10.3390/toxics11100858>.
- [10]. Buralli, Rafael, Siti Nurshahida Nazli, Leonel Cordoba, Lesliam Quiros-Alcala, Carly Hyland, María Teresa Muñoz-Quezada, Paulina Fariás, and Alexis J. Handal. 2025. “Children’s Environmental and Occupational Exposures to Pesticides in Low- and Middle-Income Countries Rural Areas - an Elephant in the Room.” *Science of The Total Environment* 990 (August 2025): 179887. <https://doi.org/10.1016/j.scitotenv.2025.179887>.
- [11]. Chowdhury, Imtiaz Faruk, Gregory S. Doran, Benjamin J. Stodart, Chengrong Chen, and Hanwen Wu. 2025. “Microbial Degradation of Herbicide Residues in Australian Soil: An Overview of Mechanistic Insights and Recent Advancements.” *Toxics* 13 (11): 949. <https://doi.org/10.3390/toxics13110949>.
- [12]. Damalas, Christos, and Spyridon Koutroubas. 2016. “Farmers’ Exposure to Pesticides: Toxicity Types and Ways of Prevention.” *Toxics* 4 (1): 1. <https://doi.org/10.3390/toxics4010001>.
- [13]. Dhuldhaj, Umesh Pravin, Rishikesh Singh, and Vipin Kumar Singh. 2022. “Pesticide Contamination in Agro-Ecosystems: Toxicity, Impacts, and Bio-Based Management Strategies.” *Environmental Science and Pollution Research* 30 (4): 9243–9270. <https://doi.org/10.1007/s11356-022-24381-y>.
- [14]. Elhamalawy, Osama, Ahmed Bakr, and Fawzy Eissa. 2024. “Impact of Pesticides on Non-Target Invertebrates in Agricultural Ecosystems.” *Pesticide Biochemistry and Physiology* 202 (June 2024): 105974. <https://doi.org/10.1016/j.pestbp.2024.105974>.
- [15]. Fisher, Penny, Karl J. Campbell, Gregg R. Howald, and Bruce Warburton. 2019. “Anticoagulant Rodenticides, Islands, and Animal Welfare Accountancy.” *Animals* 9 (11): 919. <https://doi.org/10.3390/ani9110919>.
- [16]. Garud, Aishwarya, Satyajeet Pawar, Monika S Patil, Shivani R Kale, and Satish Patil. 2024. “A Scientific Review of Pesticides: Classification, Toxicity, Health Effects, Sustainability, and Environmental Impact.” *Cureus*, ahead of print, August 27, 2024. <https://doi.org/10.7759/cureus.67945>.
- [17]. Gibbons, David, Christy Morrissey, and Pierre Mineau. 2015. “A Review of the Direct and Indirect Effects of Neonicotinoids and Fipronil on Vertebrate Wildlife.” *Environmental Science and Pollution Research* 22 (1): 103–118. <https://doi.org/10.1007/s11356-014-3180-5>.
- [18]. Hailu, Ashenafi, Gudina Terefe Tucho, Abera Gure, and Seblework Mekonen. 2025. “Pesticide Exposure and Acute Health Problems among Pesticide Processing Industry Workers in Ethiopia.” *Toxicology Reports* 14 (June 2025): 101997. <https://doi.org/10.1016/j.toxrep.2025.101997>.
- [19]. Islam, Tarequl, Danishuddin, Noshin Tabassum Tamanna, Muhammad Nurul Matin, Hasi Rani Barai, and Md Azizul Haque. 2024. “Resistance Mechanisms of Plant Pathogenic Fungi to Fungicide, Environmental Impacts of Fungicides, and Sustainable Solutions.” *Plants* 13 (19): 2737. <https://doi.org/10.3390/plants13192737>.
- [20]. Jayaraj, Ravindran, Pankajshan Megha, and Puthur Sreedev. 2016. “Review Article. Organochlorine Pesticides, Their Toxic Effects on Living Organisms and Their Fate in the Environment.” *Interdisciplinary Toxicology* 9 (3–4): 90–100. <https://doi.org/10.1515/intox-2016-0012>.

- [21]. Kalyabina, Valeriya P., Elena N. Esimbekova, Kseniya V. Kopylova, and Valentina A. Kratasyuk. 2021. "Pesticides: Formulants, Distribution Pathways and Effects on Human Health – a Review." *Toxicology Reports* 8 (2021): 1179–1192. <https://doi.org/10.1016/j.toxrep.2021.06.004>.
- [22]. Karlsson Green, Kristina, Johan A. Stenberg, and Åsa Lankinen. 2020. "Making Sense of Integrated Pest Management (IPM) in the Light of Evolution." *Evolutionary Applications* 13 (8): 1791–1805. <https://doi.org/10.1111/eva.13067>.
- [23]. Kashyap, Urvashi, Shivani Garg, and Pooja Arora. 2024. "Pesticide Pollution in India: Environmental and Health Risks, and Policy Challenges." *Toxicology Reports* 13 (December 2024): 101801. <https://doi.org/10.1016/j.toxrep.2024.101801>.
- [24]. Khursheed, Aadil, Manzoor A. Rather, Vikrant Jain, Ab Rouf Wani, Shahid Rasool, Rukhsana Nazir, Nisar Ahmad Malik, and Sheikh Abdul Majid. 2022. "Plant Based Natural Products as Potential Ecofriendly and Safer Biopesticides: A Comprehensive Overview of Their Advantages over Conventional Pesticides, Limitations and Regulatory Aspects." *Microbial Pathogenesis* 173 (December 2022): 105854. <https://doi.org/10.1016/j.micpath.2022.105854>.
- [25]. Kuppan, Narendra, Midhila Padman, Manjushree Mahadeva, Subramani Srinivasan, and Raajasubramanian Devarajan. 2024. "A Comprehensive Review of Sustainable Bioremediation Techniques: Eco Friendly Solutions for Waste and Pollution Management." *Waste Management Bulletin* 2 (3): 154–171. <https://doi.org/10.1016/j.wmb.2024.07.005>.
- [26]. Lazarević-Pašti, Tamara, Vedran Milanković, Tamara Tasić, Sandra Petrović, and Andreja Leskovic. 2025. "With or Without You?—A Critical Review on Pesticides in Food." *Foods* 14 (7): 1128. <https://doi.org/10.3390/foods14071128>.
- [27]. Liu, Shan, Jisha Yan, Bowen Xu, Xinyi Huang, Haixiong Qin, Jiayuan Zhao, Chen Xia, Shen Yan, and Gang Liu. 2024. "Fates and Models for Exposure Pathways of Pyrethroid Pesticide Residues: A Review." *Ecotoxicology and Environmental Safety* 277 (June 2024): 116342. <https://doi.org/10.1016/j.ecoenv.2024.116342>.
- [28]. Mdeni, Nonkululeko Landy, Abiodun Olagoke Adeniji, Anthony Ifeanyi Okoh, and Omobola Oluranti Okoh. 2022. "Analytical Evaluation of Carbamate and Organophosphate Pesticides in Human and Environmental Matrices: A Review." *Molecules* 27 (3): 618. <https://doi.org/10.3390/molecules27030618>.
- [29]. Mengistie, Belay Tizazu, Ram L. Ray, and Ayodeji Iyanda. 2025. "Environmental and Human Health Impacts of Agricultural Pesticides on BIPOC Communities in the United States: A Review from an Environmental Justice Perspective." *International Journal of Environmental Research and Public Health* 22 (11): 1683. <https://doi.org/10.3390/ijerph22111683>.
- [30]. Mnif, Wissem, Aziza Ibn Hadj Hassine, Aicha Bouaziz, Aghleb Bartegi, Olivier Thomas, and Benoit Roig. 2011. "Effect of Endocrine Disruptor Pesticides: A Review." *International Journal of Environmental Research and Public Health* 8 (6): 2265–2303. <https://doi.org/10.3390/ijerph8062265>.
- [31]. Muñoz-Bautista, Jesús Martín, Ariadna Thalía Bernal-Mercado, Oliviert Martínez-Cruz, Armando Burgos-Hernández, Alonso Alexis López-Zavala, Saul Ruiz-Cruz, José de Jesús Ornelas-Paz, Jesús Borboa-Flores, José Rogelio Ramos-Enríquez, and Carmen Lizette Del-Toro-Sánchez. 2025. "Environmental and Health Impacts of Pesticides and Nanotechnology as an Alternative in Agriculture." *Agronomy* 15 (8): 1878. <https://doi.org/10.3390/agronomy15081878>.
- [32]. Mustafa, Sanaa Abdulaziz, Abdulmotalib Jasim Al-Rudainy, and Noor Mohammad Salman. 2024. "Effect of Environmental Pollutants on Fish Health: An Overview." *Egyptian Journal of Aquatic Research* 50 (2): 225–233. <https://doi.org/10.1016/j.ejar.2024.02.006>.
- [33]. Nuruzzaman, Md, Md Mezbaul Bahar, and Ravi Naidu. 2025. "Diffuse Soil Pollution from Agriculture: Impacts and Remediation." *Science of The Total Environment* 962 (January 2025): 178398. <https://doi.org/10.1016/j.scitotenv.2025.178398>.
- [34]. Oirdi, Mohamed El, Muhammad Yaseen, Umme Farwa, Muhammad Asam Raza, Mohd Farhan, Zeshan Ali Sandhu, Furqan Ali, Mohammad Aatif, Hena Saeed Khan, and Insha Nahvi. 2024. "Crops and People: The Dangers and Potential Benefits of Pesticides." *Cogent Food & Agriculture* 10 (1). <https://doi.org/10.1080/23311932.2024.2334096>.
- [35]. Oleszczuk, Patryk, Izabela Joško, Barbara Futa, Sylwia Pasieczna-Patkowska, Edward Pałys, and Piotr Kraska. 2014. "Effect of Pesticides on Microorganisms, Enzymatic Activity and Plant in Biochar-Amended Soil." *Geoderma* 214–215 (February 2014): 10–18. <https://doi.org/10.1016/j.geoderma.2013.10.010>.
- [36]. Othman Said, Tarek. 2026. "Challenges and Future Orientation of Pesticides." In *Pesticides - Balancing Efficient Pest Control with Environmental and Health Safety [Working Title]*. IntechOpen. <https://doi.org/10.5772/intechopen.1012348>.
- [37]. Pathak, Vinay Mohan, Vijay K. Verma, Balwant Singh Rawat, Baljinder Kaur, Neelesh Babu, Akansha Sharma, Seeta Dewali, et al. 2022. "Current Status of Pesticide Effects on Environment, Human Health and It's Eco-Friendly

- Management as Bioremediation: A Comprehensive Review.” *Frontiers in Microbiology* 13 (August 2022). <https://doi.org/10.3389/fmicb.2022.962619>.
- [38]. Paul, Santosh Kumar, Santa Mazumder, and Ravi Naidu. 2024. “Herbicide Weed Management Practices: History and Future Prospects of Nanotechnology in an Eco-Friendly Crop Production System.” *Heliyon* 10 (5): e26527. <https://doi.org/10.1016/j.heliyon.2024.e26527>.
- [39]. Pawlak, Karolina, and Małgorzata Kołodziejczak. 2020. “The Role of Agriculture in Ensuring Food Security in Developing Countries: Considerations in the Context of the Problem of Sustainable Food Production.” *Sustainability* 12 (13): 5488. <https://doi.org/10.3390/su12135488>.
- [40]. Perpetuini, Giorgia, Pilar Anais Nzobouh Fossi, Seyi Kwak, Oscar Namessi, Awanwee Petchkongkaew, Rosanna Tofalo, and Yves Waché. 2023. “Pesticides in Foods: Towards Bioremediation Biocatalysts?” *Catalysts* 13 (7): 1055. <https://doi.org/10.3390/catal13071055>.
- [41]. Pretty, Jules, and Zareen Pervez Bharucha. 2014. “Sustainable Intensification in Agricultural Systems.” *Annals of Botany* 114 (8): 1571–1596. <https://doi.org/10.1093/aob/mcu205>.
- [42]. Punniyakotti, Parthipan, Saranya Vinayagam, Rajaram Rajamohan, SD Priya, Meivelu Moovendhan, and Thanigaivel Sundaram. 2024. “Environmental Fate and Ecotoxicological Behaviour of Pesticides and Insecticides in Non-Target Environments: Nanotechnology-Based Mitigation Strategies.” *Journal of Environmental Chemical Engineering* 12 (5): 113349. <https://doi.org/10.1016/j.jece.2024.113349>.
- [43]. Racca, Fabrizio, Andrea Vianello, Tiziana Mongini, Paolo Ruggeri, Antonio Versaci, Gian Luca Vita, and Giuseppe Vita. 2020. “Practical Approach to Respiratory Emergencies in Neurological Diseases.” *Neurological Sciences* 41 (3): 497–508. <https://doi.org/10.1007/s10072-019-04163-0>.
- [44]. Rajak, Prem, Sumedha Roy, Abhratanu Ganguly, Moutushi Mandi, Anik Dutta, Kanchana Das, Sayantani Nanda, Siddhartha Ghanty, and Gopal Biswas. 2023. “Agricultural Pesticides – Friends or Foes to Biosphere?” *Journal of Hazardous Materials Advances* 10 (May 2023): 100264. <https://doi.org/10.1016/j.hazadv.2023.100264>.
- [45]. Ray, Suryapratap, and Sanjana Thanjan Shaju. 2023. “Bioaccumulation of Pesticides in Fish Resulting Toxicities in Humans through Food Chain and Forensic Aspects.” *Environmental Analysis Health and Toxicology* 38 (3): e2023017. <https://doi.org/10.5620/eaht.2023017>.
- [46]. Ruberti, Marcello. 2024. “One Hundred Years of Pyrethroid Chemistry: A Still-Open Research Effort to Combine Efficacy, Cost-Effectiveness and Environmental Sustainability.” *Sustainability* 16 (19): 8322. <https://doi.org/10.3390/su16198322>.
- [47]. Saad, Hadeel, Shaimaa A. Elfeky, Nadia E. A. El-Gamel, and Ahmed S. Abo Dena. 2025. “Organophosphate Pesticides: A Review on Classification, Synthesis, Toxicity, Remediation and Analysis.” *RSC Advances* 15 (48): 40802–40822. <https://doi.org/10.1039/D5RA05552K>.
- [48]. Saha, Raja, and Sangita Maiti Dutta. 2024. “Pesticides’ Mode of Action on Aquatic Life.” *Toxicology Reports* 13 (December 2024): 101780. <https://doi.org/10.1016/j.toxrep.2024.101780>.
- [49]. Saharan, Baljeet Singh, Pushap Lata, Reema Deshwal, Dharmender Kumar, Swati Tyagi, Deepansh Sharma, Anita Santal, et al. 2025. “Insights of Agricultural Sustainability by the Use of Earthworms.” *Discover Agriculture* 3 (1): 231. <https://doi.org/10.1007/s44279-025-00322-4>.
- [50]. Saidon, Nadhirah B., Rita Szabó, Péter Budai, and József Lehel. 2024. “Trophic Transfer and Biomagnification Potential of Environmental Contaminants (Heavy Metals) in Aquatic Ecosystems.” *Environmental Pollution* 340 (January 2024): 122815. <https://doi.org/10.1016/j.envpol.2023.122815>.
- [51]. Sarwar, Muhammad. 2016. “Indoor Risks of Pesticide Uses Are Significantly Linked to Hazards of the Family Members.” *Cogent Medicine* 3 (1): 1155373. <https://doi.org/10.1080/2331205X.2016.1155373>.
- [52]. Shang, Huanzhang, Dejie He, Boliao Li, Xiulin Chen, Kun Luo, and Guangwei Li. 2024. “Environmentally Friendly and Effective Alternative Approaches to Pest Management: Recent Advances and Challenges.” *Agronomy* 14 (8): 1807. <https://doi.org/10.3390/agronomy14081807>.
- [53]. Shao, Xinliang, Qin Zhang, Boyan Zhang, Zihao Xie, and Kedong Xu. 2026. “Biological Control of Insect Pests in Agroecosystems: Current Challenges, Innovative Strategies, and Future Directions.” *Agriculture* 16 (5): 597. <https://doi.org/10.3390/agriculture16050597>.
- [54]. Shekhar, Chander, Reetu Khosya, Kushal Thakur, Danish Mahajan, Rakesh Kumar, Sunil Kumar, and Amit Kumar Sharma. 2024. “A Systematic Review of Pesticide Exposure, Associated Risks, and Long-Term Human Health Impacts.” *Toxicology Reports* 13 (December 2024): 101840. <https://doi.org/10.1016/j.toxrep.2024.101840>.
- [55]. Souto, Augusto Lopes, Muriel Sylvestre, Elisabeth Dantas Tölke, Josean Fechine Tavares, José Maria Barbosa-Filho, and Gerardo Cebrián-Torrejón. 2021. “Plant-Derived Pesticides as an Alternative to Pest Management and Sustainable Agricultural Production: Prospects, Applications and Challenges.” *Molecules* 26 (16): 4835. <https://doi.org/10.3390/molecules26164835>.
- [56]. Sponsler, Douglas B., Christina M. Grozinger, Claudia Hitaj, Maj Rundlöf, Cristina Botías, Aimee Code, Eric V. Lonsdorf, et al. 2019. “Pesticides and Pollinators: A Socioecological Synthesis.” *Science of The Total Environment* 662 (April 2019): 1012–1027. <https://doi.org/10.1016/j.scitotenv.2019.01.016>.

- [57]. Suwanaruang, Theeranat. 2024. *Pesticides, Toxicity and Its Effects on Human Health and Environment*. B P International. <https://doi.org/10.9734/bpi/mono/978-81-969435-6-1>.
- [58]. Tadesse, Bezuayehu, Melese Asrat, Balkew Zewge, and Asmamaw Tesfaw. 2025. "Quantitative Analysis of Pesticides in Vegetables: A Study on Tomatoes and Onions from Ethiopian Farms." *Measurement: Food* 19 (September 2025): 100242. <https://doi.org/10.1016/j.meafao.2025.100242>.
- [59]. Thapa, Ronika, Anjal Nainabasti, Ashish Lamsal, Santoshi Malla, Bronika Thapa, Yushika Subedi, and Shirish Ghimire. 2022. "Pesticide Persistence in Agriculture and Its Hazardous Effects on Environmental Components." *International Journal of Applied Sciences and Biotechnology* 10 (2): 75–83. <https://doi.org/10.3126/ijasbt.v10i2.45095>.
- [60]. Thundiyil, Josef. 2008. "Acute Pesticide Poisoning: A Proposed Classification Tool." *Bulletin of the World Health Organization* 86 (3): 205–209. <https://doi.org/10.2471/BLT.08.041814>.
- [61]. Timmis, Kenneth, and Juan Luis Ramos. 2021. "The Soil Crisis: The Need to Treat as a Global Health Problem and the Pivotal Role of Microbes in Prophylaxis and Therapy." *Microbial Biotechnology* 14 (3): 769–797. <https://doi.org/10.1111/1751-7915.13771>.
- [62]. Tudi, Muyaiaer, Huada Daniel Ruan, Li Wang, Jia Lyu, Ross Sadler, Des Connell, Cordia Chu, and Dung Tri Phung. 2021. "Agriculture Development, Pesticide Application and Its Impact on the Environment." *International Journal of Environmental Research and Public Health* 18 (3): 1112. <https://doi.org/10.3390/ijerph18031112>.
- [63]. Upadhayay, Jyoti, Mahendra Rana, Vijay Juyal, Satpal Singh Bisht, and Rohit Joshi. 2020. "Impact of Pesticide Exposure and Associated Health Effects." In *Pesticides in Crop Production*, 69–88. Wiley. <https://doi.org/10.1002/9781119432241.ch5>.
- [64]. Verdadero, Francis Xavier D., Alfred Z. Agap, Czarina Nicole E. Macatingrao, Isagani A. Ordonez, Lady Edlenill J. Tavu, David Pires, and Mark Angelo O. Balendres. 2025. "Pesticides in the Environment: Benefits, Harms, and Detection Methods." *Sci* 7 (4): 171. <https://doi.org/10.3390/sci7040171>.
- [65]. Verma, Ravi. 2025a. "Comprehensive Analysis of Marine Pollution: Sources, Environmental and Socioeconomic Impacts, and Sustainable Mitigation Strategies with Public Awareness." *IARJSET* 12 (10). <https://doi.org/10.17148/IARJSET.2025.121008>.
- [66]. Verma, Ravi. 2025b. "The Gomti River at Risk: An Integrated Review of Pollution Sources, Environmental and Public Health Impacts, and Sustainable Management Pathway." In *Journal of Indian Association for Environmental Management*, vol. 45, no. 3. <http://op.niscair.res.in/index/php/JIAEM/index>.
- [67]. Verma, Ravi. 2025. "The Impact of Indian Agriculture on Pollution and Public Health: A Review." *International Journal of Scientific Research and Engineering Development* 8. [www.ijrsred.com](http://www.ijrsred.com).
- [68]. Yahyah, Hadijah, Patricia Kameri-Mbote, and Robert Kibugi. 2024. "Implications of Pesticide Use Regulation on Soil Sustainability in Uganda." *Soil Security* 16 (September 2024): 100133. <https://doi.org/10.1016/j.soisec.2024.100133>.
- [69]. Yasir, Muhammad, Abul Hossain, and Anubhav Pratap-Singh. 2025. "Pesticide Degradation: Impacts on Soil Fertility and Nutrient Cycling." *Environments* 12 (8): 272. <https://doi.org/10.3390/environments12080272>.
- [70]. Zhou, Wentao, Yashwanth Arcot, Raul F. Medina, Julio Bernal, Luis Cisneros-Zevallos, and Mustafa E. S. Akbulut. 2024. "Integrated Pest Management: An Update on the Sustainability Approach to Crop Protection." *ACS Omega* 9 (40): 41130–41147. <https://doi.org/10.1021/acsomega.4c06628>.