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Review

Pesticides in the Environment: Benefits, Harms, and Detection Methods

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Abstract

Pesticides play a critical role in food production by enhancing crop yields and protecting against pests and pathogens, such as insects, bacteria, fungi, and weeds. However, their extensive use raises significant environmental concerns. The paper reviews and describes the reported adverse effects of pesticides on terrestrial and marine life to raise awareness of the ecological impact of pesticide use across life niches. The adverse effects on soil microorganisms, arthropods, reptiles, and amphibians highlight the extensive ecological disruption caused by these chemicals. Understanding the mechanisms of pesticide toxicity and their impact on various organisms is crucial for developing effective bioremediation techniques and on-field management practices. By implementing these strategies and enhancing environmental biomonitoring, countries can mitigate the harmful effects of pesticides, ultimately protecting biodiversity and ensuring the health of their ecosystems.

Keywords: fungicides; insecticides; herbicides; bactericides; ecological impact

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1. Introduction

Pesticides support food production by protecting plants against pests and pathogens. Using pesticides has increased crop productivity and improved the cosmetic appeal of fresh produce. While they play a crucial role in agricultural development, their use can also harm non-target organisms [1] and the environment, resulting in environmental pollution and potential health risks for humans [2]. Pesticide residues and their breakdown products can persist in non-target areas such as the atmosphere, soils, groundwater, and surface water long after application [3]. The World Health Organization [4] identifies pesticides as a leading cause of fatal self-poisoning, particularly affecting low- and middle-income countries. Soil ecosystems, which are home to a diverse range of organisms critical for maintaining nutrient cycles, soil structure, and pest control, are especially at risk from pesticide pollution, emphasizing the need to comprehend how pesticides influence soil organisms and their ecological functions [5]. Concerns exist, including water contamination, pesticide residues in food, and negative impacts on wildlife and human health [6,7]. Despite the excessive costs associated with these externalities impacting farmers' returns, pesticide use continues to rise [8]. Given their inherent toxicity and widespread environmental release, rigorous regulation and control measures are necessary to mitigate potential risks to human health and ecological balance.

Studying the effects of pesticides on terrestrial and marine organisms is essential because of the extensive use of these substances in agriculture, causing substantial environmental damage [9]. By understanding the effects of pesticides on terrestrial and marine life (Figure 1), we can better assess the ecological hazards posed by these chemicals. This will result in developing strategies to minimize their detrimental environmental impacts, safeguarding biodiversity and ecosystem health. For instance, passive samplers used to monitor pesticide levels in surface water have revealed the presence of various organic pollutants, including banned or restricted pesticides [10]. The paper reviews and describes the reported adverse effects of pesticides on terrestrial and marine life to raise awareness of the ecological impact of pesticide use across life niches (Figure 1). We begin by describing what pesticides are, the types of pesticides used in agricultural systems, how they can be detected, and their impact on terrestrial and marine life. We then discuss the current management and mitigation strategies and alternatives to pesticide use. Finally, we present some research prospects.

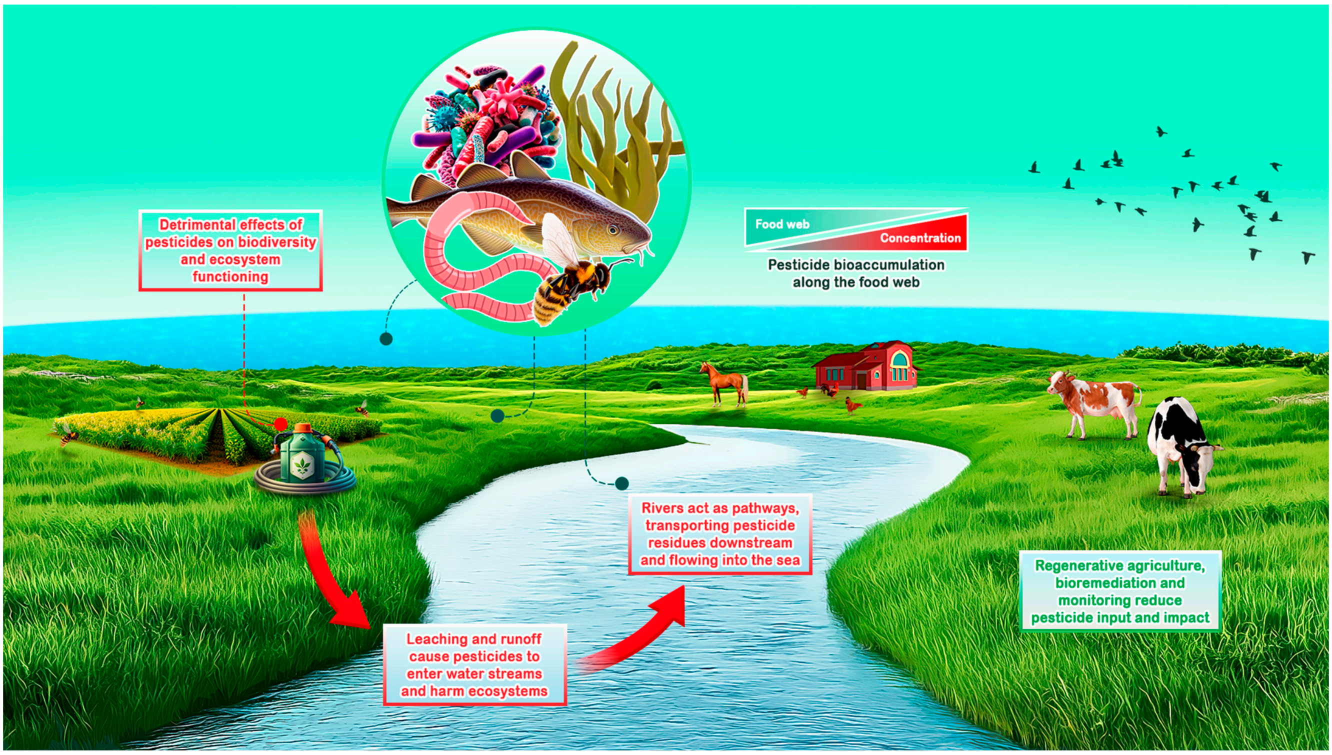

Figure 1. Environmental pathways of pesticide exposure, from farm to sea.

2. What Are Pesticides?

Pesticides encompass chemicals and biological agents that prevent, destroy, or control harmful pests in agriculture, public health, and homes. These products are composed of active substances, safeners, synergists, co-formulants, and adjuvants, which all play crucial roles in enhancing the effectiveness and safety of the formulations [11]. The variety of pesticides (Table 1) is extensive, including insecticides, herbicides, fungicides, molluscicides, bacteriocides, nematicides, scabicides, pheromones, plant growth regulators, acaricides, and repellants, reflecting the complexity and specificity required in pest management [12,13]. As synthetic organic pesticides began to be used extensively in the 1940s, they marked a turning point in pest control, revolutionizing agriculture and introducing long-lasting environmental impacts [14]. The evolution of pesticide use, particularly after World War II, with the advent of synthetic products, shows the dual nature of these chemicals. They are essential for modern agriculture but need careful management to mitigate their adverse effects [15].

Table 1. Pesticide groups, their chemical category, name, and formula.

Pesticide Group	Chemical Category	Chemical Name	Molecular Formula
Insecticides	Organochlorine	Aldrin	$C_{12}H_8Cl_6$
	Organochlorine	Chlordane	$C_{10}H_6Cl_8$
	Organochlorine	DDT (Dichloro-diphenyl-trichloroethane)	$C_{14}H_9Cl_5$
	Organochlorine	Dieldrin	$C_{12}H_8Cl_6O$
	Organochlorine	Endosulfan	$C_9H_6Cl_6O_3S$
	Organochlorine	Endrin	$C_{12}H_8Cl_6O$
	Organochlorine	Heptachlor	$C_{10}H_5Cl_7$
	Organochlorine	Hexachlorobenzene (HCB)	C_6Cl_6
	Organochlorine	Hexachlorocyclohexane (HCH)	$C_6H_6Cl_6$
	Organochlorine	Lindane	$C_6H_6Cl_6$
	Organochlorine	Methoxychlor	$C_{16}H_{15}Cl_3O_2$
	Organochlorine	Mirex	$C_{10}Cl_{12}$
	Organochlorine	Nonachlor	$C_{10}H_5Cl_9$
	Organochlorine	Pentachlorophenol	C_6Cl_5OH
	Organophosphate	Chlorpyrifos	$C_9H_{11}Cl_3NO_3PS$
	Organophosphate	Iprobenfos	$C_{13}H_{21}O_3PS$
	Organophosphate	Temephos	$C_{16}H_{20}O_6P_2S_3$
	Organophosphate	Malathion	$C_{10}H_{19}O_6PS_2$
	Carbamate	Carbaryl	$C_{12}H_{11}NO_2$
	Carbamate	Aldicarb	$C_7H_{14}N_2O_2S$
	Pyrethroid	Permethrin	$C_{21}H_{20}Cl_2O_3$
	Pyrethroid	Bifenthrin	$C_{23}H_{22}ClF_3O_2$
	Neonicotinoid	Acetamiprid	$C_{10}H_{11}ClN_4$
	Neonicotinoid	Imidacloprid	$C_9H_{10}ClN_5O_2$
	Neonicotinoid	Thiacloprid	$C_{10}H_9ClN_4S$
	Neonicotinoid	Thiamethoxam	$C_8H_{10}ClN_5O_3S$
Fungicides	Acylalanine	Metalaxyl	$C_{15}H_{21}NO_4$
	Anilinopyrimidine	Pyrimethanil	$C_{12}H_{13}N_3$
	Azole (Triazole)	Propiconazole	$C_{15}H_{17}Cl_2N_3O_2$
	Azole (Triazole)	Tebuconazole	$C_{16}H_{22}ClN_3O$
	Benzimidazole	Carbendazim	$C_9H_9N_3O_2$
	Dithiocarbamate	Mancozeb	$C_4H_6MnN_2S_4{\cdot}Zn$
	Dithiocarbamate	Ziram	$C_6H_{12}N_2S_4$
	Cyanopyrrole	Fludioxonil	$C_{12}H_6F_2N_2O_2$
	Dicarboximide	Iprodione	$C_{13}H_{13}Cl_2N_3O_3$
	Morpholine	Fenpropimorph	$C_{20}H_{33}NO$
	N-trihalomethylthio	Folpet	$C_9H_4Cl_3NO_2S$
	Organophosphorus	Fosetyl-Al	$C_6H_{18}AlO_9P_3$
	Pyrimidine	Fenarimol	$C_{17}H_{12}Cl_2N_2O$
	Pyrimidinyl Carbinol	Fenhexamid	$C_{14}H_{17}Cl_2NO_2$
	Carboxylic Acid Amide (CAA)	Mandipropamid	$C_{23}H_{22}ClNO_4$
	Carboxylic Acid Amide (CAA)	Dimethomorph	$C_{21}H_{22}ClNO_4$

Table 1. *Cont.*

Pesticide Group	Chemical Category	Chemical Name	Molecular Formula
Herbicides	Triazine	Atrazine	$C_8H_{14}ClN_5$
	Triazine	Simazine	$C_7H_{12}ClN_5$
	Organophosphonate	Glyphosate	$C_3H_8NO_5P$
	Organophosphonate	Glufosinate	$C_5H_{12}NO_4P$
	Phenoxyacetic acid	2,4-D	$C_8H_6Cl_2O_3$
	Phenylurea	Diuron	$C_9H_{10}Cl_2N_2O$
	Chloroacetamide	Alachlor	$C_{14}H_{20}ClNO_2$
	Bipyridyl	Paraquat	$C_{12}H_{14}N_2Cl_2$
	Bipyridyl	Diquat	$C_{12}H_{12}N_2$

Being toxic and deliberately spread in the environment, pesticides pose significant risks to non-target organisms, including humans, animals, and ecosystems [11]. While they have undeniably played a crucial role in increasing agricultural production and controlling disease vectors over the past five decades [16], their widespread use has also led to severe ecological disruptions and economic harm [17,18]. The development of genetically modified crops and the adaptation of chemical agents initially intended for vector control in public health to agricultural pest management [19] demonstrate the complex interplay between technological advancements and environmental stewardship. However, this progress comes at a cost [20–22].

2.1. Insecticides

Insecticides, whether chemical or biological, are crucial for controlling insect populations across diverse settings such as agriculture, horticulture, forestry, and public health [23,24]. The primary objective of insecticides is to eliminate or manage insect pests that threaten human health, agricultural productivity, and environmental stability [25,26]. They are classified based on their chemical and biological origins, each with specific mechanisms of action that target the physiological processes of insects, leading to their paralysis and death [27]. The major classes of synthetic organic insecticides, such as chlorinated hydrocarbons, organophosphorus compounds, carbamates, pyrethroids, and neonicotinoids, represent different approaches to pest control, each with its benefits and risks [27,28]. For instance, organophosphates and carbamates inhibit critical enzymes in the insect nervous system. At the same time, pyrethroids and neonicotinoids interfere with nerve impulses and receptor function, respectively [24]. However, the widespread use of these potent chemicals raises concerns about their non-target effects and potential environmental hazards, such as ecosystem contamination and resistance among pest populations. In contrast, biological insecticides, which include microbial agents, biochemical pesticides, and botanicals, offer an eco-friendlier alternative with greater target specificity [29]. Botanically derived insecticides are considered safer and more sustainable than their synthetic counterparts. However, their effectiveness in large-scale agricultural practices remains a topic of ongoing research and debate [27]. While synthetic insecticides have been instrumental in modern agriculture and public health, their use must be carefully managed to mitigate the risks of environmental contamination, non-target organism harm, and the long-term sustainability of pest control strategies. The balance between efficacy and ecological impact emphasizes the need for integrated pest management approaches that combine the strengths of both chemical and biological insecticides while minimizing their drawbacks.

Insecticides, while effective in controlling pests and providing significant agricultural, economic, and public health benefits, are not without substantial environmental consequences. Their application can lead to the contamination of water supplies, mortality of non-target organisms, and disruption of natural pest control mechanisms, contributing to ecosystem imbalances and potential contamination of the food chain [30–32]. These adverse effects highlight a critical tension between the immediate benefits of insecticide use and the long-term sustainability of ecosystems. The development of resistance in target insect populations is another significant issue stemming from the excessive use of insecticides. This resistance often demands the application of higher concentrations or using more potent chemicals, increasing production costs and environmental damage by further disrupting natural pest control mechanisms [33]. This cycle of chemical use needs more sustainable pest management practices.

2.2. Fungicides

Fungicides, comprising both chemical and biological compounds, are integral to the prevention and eradication of fungal infections in plants and seeds [34]. These substances are categorized based on their chemical structure and mode of action, reflecting their diverse agricultural applications [35,36]. The strategic use of fungicides is critical in managing crop diseases, mainly when host resistance is unavailable or unstable, thus ensuring optimum crop yields [37]. However, the reliance on fungicides also presents several challenges. While they are crucial for the protection of crops such as potatoes, melons, and grapes, which are particularly vulnerable to fungal infections, their widespread use raises concerns about environmental impact and the potential development of fungicide-resistant strains of pathogens [34,37]. This resistance issue parallels the challenges faced with insecticides, where overuse can lead to diminished effectiveness and demands higher dosages or the development of new chemicals, thus escalating costs and environmental risks.

Classifying fungicides into families such as acylalanine, anilinopyrimidine, azole, benzimidazole, and others also shows the complexity and specificity of these chemicals [38]. While this diversity allows for targeted control of various fungal pathogens, it also stresses the potential for unintended consequences, such as off-target effects and environmental persistence. Moreover, the extensive application of fungicides, particularly in crops that heavily depend on them, can disrupt local ecosystems, affecting non-target organisms and potentially leading to ecological imbalances. Fungicides play a vital role in managing fungal pathogens by inhibiting their growth and spread, a function closely tied to their chemical structure, which dictates their effectiveness and potential side effects [34]. Systemic fungicides, for instance, are absorbed by plants and distributed internally, allowing for comprehensive protection and the eradication of established infections [36]. However, this targeted action marks a more complex narrative when considering the broader environmental implications of fungicide use.

The environmental impact of fungicides is a growing concern, particularly regarding pollution from their production processes, their persistence in the environment, and their residues in food [39]. Fungicides can significantly affect soil health by reducing the activity of soil microbial enzymes, which in turn impacts soil fertility and ecosystem health [40]. Furthermore, their residues can accumulate in air, water, and soil, posing risks to non-target organisms and disrupting ecological functions [41]. This accumulation affects environmental quality and can lead to unintended consequences for human health and biodiversity.

The regulatory framework for fungicides is crucial in balancing their benefits with potential risks. The approval process must address concerns related to resistance management, environmental impact, and the need for innovative solutions in crop protection [39]. As market needs evolve and resistance issues become more pronounced, developing and approving new fungicides must consider current and future challenges. This includes addressing regulatory hurdles and meeting growing customer expectations for safer and more sustainable pest management solutions [42].

2.3. Herbicides

Herbicides, chemical substances designed to destroy or inhibit the growth of unwanted plants, especially weeds, play a critical role in modern agriculture by enhancing food production and allowing for more efficient farming practices such as reduced tillage and earlier planting dates [43,44]. By effectively managing weeds, herbicides contribute to both the quantity and quality of food crops, offering farmers a convenient and economical solution [38,45]. However, the widespread use of herbicides is not without significant risks. While they are generally effective in their intended purpose, their application raises concerns about environmental, ecological, and human health impacts [44]. Though typically low, the persistence of herbicide residues in food warrants ongoing scrutiny, as human exposure levels must be carefully managed to remain within acceptable limits [46]. The environmental impact of herbicides can lead to soil degradation, water contamination, and harm to non-target plant species, affecting biodiversity and ecosystem balance. Moreover, the reliance on herbicides in agricultural systems can lead to the development of herbicide-resistant weed species that need more potent or diverse chemical agents, increasing both environmental impact and production costs. This cycle of increasing chemical use poses long-term sustainability challenges and calls for more integrated weed management approaches that reduce dependency on chemical herbicides while maintaining crop productivity.

The effectiveness of herbicides in modern agriculture is rooted in their targeted modes of action, such as inhibiting acetolactate synthase (ALS) or inducing oxidative stress in plant cells, which are critical for controlling weed populations and ensuring sustainable crop productivity [47–49]. The widespread use of herbicides, mainly systemic and pre-emergence formulations, has led to contamination issues that seriously threaten biodiversity, environmental health, and food safety [50]. The environmental persistence of these chemicals can lead to the degradation of non-target plant species and disrupt the ecological balance, a growing concern in agricultural sustainability. Despite these challenges, advancements in herbicide technology have led to more sustainable practices, reflecting an improvement in the balance between effective weed control and environmental stewardship [51]. This progress shows the importance of ongoing research and development in herbicide formulations, focusing on minimizing ecological impact while maintaining agricultural productivity. Nevertheless, the potential risks associated with herbicide use require continuous monitoring and regulation to ensure these chemicals do not undermine the ecosystems they protect.

While pesticides are crucial for sustaining crop yields and controlling pests, their widespread use also raises concerns about persistence, bioaccumulation, biodiversity loss, and chronic health effects, emphasizing the need for sustainable pest management practices (Table 2).

Table 2. Major groups of pesticides with representative chemical examples, their agricultural use and benefits, and the associated harms to ecosystems, health, and biota.

Representative Chemicals	Benefits	Harms (Environmental/Health)	Biota Impacts
Insecticide			
Chlorinated hydrocarbons	Effective in eliminating or managing insect pests that threaten human health, agricultural productivity, and environmental stability [23–26]	Persistence in the environment; potential contamination [27,28]	Mortality of non-target organisms; disruption of natural pest control mechanisms; contamination of food chains [30–32]
Organophosphorus compounds	Inhibit critical enzymes in the insect nervous system [24,27,28]	Potential environmental hazards [27,28]	Toxicity to non-target organisms; ecosystem imbalances [30–32]

Table 2. *Cont.*

Representative Chemicals	Benefits	Harms (Environmental/Health)	Biota Impacts
Carbamates	Inhibit critical enzymes in the insect nervous system [24,27,28]	Potential environmental hazards [27,28]	Toxicity to non-target organisms; ecosystem imbalances [30–32]
Pyrethroids	Interfere with insect nerve impulses [24,27,28]	Potential environmental hazards [27,28]	Resistance development in insect populations [33]
Neonicotinoids	Interfere with receptor function in the insect nervous system [24,27,28]	Potential environmental hazards [27,28]	Resistance development in insect populations [33]
Biological insecticides (microbial, biochemical, botanicals)	More eco-friendly with greater target specificity; considered safer and more sustainable than synthetic insecticides [29]	Effectiveness in large-scale agriculture remains under study [27]	Generally lower impact on non-target organisms [29]
Fungicide			
Acylalanine, Anilinopyrimidine, Azole, Benzimidazole, and others	Prevention and eradication of fungal infections in plants and seeds; ensure optimum crop yields, particularly in vulnerable crops such as potatoes, melons, and grapes [34–37]	Overuse can lead to fungicide-resistant strains of pathogens, requiring higher dosages or new chemicals, increasing costs and environmental risks [34,37]	Disrupt local ecosystems; affect non-target organisms; contribute to ecological imbalances [34,37,38]
Systemic fungicides (absorbed and distributed within plants)	Provide comprehensive protection by eradicating established infections and preventing new ones [36]	Persistence and residues in food, soil, air, and water; pollution from production processes [39]	Reduce soil microbial enzyme activity, lowering soil fertility and ecosystem health; accumulation disrupts ecological functions and biodiversity [40,41]
General fungicide use (various families)	Vital for managing fungal pathogens by inhibiting their growth and spread [34–36]	Environmental persistence; regulatory challenges related to resistance and ecological risks [38,39,42]	Residues accumulate in the environment, posing risks to biodiversity and human health [39–41]
Herbicide			
General herbicides (chemical substances targeting weeds)	Enhance food production by reducing weed competition; allow more efficient farming practices such as reduced tillage and earlier planting dates [43,44]; improve crop quantity and quality; economical weed control solution [38,45]	Environmental, ecological, and human health risks associated with widespread use [44]; persistence of residues in food raises human exposure concerns [46]	Soil degradation, water contamination, and harm to non-target plant species, reducing biodiversity and disrupting ecosystem balance [44]
Targeted herbicide actions (e.g., ALS inhibitors, oxidative stress inducers)	Provide precise weed population control; ensure sustainable crop productivity [47–49]	Development of herbicide-resistant weed species increases environmental impact and production costs [44]	Long-term ecological imbalance due to resistant weed species and reliance on more potent chemicals [44]
Systemic and pre-emergence herbicides	Effective in controlling weeds before or during germination; improve crop productivity [47–49]	Environmental persistence threatens biodiversity, environmental health, and food safety [50]	Persistence leads to degradation of non-target plant species and disruption of ecological balance [50]

3. Pesticide Detection

The initial stage of pesticide detection involves preparing the sample to enrich and purify the pesticide analytes. This step is crucial due to the complexity of environmental samples, particularly soil and food. Several extraction methods are employed during this stage.

A widely used method is liquid–liquid extraction (LLE). In LLE, pesticides are dissolved in two immiscible liquids, typically water and an organic solvent. Different extraction solutions are used: dichloromethane/acetone was used to detect fungicides such as cyprodinil, fludioxonil, procymidone, and vinclozoline from grape juice [52]. DCM: Pentane (3:1) mix was tested for extraction from soil and sediment samples [53]. Another reliable method for sample clean-up and trace enrichment in food and environmental analysis is solid-phase extraction (SPE) [54,55]. In contrast to LLE, SPE is faster, uses significantly less solvent, avoids emulsion formation, allows for smaller sample volumes, and is much easier to automate [56]. Matrix Solid-Phase Dispersion (MSPD) integrates extraction and clean-up in a single step, making the process efficient and cost-effective. This method was utilized by Balsebre et al. [57] to determine a representative group of twelve pesticides in honeybees with particular concern in the apicultural field. Recently, the QuEChERS (Quick, Easy, Cheap, Effective, Rugged, and Safe) sample preparation technique has been extensively used for the multi-class or multi-residue analysis of pesticides, particularly in agricultural samples. As Anastassiades et al. [58] described, this method can extract both polar and non-polar compounds simultaneously, offering versatility and efficiency in pesticide analysis. It has been applied to various vegetables, fruits, grains, and dough [59–61].

3.1. Analytical Detection Methods

After proper sample preparation, analytical methods can be used to determine the composition of the processed sample and the concentration of specific substances. Pesticides are typically detected using classical analytical methods such as Gas Chromatography (GC) and Liquid Chromatography (LC). They are often coupled with different detectors to enhance their specificity and sensitivity across various sample types. In GC studies, the Electron Capture Detector (ECD) has been effectively used to detect organochlorine pesticides in wastewater [62], as well as in vegetables, fruits, and edible fungi [63]. The Flame Photometric Detector (FPD) has been employed to identify organophosphorus pesticides in environmental water samples [64] and agricultural produce [63]. Mass Spectrometric Detectors (MS and tandem MS) have enabled the comprehensive analysis of pesticide metabolites in tea products [65]. On the other hand, liquid chromatography coupled with mass spectrometry has proven effective in analyzing pesticide residues and their transformation products across different water samples [66–68]. In addition, Ma et al. [69] have also developed a new method for screening and identifying 420 pesticide residues in fruits and vegetables using ultra-performance liquid chromatography coupled with quadrupole-time of flight mass spectrometry (UPLC-Q-TOF/MS).

In recent years, capillary electrophoresis (CE) has emerged as a powerful method for separating complex mixtures due to its separation efficiency, rapid analysis time, minimal sample requirements, and applicability to a broad spectrum of analytes [70]. CE, combined with column-end electrochemiluminescence (ECL) detection, yielded efficient recoveries of vegetable carbamate pesticides. Other notable methods include immunochemical techniques, particularly ELISA, which have gained popularity as rapid and cost-effective methods for isolating and detecting pesticide components. The primary advantage of ELISA lies in its simple sample preparation procedures, bypassing the complex and time-consuming pre-treatment steps required by chromatographic methods. ELISA is also characterized by its ease of use, lack of advanced expertise, and affordability, as it does not require expensive equipment. These attributes make ELISA a practical option for use outside of traditional laboratory settings, as demonstrated in the efficient detection of pesticides in grapes, Chinese cabbage, soil, and water [71].

3.2. Biosensor-Based Detection Methods

Analytical methods provide sensitive, specific, and precise results but are time-consuming, expensive, and require large amounts of organic solvents. These methods also have drawbacks such as complexity, labor intensiveness, high instrumentation costs, and the need for skilled personnel [72]. Recent studies have been focused on addressing these limitations by exploring innovative sensing platforms for pesticide detection. One promising approach involves using sensors that offer advantages over traditional methods, including simplicity, speed, cost-effectiveness, and the ability for on-site analysis [73].

Advanced methods, such as biosensors, are easy and quick to implement and offer promising monitoring solutions with good results. A biosensor is an analytical device that detects chemical substances by combining a biological element with a physicochemical detector. The sensitive biological component interacts with or recognizes the target analyte. The transducer or detector element possesses optical, piezoelectric, electrochemical, molecularly imprinted, or electro-chemiluminescence properties, converting this interaction into a measurable signal.

3.2.1. Electrochemical Biosensors

Electrochemical biosensors combine an immobilized biomolecule with an electroactive analyte to generate an electrochemical signal, which is then analyzed by an electrochemical detector. Biorecognition elements in these biosensors include microbial cells, antibodies, DNA, enzymes, and aptamers. Several studies have demonstrated the effectiveness of electrochemical biosensors in pesticide detection. For instance, Çevik et al. [74] developed an acetylthiocholine (ATCh) biosensor using poly (allylamine hydrochloride) functionalized multiwalled carbon nanotubes for pesticide detection in grape, tomato, and mineralized water samples. Xie et al. [75] utilized a multi-residue electrochemical biosensor to detect 11 apple organophosphorus pesticides. Liu et al. [76] developed a portable, quantitative, and user-friendly electrochemical biosensor. They found it helpful in evaluating the residual level of pesticides in Chinese celery cabbage.

3.2.2. Fluorescence Biosensors

The fluorescence sensor is widely used for biomolecular interaction detection due to its suitability for many detection scenarios. In a recent study, Li et al. [77] developed the first fluorescent sensor for triclopyr 2-butoxyethyl ester. The sensor is based on a derivative of n-butyl-1,8-naphthimide Schiff-base (NSB) and was used to detect triclopyr 2-butoxyethyl ester in actual samples of wheat seedlings, sugarcane, broadleaf weedane, and water. This suggests the sensor has excellent potential for simple, rapid, and in situ detection of triclopyr 2-butoxyethyl ester in daily environments.

Li et al. [77] also combined machine learning and a fluorescence sensor array for qualitative and quantitative analysis of pyrethroid pesticides (PPs). This addressed the challenge of simultaneously detecting multiple residues on vegetables and fruits. The sensor arrays, consisting of three nanocomposite complexes, effectively distinguished structurally similar PPs such as deltamethrin, fenvalerate, cyfluthrin, and fenpropathrin by utilizing varying receptor/analyte affinities and fluorescence signal responses. Their approach achieved 100% classification accuracy in unknown samples through multivariate pattern recognition analysis and precise concentration prediction using machine learning techniques.

3.2.3. Colorimetric Biosensors

Colorimetry is commonly used for detecting pesticide pollutants in food and the environment due to its ease of preparation, cost-effectiveness, and precise observation of results with the naked eye. Sahu et al. [78] developed an alpha-cyclodextrin-capped silver nanoparticle (AgNPs/α-CD) as a colorimetric sensor for microextraction and trace-level detection of chlorpyrifos pesticide in fruits and vegetables. Tai et al. [79] developed a colorimetric sensor array to inhibit the peroxidase-like activities of different nanozymes, enabling the discrimination and quantitative analysis of six pesticides. This method has successfully discriminated against pesticides in lake water and apple samples.

Biosensors face significant challenges in detecting pesticides, including continually enhancing biological components and recognition molecules for better sensitivity and specificity. The complexity of fruit and vegetable samples, which contain various interfering substances, poses challenges that require strategies to mitigate matrix effects for accurate detection. Despite these challenges, biosensors hold promise for advancing pesticide residue detection and have the potential to transform precision agriculture by optimizing pesticide use to enhance food quality and safety. Integration with automation and Internet technologies allows for remote monitoring and data sharing, improving oversight in agricultural practices. Biosensors also contribute to promoting sustainability by reducing environmental impact and fostering ecosystem health.

4. Influential Factors in Pesticide Leaching

The physicochemical characteristics of each pesticide and soil-related and hydrological factors can affect pesticide leaching into surface waters or shallow groundwater. According to Nolan et al. [80], climate factors, such as precipitation amount and timing, significantly influence pesticide loss in leaching and tile drains, impacting European-scale risk assessment for pesticide fate. Climate variability, pesticide adsorption coefficient, soil boundary hydraulic conductivity, and pesticide degradation half-life are the most influential factors in modeling pesticide leaching in cropping systems [81]. Pesticide leaching through soil profiles can cause groundwater pollution, with higher risks in climates with high precipitation and low temperatures and soils with low organic matter and sandy texture, according to Pérez-Lucas et al. [82]. The leach loads in soils vary based on sorption capacity, degradation, and sorption kinetics, with rapid declines observed in clay soils [83].

5. Pesticide Properties and Weather Conditions

Pesticide leaching into soil water depends on the pesticide's properties, soil properties, and weather conditions. According to Nicholls [84], lipophilicity, organic matter content, soil pH, and weather contribute to pesticide leaching, with applications in autumn being more likely to reach groundwater due to low soil temperatures and rainfall. Runoff, spray drift, leaching, and subsurface drainage are how pesticides enter water bodies; these methods harm aquatic ecosystems and people [85]. Pesticides can degrade, volatilize, and transport offsite through various processes, affecting their fate in soil, sediment, and water environments. Factors contributing to pesticide leaching into seas include physical, chemical, and biological factors, volatilization, soil colloids, surface runoff, and agricultural practices [86].

6. Effects of Pesticides on Terrestrial and Marine Life

6.1. Impact on Humans and Animals

Farmers frequently reported respiratory symptoms such as coughing, difficulty in breathing, and pulmonary secretions [87]. Studies have shown symptoms affecting other body systems, including gastrointestinal and integumentary systems, and abnormalities in laboratory parameters indicative of pesticide exposure. Additionally, the lack of safety training, inadequate protective equipment, and pesticide-related illnesses among plantation workers and surrounding communities further emphasize the detrimental health effects of pesticide exposure in the Philippines [88].

Furthermore, studies have shown that pesticide pollution can significantly reduce the species and quantities of soil animals, affecting their respiratory function and causing damage to their bodies, mainly observed in earthworms [89]. The toxicological research emphasizes that pesticide-induced oxidative stress is a key mechanism of toxicity, leading to tissue damage and apoptosis [90]. An increasing trend of pesticide poisoning cases and the presence of risk factors related to pesticide exposure were observed in the country [91]. Some Pesticides found in the terrestrial environment are presented in Table 3.

6.2. Impact on Soil Microorganisms

Pesticides adversely impact soil microorganisms, affecting their diversity, abundance, and functions. Studies have shown that pesticide residues can decrease bacterial diversity and abundance in soils, particularly affecting genera crucial for nutrient cycling and organic matter decomposition [92]. Furthermore, the repeated application of pesticides can alter the microbial community structure by affecting specific phylogenetic groups, such as a decrease in the proportion of Ascomycota and changes in the relative abundance of specific genera like *Haliangium* and *Solicoccozyma* [93]. Environmental disturbances, like heat waves, can exacerbate these effects, with disturbances having a more substantial impact on microbial endpoints than pesticide exposure alone [94].

Table 3. Pesticides found in the terrestrial environment.

Chemical Category	Contaminated Ecosystem	References
Organophosphates, viologens, pyrethroids, anticholinesterases, neonicotinoids, triazines	soils, forests harboring fauna (arthropods, reptiles, amphibians)	[89,95–99]
Organochlorines, biocides, carbamates, repellants, biopesticides, household pesticides	agricultural lands isolated from and near residential lands, residential lands	[87,88,90,91]
Benomyl, metribuzin, imidacloprid	soil microbiome, rhizosphere	[92,93]

6.3. Impact on Arthropods

Pesticides, especially insecticides, can have indirect effects on arthropods by disrupting ecological mechanisms and species interactions, such as the release of herbivores from predation and competition, resulting in subsequent pest outbreaks and reduced populations of natural enemies of crop pests [95]. Studies have shown that pesticides generally elicit adverse effects on soil fauna diversity and abundance, with more substantial adverse effects observed for multiple substances, broad-spectrum substances, and insecticides targeting invertebrates [5].

6.4. Impact on Reptiles and Amphibians

Pesticides threaten reptiles and amphibians globally, including in the Philippines. Studies have shown that pesticide exposure can lead to adverse effects on these species, such as reduced diversity patterns, elimination of amphibians, disruption of endocrine systems, and decreased egg size in fish populations [96–98]. The enzyme and hormone-disrupting capabilities of pesticides contribute to the decline of these populations, with chemicals accumulating in organisms' fatty tissues and affecting their reproductive success. Specific pesticides like atrazine have been linked to sexual development issues in frogs [99]. At the same time, pyrethroids and neonicotinoids have been shown to cause various disorders and abnormalities in tadpoles, impacting their survival and development [98].

6.5. Mechanisms of Toxicity

Pesticides exhibit toxicity against terrestrial organisms through various mechanisms. Organophosphates and carbamates inhibit acetylcholinesterase, leading to cholinergic toxicity. Highly lipophilic organochlorines accumulate in adipose tissue, causing high toxicities in mammals. Triazines have been associated with increased cancer risk and congenital disabilities, while pyrethroids act as neurotoxins on insect nerve membranes [100]. Pesticides form bidentate metal complexes, interact with nucleotides and enzymes, and induce cell energy deficiency [101]. The concept of a common mechanism of toxicity is crucial in pesticide regulation, ensuring the consideration of shared toxicological actions when setting acceptable pesticide levels [102]. Understanding pesticide toxicity's molecular targets and mechanisms is essential for assessing their impact on public health [103]. Earthworms are important bioindicators that metabolize pesticides and experience toxicity based on uptake, metabolism, and excretion processes [104].

6.6. Impact on Marine Life

Pesticide residue can be found anywhere in the marine environment [105]. This should not be a surprise since most pesticides applied on land will eventually reach the seas due to natural (e.g., runoff, erosion, leaching, atmospheric) or anthropogenic processes (e.g., deliberate application, dumping, accidental spills). It appears that the most ubiquitous kind of pesticide found in the marine environment is organochlorines (OCs; see Table 4). Organophosphates (OPs), triazine, and carbamate have also been found in the marine environment, but to a lesser extent. However, many other pesticide residues probably reach the marine environment since oceans are the ultimate sink or endpoint for these chemicals. Understandably, much attention has been given to OCs since they are more toxic and long-lasting by design [106]. The best example is the organochlorine DDT, which has been banned since the 1970s [107]. Still, traces of DDT have been found in different marine environments decades after the chemical was banned—negatively impacting many marine flora and fauna [108]. Despite being banned, DDT is still being used by other countries since it is cheap and effective at controlling disease-carrying mosquitoes and other agricultural pests [109,110]. Therefore, we can expect DDT to persist in the marine environment for a long time. Nowadays, more recent studies are already looking into the persistence of more "modern" pesticides such as OPs, carbamates, pyrethroids, neonicotinoids, and biopesticides [111–113].

Table 4. Pesticides found in the marine environment.

Chemical Category	Contaminated Ecosystem	References
Organochlorine		
2,4-Dichlorophenoxyacetic acid	mangrove forest	[114]
Aldrin	estuary, marine sediment, seaweed bed	[110,115]
Chlordane	marine sediment, coral reef	[114–116]
dicholor-diethy-tricholorethane (DDT)	marine sediment, mangrove forest, seagrass meadow, seaweed bed, coral reef	[110,114–116]
Dieldrin	marine sediment, coral reef	[114–116]
Endosulfan	estuary, seaweed bed, coral reef	[114–116]
Endrin	marine sediment, seaweed bed, coral reef	[114–116]
Heptachlor	marine sediment, seaweed bed, coral reef	[110,114,116]
Hexochlorobenzene (HCB)	marine sediment	[116]
Hexocholorcyclohexane (HCH)	marine sediment, seaweed bed	[110,116]

Table 4. *Cont.*

Chemical Category	Contaminated Ecosystem	References
Lindane	marine sediment, seagrass meadow, coral reef	[110,114–116]
Methoxychlor	seaweed bed, coral reef	[110,114,115]
Mirex	coral reef	[115]
Nonachlor	marine sediment	[116]
Pentachlorophenol	seagrass meadow	[114]
Organophosphate		
Chlorpyrifos	estuary	[114]
Iprobenfos	marine sediment	[112]
Temephos	mangrove forest	[114]
Pyrethroid		
Bifenthrin	estuary	[111]
Triazine		
Atrazine	mangrove forest, seagrass meadow, coral reef	[114,117–119]
Carbamate		
Carbaryl	seagrass meadow	[114]

Determining the direct or clear impacts of pesticides on the marine environment is highly challenging since there are (1) various sets of environmental conditions, (2) varying kinds and levels of pesticides present, (3) several chemical transformations that pesticides go through, (4) different responses and sensitivity of populations and organisms, (5) presence and levels of other pollutants, and (6) the multitude of possible interactions between and among those previously stated [116]. This is probably why much of the available literature is focused on risk assessment of pesticide residues in the environment instead of specific impacts of pesticides on marine species. Moreover, only controlled laboratory experiments can establish cause-and-effect relationships between a pesticide of interest and a target organism. Nevertheless, enough evidence in the literature demonstrates the impacts of common pesticides to warrant great caution in the continued use of certain pesticides and convince societies and governments to take action to mitigate and manage the global pesticide problem.

Organochlorines generally have deleterious impacts on the reproduction of fish, birds, and mammals. Islam and Tanaka [120] report that populations of gastropods, fish (e.g., white croaker), and birds (e.g., white-tailed eagle) have suffered from OCs. Moreover, OCs have also been found to cause liver damage in many animals, impacting their overall health [110]. Similarly, the epithelial tissues of certain coral species and seals become compromised when exposed to OCs, which makes these animals more prone to diseases or even necrosis [115,120]. Organochlorines are also toxic to marine plants. At high concentrations, the cell walls of mangroves and seagrass become damaged when exposed to OCs, which leads to death [114].

Organophosphates, carbamates, and pyrethroids generally act as neurotoxins that alter the behavior of animals, affecting movement, eating, territorial behavior, and reproduction [113,121]. Furthermore, Osuna-Flores et al. [122] have documented that OPs reduce white shrimp's muscle and fat mass. More recently, OPs have been found to change the typical microbial community in waters where salmon are cultured, leading to altered nitrogen levels in the ambient environment [123]. Several studies on the negative impacts of OPs, carbamates, and pyrethroids can be found in the literature. However, most are about freshwater organisms [124]. One possible explanation is that OPs, carbamates, and pyrethroids are more readily degradable than OCs. Therefore, it is likely that these chemicals become more diluted as they go through the terrestrial environment and food chain [125].

Unlike OPs, carbamates, and pyrethroids, triazine Atrazine is also used as an antibiofouling chemical at sea; thus, high concentrations are found in the marine environment [117,126]. Atrazine is a potent herbicide toxic to mangroves, seagrass, and the symbiotic algae of corals [114,117]. Atrazine has been found to reduce the photosynthetic activity of seagrass and the production of its above-ground biomass (ramets and blades; 114). Atrazine has also been found to reduce the amount of zooxanthellae (symbiotic algae) found in coral tissues. This leads to coral bleaching and increased disease susceptibility (117). Copepods exposed to high levels of Atrazine showed that specific genes were downregulated, body size decreased, and metamorphosis and molting delated [127]. Brain et al. [126] demonstrated that oysters exposed to Atrazine would have smaller shells, while mysid shrimps either had reduced growth or died after chronic exposure. In the same study, the authors concluded that oysters and mysids shrimps could be used as biomarkers. Similarly, Francolino et al. [128] have found that the marine nematode *Litoditis marina* can also be a promising biomarker since exposure to Atrazine decreases the growth and development of the animal.

7. Mitigation and Management Strategies

Mitigation and management strategies for pesticide toxicity against terrestrial organisms in the Philippines involve various approaches. Bioremediation techniques such as phytoremediation, immobilization by biochar, and the use of arbuscular mycorrhizal fungi (AMF) are effective in reducing pesticide contamination in soils [129–131]. Additionally, implementing on-field management practices and off-field measures like windbreaks, buffer zones, vegetated treatment systems, and biobeds can significantly minimize the negative impacts of pesticide application on terrestrial ecosystems [129]. Using bioindicators like human hair, lichens, and chromosomal damage biomarkers can help assess the genotoxic effects of pesticides on biological species in the environment, highlighting the need for continuous environmental biomonitoring efforts in the country [130]. By integrating these remediation technologies and monitoring strategies, the Philippines can work towards restoring soil and air quality, safeguarding terrestrial organisms from the detrimental effects of pesticide toxicity.

Rose and Carter [132] state that rapid pesticide transport from sloping farmland to surface waters can be mitigated through vegetated strips, drainage ditches, and good agricultural practices. These methods can significantly reduce the movement of pesticides, thereby protecting water quality. Organic residues and conventional tillage practices significantly reduce pesticide leaching and water percolation in cropping systems [133]. Avoiding applications on wet soil in autumn and avoiding applications during high precipitation risk in spring can potentially reduce pesticide losses and acute toxicological effects, according to Lewan et al. [134]. To create effective mitigation strategies, it is essential to comprehend the factors that contribute to pesticide leaching and transport. We can guard against the damaging effects of pesticide pollution on aquatic ecosystems and human health by putting sustainable agricultural practices into place and enhancing environmental inspections. Ongoing research and practice adaptation is required to guarantee the long-term sustainability of agricultural systems and the security of our water resources.

8. Alternative Practices and Solutions

Low pesticide use rarely decreases productivity and profitability in arable farms, with the potential for a 42% reduction in 59% of farms [135]. Farmers are less willing to reduce pesticide use due to the risk of production losses and administrative burdens. However, they are more willing to adopt low-pesticide practices if they earn revenue from outside their farms or believe yields can be maintained [136]. Moreover, farm machine use significantly reduces pesticide expenditure, especially in maize production, improving human health and environmental performance [137]. Organic farming promotes overall pest control, with lower pathogen infestations, similar animal pest levels, and higher weed infestations than conventional agriculture [138].

Reduced use of pesticides and appropriate use of personal protective equipment during all phases of pesticide handling can lower farmers' exposure to pesticides [139]. A new agricultural concept is needed to produce safer food for humans and the environment, focusing on sustainable practices and food sovereignty [140]. Ecological engineering (EE) in Cambodian rice fields, where non-rice crops are grown in the surrounding areas, provides environmental and economic benefits while maintaining rice yields [141]. STICS-MACRO is a promising tool for assessing the environmental risks of pesticides in cropping systems, considering complex agricultural practices and crop transpiration [133].

Based on the study of Abdollahzadeh et al. [142], perceptions of the benefits and harms of pesticides influence their acceptance and use among farmers in developing countries. Since these perceptions vary widely, continuous research is essential for developing effective intervention initiatives. Therefore, balancing pesticide use and adopting sustainable agricultural practices is crucial for minimizing environmental harm and safeguarding human health.

9. Conclusions and Research Prospects

In conclusion, the pervasive use of pesticides presents significant challenges to human health and the environment, underscoring the urgent need for comprehensive management and mitigation strategies. The adverse effects on humans, soil microorganisms, arthropods, reptiles, and amphibians highlight the extensive ecological disruption caused by these chemicals (Figure 1). Understanding the mechanisms of pesticide toxicity and their impact on various organisms is crucial for developing effective bioremediation techniques and on-field management practices. By implementing these strategies and enhancing environmental biomonitoring, countries can mitigate the harmful effects of pesticides, ultimately protecting biodiversity and ensuring the health of their ecosystems.

Pesticides play a critical role in food production, but their harmful environmental effects cannot be overlooked. The toxicity of pesticide residues on people and crops increased the need for pesticide residue monitoring. As a result, various extraction techniques have been developed using different reagents, solvents, and a range of traditional to modern analytical methods. Selecting the best analytical method is challenging due to the vast diversity of pesticides across different chemical classes and matrices. Traditional and modern techniques have strengths and limitations, and the laboratory's capabilities and personnel expertise influence the choice. However, prioritizing fast and efficient results is crucial to reducing the persistence and spread of pesticides and their harmful effects on human health. Further research is needed to develop environmentally safe, rapid, and cost-effective methods for pesticide analysis.

Pesticide use carries significant environmental, ecological, and human health impacts, influenced by microbial and chemical degradation, runoff, adsorption, volatilization, photodecomposition, and leaching. The complexity of these processes shows the challenge of predicting the different pesticide behavior in diverse environments, often leading to unintended consequences. For instance, the indirect effects of herbicides on ecosystems can be severe, impacting biodiversity, food web interactions, and natural biocontrol processes. The gaps in knowledge regarding real-world exposure and effects, particularly under conditions of multiple and mixed pesticide applications, stress the need for more comprehensive research [143].

Even pesticides entering the marine environment are a growing problem despite being old. This is because, as a society, we are highly dependent on pesticides to ensure food security for an ever-growing population. In the Philippines, wide-scale risk assessments on pesticide residues started and ended about a decade ago due to findings of below-threshold concentrations for many pesticides [116,144]. It is, therefore, high time that those risk assessments be updated and applied nationwide. Other Asian countries are already ahead of this and are investing in mitigating the problems posed by pesticides and other pollutants [145,146].

Moreover, assessing the persistence of the kinds and concentrations of pesticides should include more modern pesticides, not just organochlorines. Policies and regulations on pesticides commonly used must also be revisited and updated. The country boasts many marine species, many of which are waiting to be discovered, studied, and possibly utilized. For example, other researchers have found that marine-based bacteria and fungi are very effective at bioremediating pesticide residues [147,148]. Lastly, to ensure food security without sacrificing environmental sustainability, agricultural activities and technologies must also be revisited and updated [149].

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