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Invited Review

Official Journal of Erciyes University Faculty of Medicine

DOI: 10.14744/cpr.2026.10880
J Clin Pract Res 2026;48(2):99–109

Pesticides, Environmental Contamination, and Public Health: A One Health Perspective

Filiz Dadaser-Celik,[1] Zafer Sezer,[2] Nuray Ates[1]

[1]Department of Environmental Engineering, Erciyes University Faculty of Engineering, Kayseri, Türkiye
[2]Department of Medical Pharmacology, Erciyes University Faculty of Medicine, Kayseri, Türkiye

ABSTRACT

Pesticides are chemicals used in the agricultural, industrial, and public health sectors to increase crop productivity, prevent plant diseases, and reduce pest-related hazards. They can be classified as herbicides, insecticides, fungicides, and rodenticides based on the pests they target. Their active ingredients include organochlorines, organophosphorus compounds, carbamates, pyrethrins, and pyrethroids. Although the use of pesticides has provided significant benefits to humans, their widespread application has also led to the contamination of air, soil, water, and food systems. After application and distribution among air, water, soil, and biota, several processes control the fate and transport of pesticides in the environment, as well as their transformation through biological, chemical, and physical reactions. Humans and animals are exposed to pesticides through various pathways, including drinking contaminated water, consuming pesticide-contaminated food, and living in areas treated with pesticides. Both acute and chronic exposure to pesticides can cause several adverse health effects on the neurological, endocrine, and reproductive systems and may pose carcinogenic risks. This study provides a comprehensive review of research on the occurrence and fate of pesticides in the environment. It also presents the risks to human health associated with occupational and environmental exposure to pesticides. Available techniques for reducing pesticide-related risks are also discussed. This review showed that human, animal, and ecological health are interconnected and that, therefore, an integrated strategy such as the One Health approach is needed to effectively manage pesticide-related risks.

Keywords: Environmental exposure, environmental health, one health, pesticides, public health.

Cite this article as:
Dadaser-Celik F, Sezer Z, Ates N. Pesticides, Environmental Contamination, and Public Health: A One Health Perspective. J Clin Pract Res 2026;48(2):99–109.

Address for correspondence:
Filiz Dadaser-Celik.
Department of Environmental Engineering, Erciyes University Faculty of Engineering, Kayseri, Türkiye
Phone: +90 352 207 66 66 /32804
E-mail: fdadaser@erciyes.edu.tr

Submitted: 20.02.2026
Revised: 17.04.2026
Accepted: 17.04.2026
Available Online: 07.05.2026

Erciyes University Faculty of Medicine Publications - Available online at www.jcpres.com

INTRODUCTION

An integrated perspective has become crucial for understanding and addressing the significant global challenges we are confronting. In recent years, several examples have demonstrated the necessity of this perspective. For instance, to address the impacts and risks associated with climate change, the need for integrating ecological, economic, and social systems has been emphasized.[1] The challenge of antimicrobial resistance has highlighted the interconnections among human, animal, and environmental health, calling for an interdisciplinary, integrated management approach.[2]

One approach that embodies such an integrated perspective is One Health.[3] One Health acknowledges the interconnectedness of human, animal, and ecosystem health and seeks to create integrated solutions to address complex environmental and health challenges. These challenges are diverse, including antimicrobial resistance, infectious diseases, and diseases related to exposure to toxic chemicals (e.g., pesticides) at the forefront of the list.[4] One Health is an interdisciplinary field encompassing medical sciences, veterinary sciences, ecology, public health, and related disciplines. As such, input from diverse fields and their effective integration are required.[5] However, despite its interdisciplinary nature, the application of One Health often remains conceptual, with limited integration across disciplines in practice. Strengthening its practical integration is essential to address health challenges holistically and achieve overall protection of human, animal, and ecosystem health.

Pesticides are chemicals extensively used in the agricultural, industrial, and public health sectors to increase crop productivity, prevent plant diseases, and repel pests. These are typically complex organic compounds that are relatively resistant to degradation. While this resistance makes them effective for pest control, it also increases their persistence in the environment and potential toxicity to humans. Long-term exposure to pesticides can result in chronic toxic effects, while acute high-dose exposure can lead to severe toxic effects, including death.[6] Conventional pesticide risk assessment approaches are based on human health risk assessment and ecological risk assessment. These methods focus on specific receptors (e.g., humans or aquatic organisms), single substances, and direct exposure pathways. In other words, they often consider separate or primarily single compartments and do not fully account for the interactions among different environmental media, cumulative exposures, or indirect effects.

In contrast, the One Health approach evaluates multiple exposure pathways (e.g., air, soil, water) and their simultaneous and cumulative impacts on multiple receptors. This approach allows for the analysis of feedback mechanisms between environmental processes and human health impacts. By promoting interdisciplinary integration, One Health provides a more comprehensive basis for understanding and managing the complex risks associated with pesticide use.

This review aims to characterize and identify the challenges associated with pesticide contamination from a One Health perspective by discussing the nature of the problem, current approaches, and the lack of integrated frameworks that connect environmental processes to human health outcomes. In the past, many studies have evaluated pesticide occurrence, fate, and toxicity; however, their analyses were often confined to disciplinary boundaries, and the understanding of interactions among these disciplines was limited. This study begins by discussing the occurrence of pesticides in surface waters, groundwater, and soils. It then explains the pathways through which pesticides are introduced into the environment, along with their fate and transport mechanisms. Human and animal exposure pathways, along with the associated health effects of pesticide exposure, are discussed. Finally, the approaches used to manage pesticide-related risks are reviewed, and further research needs are highlighted to emphasize the added value of integrating environmental, ecological, and health-based perspectives for more comprehensive risk evaluation and management.

ENVIRONMENTAL OCCURRENCE OF PESTICIDES

Pesticides are not a uniform group; they comprise a highly heterogeneous class of compounds with distinct target organisms, modes of action, and environmental behaviors. They are classified as herbicides (target weeds), insecticides (target insects), fungicides (target fungi), and rodenticides (target rodents). Their chemical compositions are highly variable, including organochlorines, organophosphorus compounds, carbamates, pyrethrins, and pyrethroids. These differences strongly influence their properties, such as persistence, mobility, bioaccumulation potential, and toxicity. Therefore, the environmental fate, transport pathways, and associated risks of pesticides vary across these classes.

At the global level, total pesticide use has increased significantly in recent decades. According to the FAO's report,[7] the global volume of pesticides used in agricultural production was about 3.73 million tons of active ingredients in 2023. Approximately 51% of global consumption consists of herbicides, while insecticides, fungicides, and bactericides account for 22% each. The remainder consists of rodenticides and other special-purpose pesticides. The consumption of pesticides worldwide varies, with the largest use occurring in Brazil (21.5%), followed by the United States (11.5%), Indonesia (7.9%), Argentina (7.1%), and China (5.8%).[7]

Monitoring studies have shown that pesticide pollution follows a consistent pattern in different countries, both in terms of compound types and concentration levels. Among herbicides, the most frequently reported active substances are atrazine, metolachlor, alachlor, diuron, simazine, and terbuthylazine, while among insecticides, imidacloprid, acetamiprid, thiamethoxam, chlorpyrifos, and dimethoate are most commonly detected, typically in the ng/L–low µg/L range in surface waters.[8,9] In North China, organophosphate pesticides such as dimethoate, dichlorvos, methyl-parathion, and malathion exhibit significant seasonal variability, with total concentrations ranging from 174-321 ng/L, averages of 3.9-7.1 ng/L, and detection rates of 47-69% during the summer period, and total concentrations of 152-269 ng/L, averages of 3.4-6.0 ng/L, and detection rates of 23-62% during the winter period.[10] In the Llobregat River and its aquifer in Barcelona, significant pesticide pollution was reported, with maximum concentrations of several µg/L for carbendazim, N,N-dietil-m-toluamid, diuron, and propiconazole, and concentrations of 0.1–0.5 µg/L for imidacloprid, simazine, bentazone, metazachlor, and tebuconazole.[11] Long-term monitoring in Germany shows that most substances detected in surface waters are pesticide metabolites, with metazachlor sulfonic acid, metolachlor ethanesulfonic acid, and metazachlor oxanilic acid occurring at higher and more persistent levels than their parent compounds, leading to long-term exposure concerns.[12] Similarly, in the United States, atrazine, metolachlor, glyphosate, and imidacloprid were commonly detected during the 2013-2017 period. Imidacloprid, in particular, was identified as one of the major pesticides posing a chronic ecotoxic risk to aquatic organisms, detected at concentrations of 0.1-1 µg/L in some agriculturally and urban-based impacted areas.[13]

Although pesticides are generally detected at lower concentrations in groundwater than in surface water, levels can be high, especially in areas with intensive agricultural activity. Groundwater samples in France, Denmark, England, and Switzerland commonly contain active substances such as atrazine, metolachlor, bentazone, and simazine, as well as their metabolites. The concentrations of these substances typically range from 0.05 to 0.5 µg/L, and at many sampling points, the European Union (EU) drinking water limit of 0.1 µg/L is exceeded. The greater mobility and persistence of metabolites compared to parent compounds contribute to a dominant, persistent pesticide pollution profile in groundwater.[14]

Among the most common pesticides in agricultural soils are glyphosate and its metabolite aminomethylphosphonic acid (AMPA). Concentrations reaching 100-1900 µg/kg for AMPA and 50-2000 µg/kg for glyphosate have been reported in EU countries. Insecticides such as imidacloprid and chlorpyrifos are measured in the range of 10-120 µg/kg and 5-50 µg/kg, respectively, in intensively farmed areas of Mediterranean countries and China, while herbicides such as terbutylazine, metolachlor, and alachlor are reported to be mostly at levels of 20-1000 µg/kg in the soils of the US, Europe, and South America.

ENVIRONMENTAL FATE AND TRANSPORT OF PESTICIDES

Pesticides are introduced into the environment through multiple pathways. These pathways vary based on the type of application, target use, and physicochemical properties. In agricultural systems, pesticides are applied directly to crops and are distributed in the environment through spray drift, surface runoff, and leaching. In urban and municipal areas, applications for pest control result in surface runoff over impervious surfaces, with final discharge to stormwater collection systems. Localized releases from industrial uses and manufacturing processes occur through effluents or improper handling. These pathways differ substantially among pesticide classes and application practices, influencing their distribution, persistence, and potential exposure routes in environmental systems (Fig. 1).

Crop patterns and application frequency have a significant impact on soil pesticide levels, which can accumulate in agricultural soils over time.[15] For example, fruits and vegetables generally require higher pesticide inputs than cereals, as they are more susceptible to pests and diseases.[16] In urban areas, herbicides and insecticides are widely used in parks, lawns, home gardens, and indoor applications, resulting in more concentrated applications than in agricultural areas. This leads to a condensed application compared to agricultural areas. In the US, lawns and home-and-garden applications are reported to account for 8% of total herbicides, 15% of insecticides, and 10% of fungicides. Urban dust and air have been shown to contain pyrethroid and organochlorine pesticides, and surface waters have been found to contain substances such as atrazine, diuron, metolachlor, and chlorpyrifos, which pose a serious threat to ecosystems and human health.[17]

Pesticide manufacturing facilities create another primary source of pesticides in the environment. These facilities can cause both point and distributed pollution. Pesticides can remain in wastewater even after treatment.[18] Treated or untreated wastewater is eventually discharged into receiving water bodies. Moreover, chemical spills, improper waste disposal, or emissions during production processes in these facilities can provide another route to the environment.[19]

Once pesticides are introduced into the environment, a variety of physical, chemical, and biological processes determine their fate and transport, as well as their distribution among environmental compartments such as the atmosphere, soil, surface water, and groundwater. In the atmosphere, processes such as volatilization and air transport can carry pesticides over long distances. In soils, sorption, degradation, and leaching control their potential transfer to other media or retention. Runoff, erosion, and dilution processes determine surface-water concentrations, along with degradation and sediment interactions. In groundwater, leaching controls transport. In general, the behavior of pesticides in the environment is controlled by transport, transfer, and transformation processes.[20]

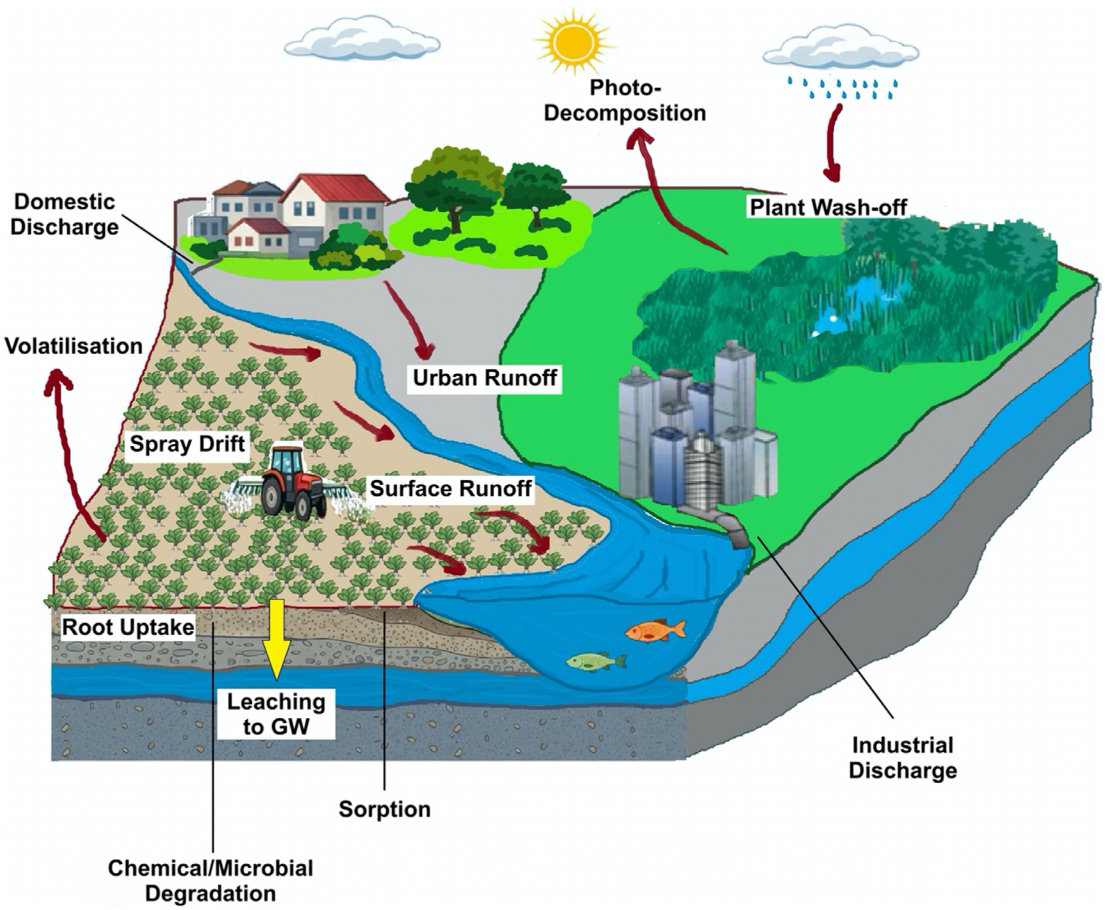

Figure 1. Fate and transport of pesticides in the environment.

Transport processes carry pesticides away from their point of application through air and water, determining the spatial extent of pesticide contamination. During transport, pesticides can be in the form of solid, gas, or liquid. They are first introduced to the air by spray drift during application. However, the transfer to the atmosphere continues after application through evaporation or volatilization from soil and plant surfaces.[21] Air is the major medium for transporting materials over longer distances and is strongly dependent on the method of application and the properties of the compound.[21] The variety of droplet sizes, atmospheric conditions during and after application, and the composition of the spray can all affect spray drift. After application, pesticide passage to air is controlled by pesticide characteristics. Pesticides with higher vapor pressures are more likely to volatilize after application, thus having higher atmospheric concentrations.[21]

Transfer processes affect the distribution of pesticides among water, soil, and biota after application. These processes include volatilization, surface runoff, leaching, adsorption, and plant uptake.[20] Pesticide characteristics (e.g., water solubility, volatility, soil adsorption, and persistence) and soil characteristics (e.g., texture, permeability, depth, pH, organic matter content) affect transfer processes.[20] Meteorological conditions, particularly rainfall timing and intensity following pesticide application, also play a significant role.

Among transfer processes, volatilization is the process through which pesticides are carried from soil or plant surfaces into the atmosphere. Pesticides with higher vapor pressure can easily transition to the gaseous phase after application.[21] The volatilization process is reversible, meaning that pesticides enter the atmosphere but can also redeposit onto soil or plant surfaces. Surface runoff is a process that occurs after rainfall or irrigation events. It is considered one of the primary routes by which pesticides are transported to surface waters, including rivers, lakes, and reservoirs. After a rainfall event or irrigation, excess water flows over the land surface as sheet flow, carrying pesticides from application sites to the nearest surface waters.[22] In surface runoff, pesticides are transported either as dissolved material or particulate matter. The phase of the pesticide is influenced by its solubility and sorption characteristics.

Leaching is the process that controls the downward movement of pesticides in the soil profile through infiltration or percolation processes. This process represents the major route by which pesticides can enter groundwater.[23] Pesticides with higher water solubility and lower sorption affinity to soil particles are generally transported more easily through the soil. Soils with higher permeability also allow greater pesticide movement through leaching. Adsorption refers to the process by which pesticides attach to the surface of soil particles. Adsorption is a reversible process where adsorption and desorption occur continuously, which moves pesticides between the dissolved and particulate phases. The adsorptive capacity of soils is largely influenced by properties such as pH, organic matter content, the presence of clay minerals, and oxide hydroxides.[20] The physicochemical characteristics of pesticides are also important in the adsorption-desorption process. Some pesticides have a higher adsorptive affinity (e.g., hydrophobic pesticides), meaning they are more strongly held on soil particles.

Plant uptake is another important transfer pathway, whereby pesticides are absorbed by plant roots or foliage. After the pesticides are taken up by plants, they may be carried within plant tissues, metabolized, or accumulated.[24]

Transformation processes refer to biological, physical, and chemical reactions that convert pesticides into other substances.[25] The degradation of pesticides involves transformation processes carried out by microorganisms or plants, as well as chemical and photochemical reactions.[25] In microbial degradation, microorganisms consume and transform chemicals into other forms in soil, water, or sediment environments. Chemical and photochemical processes involve hydrolysis, oxidation/reduction, and photolysis, typically occurring at the soil surface and in surface waters. It is possible that the final product can be more toxic than the parent pesticide.[25] Both environmental conditions (e.g., temperature, moisture, redox conditions, and light availability) and pesticide properties (e.g., molecular structure and functional groups) affect the type and rate of transformation.[25]

HUMAN AND ANIMAL EXPOSURE PATHWAYS

Humans are exposed to pesticides through occupational or environmental contact via various mechanisms in work or home environments, such as work-related activities, consuming foods and drinks, using medicines, and during travel and recreational activities. Pesticides can enter the human body through dermal, oral, eye, and respiratory routes.[26] Several factors affect the actual amount of pesticide that enters the human body. These include the physicochemical characteristics of the pesticide (e.g., water solubility, volatility, and persistence), contact duration and frequency, availability of protective equipment, and personal factors such as age.[26]

Occupational exposure refers to direct contact with pesticides, often during work activities. Occupational contact creates the highest-risk type of pesticide exposure because workers (i.e., farm workers, gardeners, workers in pesticide manufacturing plants) involved in the production, transfer, and application of pesticides use them regularly and often in concentrated forms.[6] Protective clothing and equipment can limit exposure; however, these measures are often neglected because they are uncomfortable to use continuously, especially under unsuitable environmental conditions.[26] Even with protective clothing/equipment, skin contact and inhalation can still pose risks for workers.

Environmental exposure occurs through contaminated air, water, soil, and food. Food serves as a significant environmental exposure route. Pesticides applied on farms can remain in smaller concentrations on fruits, vegetables, and grains even after harvesting. Washing and peeling can reduce pesticide residues to some extent, but some pesticides can penetrate the food itself. For instance, it was estimated that by consuming wheat products, humans can ingest 22 mg-2.1 g of pesticide per kilogram applied to wheat.[27] Through the food chain, pesticides can also accumulate in meat, dairy, and fish.[28] Exposure to pesticides can occur by using contaminated water, either as drinking water or during recreational water use. The health risks due to pesticides in drinking water sources have been discussed.[29] Soil exposure occurs when humans come into contact with contaminated agricultural soils. Contact can be in the form of direct handling, inhalation of resuspended soil particles, or incidental ingestion. Air exposure occurs through pesticide volatilization after application and the drift of spray droplets during spraying.[21] Pesticides can be carried over long distances in the atmosphere and may remain in the air or deposit onto soil or water, where human contact may occur.

HEALTH EFFECTS OF PESTICIDE EXPOSURE

Pesticides can cause acute toxicity through inhalation, ingestion, or contact with the skin and eyes. Long-term or repeated exposure to lower doses can lead to chronic toxicity.

Acute Health Effects

An increased incidence of respiratory problems and neurodegenerative diseases has often been reported due to occupational exposure, particularly the exposure of agricultural workers to pesticides.[6] In the US, exposure to chlorpyrifos and other organophosphates is estimated to cause billions of dollars in annual losses due to cognitive decline and abnormalities in brain development. Chlorpyrifos was prohibited in the EU in 2020 and in the US in 2021, while it remains prevalent on other continents.[30] Organophosphate pesticides act as acetylcholinesterase (AChE) inhibitors. By blocking AChE, they prevent the breakdown of acetylcholine (ACh), causing its accumulation at cholinergic nerve endings. This leads to postsynaptic receptor overstimulation and adverse effects in both the central and peripheral nervous systems.[31]

Some of the anticholinesterase (anti-ChE) agents, such as tabun, sarin, and soman, are extremely toxic and have been used as biological weapons in warfare or in terrorist attacks, such as the one in Tokyo.[32] Acute intoxication by anti-ChE agents produces both muscarinic and nicotinic effects, and except for compounds with very low lipid solubility, also affects the central nervous system. Systemic symptoms usually appear within minutes after inhalation, while onset is slower after gastrointestinal or skin absorption. Ocular and respiratory symptoms occur first. Ocular effects include marked miosis, eye pain, blurred vision, and ciliary spasm, although miosis may be absent during severe systemic poisoning due to sympathetic responses. Respiratory effects include rhinorrhea, chest tightness, wheezing, bronchoconstriction, and increased bronchial secretions. Gastrointestinal symptoms include nausea, vomiting, abdominal cramps, and diarrhea.

With skin exposure, localized sweating and muscle fasciculations are often the first signs. Severe poisoning is characterized by excessive salivation, sweating, lacrimation, involuntary urination and defecation, bradycardia, and hypotension. Nicotinic effects at the neuromuscular junction cause muscle weakness, twitching, and eventually paralysis. The most serious outcome is paralysis of the respiratory muscles, and death usually occurs due to respiratory failure, often with a secondary cardiovascular component.[31,33]

Chronic and Long-Term Health Outcomes

Prolonged pesticide exposure may result in severe impairments in cognitive, somatic movement, visceral, sensory, affective, and neurodevelopmental abilities. A study that included 431 children aged 6-12 from three communities—two in an agricultural region (Community A and B), where mainly organophosphate and pyrethroid pesticides were reported, and one reference population (Community C), located far from agricultural fields in Mexico—showed that dialkylphosphates and 8-hydroxy-2′-deoxyguanosine in urine, as well as malondialdehyde in serum concentrations, significantly increased in communities A and B compared to community C. Proinflammatory cytokine IL-8 also showed a significant increase in community A compared to community C, indicating increased oxidative stress, DNA damage, and inflammation.[34]

A systematic review covering data from 12 countries revealed positive associations between Non-Hodgkin Lymphoma (NHL) and carbamate insecticides, organophosphorus insecticides, lindane (an organochlorine insecticide), and 2-methyl-4-chlorophenoxyacetic acid (a phenoxy herbicide).[35] Glyphosate exposure was also associated with an increased risk of NHL in humans in another meta-analysis.[36]

Pesticides can alter the immune system by disrupting normal immune responses to tumor antigens, allergens, self-antigens, and microbial agents, which may increase the risk of cancers, allergies, autoimmune disorders, and infectious diseases. One of the main mechanisms is the disturbance of cytokine balance, which affects immune regulation.[37] Pesticides have also been linked to an increased risk of obstructive lung diseases such as chronic bronchitis and chronic obstructive pulmonary disease.[38]

Chronic ambient exposure to organophosphates may alter the composition and predicted metabolic functions of the human gut microbiome. In a study of 190 participants from an agricultural region in California, organophosphate exposure was associated with changes in the abundance of several bacterial groups and shifts in microbial metabolic pathways. These changes included disturbances in cellular respiration, increased biosynthesis and degradation of bacterial cell wall components, increased production of RNA and DNA precursors, and reduced synthesis of vitamins B1 and B6.[39] Chronic exposure has also been linked to a higher prevalence of metabolic disorders such as obesity and type 2 diabetes. Dysmetabolism is associated with low-grade inflammation, and the gut microbiota plays a significant role in its development. One key change observed is a decrease in Bacteroidetes and an increase in Firmicutes, a pattern linked to both pesticide exposure and dysmetabolic risk.[40]

In vitro and ex vivo studies showed that acute exposure to the pesticide malathion reduced the viability of pancreatic islet cells and promoted signs of damage in α and β cells at the subcellular level. Moreover, chronic exposure to malathion affected β-cell viability and α-cell voltage-gated K^+ currents. Pesticide exposure may increase the prevalence of type 2 diabetes.[41]

A randomized controlled dietary intervention trial evaluated the effects of changing from conventional to organic food consumption. Healthy adults were randomly allocated to either an organic food (n=13) or conventional (n=14) group. The conversion to organic food with a Mediterranean diet reduced exposure to all types of pesticides from different sources by >90%.[42]

To demonstrate how long-term, low-level exposure to glyphosate, metals, and their combination damages kidney structure and function, a study used adult zebrafish as a mechanistic model. Exposure to both glyphosate and metals caused a synergistic effect, leading to more damage to kidney health compared to exposure to individual chemicals. In this study, mitochondria-rich proximal tubules were identified as the main targets of chronic glyphosate-metal combination exposure.[43]

A study in China showed a consistent positive relationship between abnormal blood cell, liver, and peripheral nervous system test results and the intensity of pesticide exposure. Sensory abnormalities were more common than motor problems, and abnormal electrophysiological findings were predominantly observed in sensory nerves in the higher-exposure group, indicating neurotoxicity.[44] Organophosphate, carbamate, pyrethroid, and organochlorine insecticides are known to cause acute neurotoxic effects. Many epidemiological studies have also reported increased risks of long-term behavioral and neurological disorders in populations with chronic exposure. These effects have been linked to mechanisms such as oxidative stress, altered dopamine transporters, mitochondrial dysfunction, α-synuclein aggregation, and neuroinflammation, which are associated with neurodegenerative diseases like Parkinson's and Alzheimer's disease.[45]

Pesticides significantly impact female reproductive health by targeting the ovary. Epidemiological research links these exposures to menstrual cycle disorders, polycystic ovary syndrome, primary ovarian insufficiency, and reduced fertility in women. Toxicological studies demonstrate that pesticides disrupt the estrous cycle, deplete the follicle pool, and impair oocyte maturation. Pesticides influence steroid hormone synthesis due to alterations in the activity of key enzymes and affect ovarian function. Pesticides can also induce oxidative stress, inflammation, and apoptosis, which may cause DNA damage and altered gene expression in ovarian cells.[46] Pesticides also affect male reproductive systems through impaired sperm quality and altered hormone levels. Insecticide exposure significantly impairs fertility in a dose-dependent manner.[47]

Organophosphate chemicals have been found to inhibit the acetylcholinesterase enzyme, as well as a number of other biological targets, including hormones, neurotransmitters, neurotrophic factors, enzymes involved in the breakdown of beta-amyloid protein, and inflammatory alterations.[48] Evidence from animal studies links exposure to the organophosphate chlorpyrifos with neurodegeneration, including elevated beta-amyloid levels and impaired cognition. However, the relationship between these effects is still unclear. Two different pathways may be involved: one in which cognitive deficits result from cholinergic overstimulation, and another that acts directly on the beta-amyloid pathway.[49] On the other hand, the relationship between pesticide exposure and Parkinson's disease is proposed to be related to inhibition of mitochondrial Complex I and oxidative stress. Additionally, organophosphates can cause oxidative stress.[50]

The repetitive or long-term exposure to cholinesterase inhibitors, such as carbamates and organophosphates, is most commonly observed in farm workers. Roldan-Tapia et al.[51] investigated the long-term cognitive effects of pesticide exposure on greenhouse workers in Almería, Spain, to assess whether chronic, low-level exposure to cholinesterase-inhibiting pesticides leads to neuropsychological dysfunction or emotional disturbances. Significant deficiencies in visuo-constructional praxis and integrative perception were observed in workers who had been exposed for more than ten years. Chronic exposure to pesticides for over a decade results in measurable impairments in visual and motor integration as neuropsychological functions.

Even exposure to low doses of pesticides is associated with neurodevelopmental disorders.[30] Organophosphate pesticide exposure during pregnancy may have a detrimental effect on a child's early behavior, motor skills, and mental development. Although the consequences of postnatal exposure are less clear, they may nonetheless affect motor and cognitive abilities and raise the possibility of attention issues.[52]

Another study on 175 pregnant tea garden workers in India evaluated the effects of pesticide exposure on pregnancy outcomes. The results showed significantly reduced AChE activity in both maternal and cord blood among the workers compared to housewives, especially in the low birth weight group. This implies pathological alterations during pregnancy, such as elevated expression of hypoxia-inducible factor (HIF-1α), which could lead to placental insufficiency and fetal growth restriction.[53]

A large study in the Almería region of Spain, an area with one of the world's highest concentrations of greenhouses, examined 4,830 children referred to Early Intervention Centers between 2011 and 2022 from a total population of about 119,897 children. Chromosomal abnormalities were the most common prenatal diagnoses, gestational age under 32 weeks was the main perinatal condition, and brain damage was the most frequent postnatal diagnosis. The findings suggest a possible link between intensive pesticide use in greenhouse areas and neurodevelopmental and learning problems in children.[54]

Selective toxicity of pesticides is extremely desirable; however, all pesticides can elicit toxicological responses in humans.

MANAGEMENT OF RISKS ASSOCIATED WITH PESTICIDES

Studies have shown that only a very limited fraction of the pesticides applied during agricultural practices directly affect the target pest organisms, while the vast majority are transported through soil, surface water, groundwater, and atmospheric systems. Numerous ecotoxicological and epidemiological studies published in recent years have revealed that addressing pesticide management solely from an agricultural productivity perspective is unsustainable. Therefore, pesticide management is considered not only at the agricultural application scale but also within the framework of human health risk analysis.[55,56]

Integrated Pest Management (IPM) has become a significant approach for pest control in recent years. In the EU, Directive 2009/128/EC makes IPM mandatory for professional users. This approach aims to keep pest populations at a level that does not cause economic damage; in other words, it does not focus on the complete disappearance of pest populations. IPM uses chemical, biological, cultural, and mechanical control methods interactively in a systematic and adaptable way.[56] Barzman et al.[57] defined eight fundamental IPM strategies. These include: (i) designing resistant production systems for pest prevention, (ii) regular monitoring and early warning systems, (iii) threshold-based decision-making processes, (iv) prioritizing non-chemical methods, (v) preferring selective and low-risk pesticides, (vi) reducing pesticide application intensity, (vii) resistance management, and (viii) evaluating the multi-year environmental impacts of applications. This framework transforms pesticide management from a short-term, single-product-focused approach into a dynamic process that needs to be evaluated at the agroecosystem scale.[57]

Biological and "green" control methods, developed as alternatives to chemical pesticides, are fundamental components of IPM systems. In particular, bacterial insecticides (such as Bacillus thuringiensis, B. sphaericus, and Saccharopolyspora spinosa) are safer alternatives to synthetic pesticides due to their high target specificity, rapid degradation in the environment, and low residue risk. These biopesticides play a critical role not only in suppressing pest populations but also in reducing the environmental burden by decreasing the use of chemical pesticides.[58]

Current pesticide management is also significantly transformed by technological innovations. Remote sensing techniques, sensor-based monitoring systems, unmanned aerial vehicles, and digital decision-support platforms enable the monitoring of harmful pest concentrations at high spatial and temporal resolution. These technologies significantly reduce the number of applications and the risk of environmental spread by ensuring that pesticides are applied only in the necessary areas and at the appropriate times. This approach is described in the literature as "precision agriculture-based IPM".[59]

Pesticide management also includes social, economic, and managerial dimensions. The new IPM paradigm proposed by Dara[59] expands the classical ecological IPM approach by incorporating management, business model, and sustainability components. It considers producer-consumer-market interactions to be an integral part of pesticide control. In this model, pesticide management aims to optimize economic feasibility, environmental safety, and social acceptability criteria together.

Overall, the current state of pesticide management and control has evolved from short-term, one-dimensional solutions based on chemical inputs towards an IPM-based, multidisciplinary, and risk-oriented structure. The basic principles of sustainable pesticide management include reducing pesticide use, encouraging biological and cultural approaches, incorporating modern monitoring and decision support technology, and complying with legislation based on scientific findings.[56,57,59]

However, although IPM represents a significant improvement and provides a structured and practical framework for reducing pesticide use and environmental impacts at the agroecosystem scale, its scope still largely focuses on pest control and agricultural sustainability. In practice, IPM applications often evaluate impacts within specific sectors or compartments and may not fully account for cross-media transport, indirect effects, or cumulative exposures affecting human and animal health.[60] In this context, the One Health approach extends the IPM perspective by explicitly addressing the interconnectedness of environmental, human, and animal health systems. Therefore, IPM can be considered an important operational component within a broader One Health framework; however, a more explicit integration across disciplines, environmental compartments, and exposure pathways is needed to capture cumulative risks and support more comprehensive pesticide management strategies.[61]

CONCLUSIONS

In this review, we examined the challenges created by intensive pesticide use in agriculture and other sectors. The review showed that after pesticides are introduced into the environment, they are carried through several pathways and accumulate in surface waters, groundwater, and soils. Pesticide use and occurrence are variable but widespread globally. Both acute and chronic exposure to pesticides create risks for human health. Humans can be exposed to pesticides in different ways, including through drinking water and eating food containing pesticide residues.

For both future research and management, this review addresses the need for a One Health approach. Pesticide pollution is not only an environmental problem but also a public health issue. Starting with pesticide production processes and their application in agricultural fields, households, and urban areas, pesticides contaminate air, water, and soil, affect ecological processes, and enter the food chain, eventually reaching wildlife, livestock, and humans. The One Health approach can provide a holistic perspective for evaluating pesticide-related risks, recognizing linkages among human, animal, and ecosystem health. By understanding the effects of pest control strategies, the unintended human and ecological health impacts can be minimized. Preventive strategies included in the integrated pest management framework, such as biological control, reducing the use of chemical inputs, and advancing to precision agriculture with technology, can reduce pesticide-related risks not only for humans but also for the entire ecological system.

Conflict of Interest: The authors have no conflicts of interest to declare.

Funding: The authors declared that this study received no financial support.

Use of AI for Writing Assistance: AI Tools (ChatGPT) was used to check grammar and improve clarity of the text. The authors take full responsibility for the content, accuracy, and originality of the manuscript.

Author Contributions: Concept – FDC, ZS, NA; Design – FDC, ZS, NA; Analysis and/or Interpretation - FDC, ZS, NA; Literature Review – FDC, ZS, NA; Writing – FDC, ZS, NA.

Peer-review: Externally peer-reviewed.

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