

When Pesticides Leave the Farms: The Hidden Threats to Aquatic Ecosystems

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Pesticides have become integral to modern agriculture, supporting crop protection and productivity; however, their environmental journey often extends far beyond the field of application. Through surface runoff, leaching, soil erosion, spray drift and agricultural drainage, pesticide residues can enter rivers, lakes, reservoirs, estuaries and coastal waters. Once in aquatic systems, these contaminants may persist, undergo transformation, partition into sediments or accumulate in aquatic organisms. Exposure can affect a broad spectrum of non-target organisms, including phytoplankton, zooplankton, crustaceans and fish, through mechanisms involving oxidative stress, neurotoxicity, endocrine disruption, genotoxicity and physiological dysfunction. Importantly, impacts may occur even at sub-lethal concentrations, with consequences for growth, reproduction, behaviour, biodiversity, trophic interactions and overall ecosystem functioning. Persistent and bioaccumulative pesticides may further move through aquatic food webs, increasing the duration and ecological significance of contamination and raising concerns for fisheries and human health. This article explores the pathways, environmental fate and ecological consequences of pesticide contamination in aquatic ecosystems and highlights the need for integrated pest management, precision application, runoff mitigation, ecological monitoring and sustainable agricultural practices. Protecting water resources from pesticide pollution is essential for maintaining aquatic biodiversity, sustaining fisheries and securing long-term food and environmental security.

Keywords: Agricultural runoff; Aquatic toxicity; Bioaccumulation; Ecosystem; Pesticide

Introduction

Pesticides are biologically active chemicals, including insecticides, herbicides, fungicides, nematicides and rodenticides, widely used to control agricultural pests and improve crop productivity. However, pesticide residues can move beyond treated fields through runoff, erosion, leaching, spray drift and drainage, contaminating rivers, lakes, wetlands and groundwater (Kumar et al., 2023). In aquatic ecosystems, these contaminants may remain in water and sediments or transform into biologically active metabolites, adversely affecting phytoplankton, zooplankton, benthic organisms, aquatic plants and fish through oxidative stress, neurotoxicity, endocrine disruption, genotoxicity and physiological disturbances (Saha & Maiti Dutta, 2024). Such effects can alter growth, reproduction, biodiversity, trophic interactions and ecosystem functioning, while persistent pesticides may bioaccumulate and undergo trophic transfer (AbuQamar et al., 2024). Thus, agricultural pesticide contamination represents a major ecological concern with consequences ranging from individual-level toxicity to ecosystem-wide disturbances.

Types of Pesticides and Their Major Environmental Effects



Fig. 1. Types of pesticides

(Source: https://static.vecteezy.com/system/resources/previews/011/512/357/non_2x/types-of-pesticides-include-herbicides-insecticides-fungicides-molluscicides-plant-protections-in-agriculture-vector.jpg)

Transformation of Pesticides from Land to Water

Types of pesticides	Definition	Examples	Major active/reactive compounds or chemical groups
Insecticides	Chemicals used to control or kill insect pests.	Chlorpyrifos, imidacloprid, cypermethrin, malathion	Organophosphates: chlorpyrifos, malathion; carbamates: carbaryl; pyrethroids: cypermethrin; neonicotinoids: imidacloprid
Herbicides	Chemicals used to control unwanted weeds and aquatic or terrestrial plants.	Pretilachlor, glyphosate, atrazine, paraquat, 2,4-D	Chloroacetanilides: pretilachlor; triazines: atrazine; bipyridyls: paraquat; organophosphonates: glyphosate
Fungicides	Chemicals used to prevent or control fungal diseases in crops.	Carbendazim, copper sulfate, mancozeb, propiconazole	Benzimidazoles: carbendazim; dithiocarbamates: mancozeb; triazoles: propiconazole; copper compounds: Cu ²⁺
Nematicides	Chemicals used to control plant-parasitic nematodes in agricultural soils.	Carbofuran, aldicarb, oxamyl	Carbamates: carbofuran, aldicarb; oxime carbamates: oxamyl
Rodenticides	Chemicals used to control rats, mice and other rodents.	Warfarin, bromadiolone, brodifacoum, zinc phosphide	Anticoagulants: warfarin, bromadiolone, brodifacoum; phosphides: zinc phosphide
Molluscicides	Chemicals used to control snails, slugs and other molluscs, particularly in agricultural and aquatic systems.	Niclosamide, metaldehyde, copper sulfate	Salicylanilides: niclosamide; copper ions: Cu ²⁺ ; aldehydes: metaldehyde
Acaricides	Chemicals specifically used to control mites and ticks.	Abamectin, amitraz, dicofol	Macrocyclic lactones: abamectin; formamidines: amitraz; organochlorines: dicofol

Following agricultural application, pesticides can be transported from terrestrial environments into aquatic ecosystems through several interconnected pathways, including surface runoff, soil erosion, leaching, spray drift, irrigation return flow and drainage. During rainfall or irrigation, pesticide residues deposited on crop surfaces and soil particles can be mobilized and transported into nearby rivers, ponds, lakes, wetlands and groundwater. The extent of this transfer depends on pesticide properties such as water solubility, adsorption coefficient (K_{oc}), persistence, volatility and degradation rate, as well as soil characteristics, rainfall intensity, slope and land-use patterns. Once pesticides reach aquatic environments, they may remain dissolved in the water column, become associated with suspended particles or accumulate in bottom sediments. They can subsequently undergo photolysis, hydrolysis, microbial degradation and oxidation, producing transformation products that may differ from the parent compound in persistence, mobility and toxicity. Consequently, pesticide contamination can extend beyond the original agricultural application site and create prolonged exposure of aquatic organisms to both parent pesticides and their transformation products, potentially disrupting aquatic communities and ecosystem processes (Kumar et al., 2023; AbuQamar et al., 2024).

Impact of Pesticides on Aquatic Ecosystems

Pesticide contamination can produce cascading effects across multiple trophic levels, beginning with microorganisms and primary producers and extending to plankton, crustaceans, fish, aquatic birds, and ultimately humans through contaminated water and seafood. The major impacts can be summarized as follows:

Aquatic component	Major effects of pesticide exposure	Important mechanisms / responses
Phytoplankton & algae	Reduced growth and primary productivity; altered species composition; decreased chlorophyll production	Inhibition of photosynthesis, oxidative stress, disruption of pigments and cellular metabolism
Zooplankton	Mortality, reduced abundance, impaired reproduction and altered community structure	Neurotoxicity, oxidative stress, developmental toxicity; particularly sensitive to insecticides
Crustaceans	Reduced survival, moulting and reproduction; behavioural and physiological disturbances	Oxidative stress, endocrine disruption, neurotoxicity, impaired energy metabolism
Fish	Mortality at high concentrations; reduced growth, feeding and swimming activity; reproductive and developmental abnormalities	Oxidative stress, AChE inhibition, gill damage, osmoregulatory disturbance, endocrine disruption, immunotoxicity and genotoxicity
Benthic organisms	Reduced abundance and diversity; sediment-associated exposure	Adsorption of pesticides to sediments followed by chronic exposure and accumulation
Aquatic plants	Reduced biomass and photosynthetic activity	Herbicide-induced inhibition of photosynthetic and metabolic pathways
Aquatic microorganisms	Changes in microbial abundance and community function	Alteration of microbial metabolism, enzyme activity and nutrient transformation
Aquatic birds & predators	Reduced reproductive success and secondary exposure through contaminated prey	Bioaccumulation and biomagnification of persistent compounds
Food web	Altered predator–prey relationships and trophic interactions	Loss of sensitive species, reduced prey availability and trophic transfer
Human health	Exposure through contaminated drinking water and consumption of contaminated fish and shellfish	Dietary exposure, chronic toxicity, endocrine effects, neurotoxicity and potential genotoxic/carcinogenic effects depending on pesticide and exposure level

Pesticide contamination of aquatic environments can trigger cascading ecological effects across multiple trophic levels, extending from molecular and cellular alterations to population- and ecosystem-level disturbances. Exposure may initially induce oxidative stress, enzymatic dysfunction and DNA damage in aquatic organisms; however, continued or chronic exposure can result in impaired physiological performance, reduced growth and reproductive capacity, population-level declines and shifts in community structure. The depletion of sensitive organisms such as zooplankton and crustaceans can reduce prey availability for fish and other higher trophic-level consumers, whereas the suppression of phytoplankton and aquatic macrophytes can impair primary productivity and modify oxygen availability and nutrient cycling.

Persistent pesticide residues may also become associated with sediments and biological tissues, facilitating bioaccumulation and trophic transfer through aquatic food webs. Collectively, these processes can disrupt biodiversity, energy transfer, nutrient dynamics, trophic interactions, food-web stability and ecosystem resilience. Furthermore, pesticide residues entering aquatic food resources or drinking-water sources may create pathways of human exposure, particularly through the consumption of contaminated fish and shellfish, thereby linking aquatic pesticide pollution with both ecosystem health and food-safety risks (Kumar et al., 2023; AbuQamar et al., 2024).

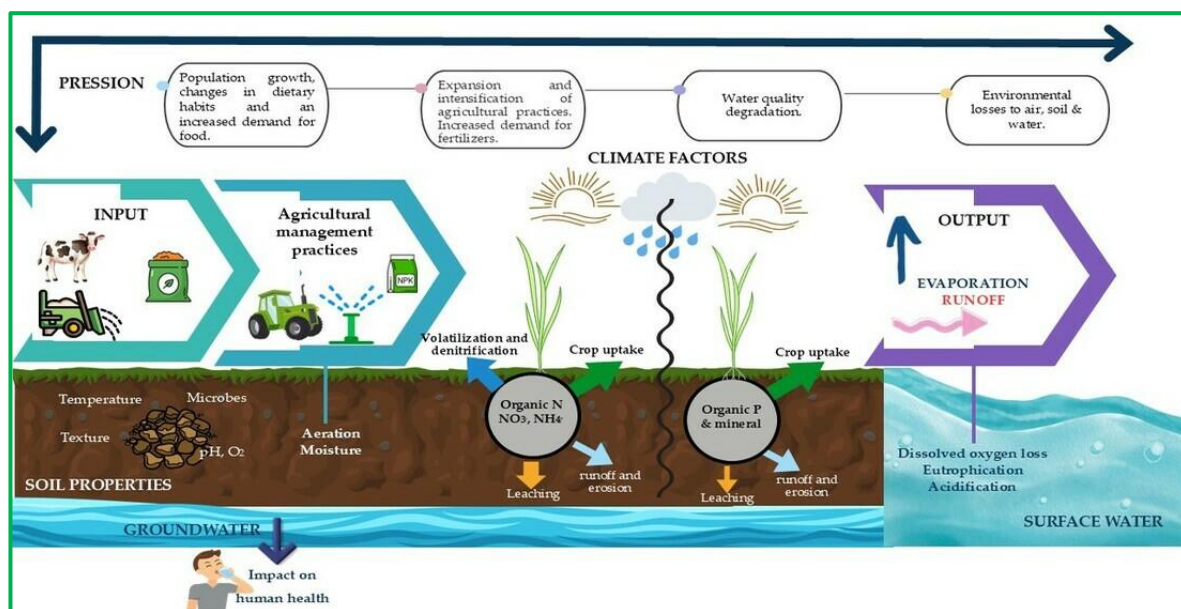


Fig.2 Conceptual framework showing pesticide inputs, environmental pathways, and their impacts on soil, groundwater, and surface-water quality

(Source: https://pub.mdpi-res.com/water/water-16-03146/article_deploy/html/images/water-16-03146-ag.png?1730956539)

Conclusion

Pesticide pollution constitutes a complex and growing environmental pressure on aquatic ecosystems, as agricultural chemicals can be transported beyond treated fields through runoff, leaching, drainage and other environmental pathways. After reaching aquatic systems, pesticides and their transformation products may exert effects at different levels of biological organization, ranging from molecular and biochemical disturbances to physiological impairment and population-, community- and ecosystem-level changes. Exposure can adversely influence phytoplankton, zooplankton, crustaceans, fish and other aquatic organisms, resulting in alterations in primary productivity, growth, reproduction, trophic relationships, biodiversity and nutrient cycling. The persistence and bioaccumulative behaviour of certain pesticide residues can further facilitate their transfer through aquatic food webs, increasing the likelihood of prolonged ecological exposure and potential human exposure through contaminated water and aquatic food products. Consequently, effective mitigation requires an integrated pesticide-management framework incorporating responsible pesticide application, vegetative buffer zones, reduction of agricultural runoff, continuous environmental monitoring, adoption of less hazardous alternatives and sustainable farming practices. Such measures are essential for preserving aquatic biodiversity, ecosystem resilience, fisheries productivity and food security, while simultaneously reducing risks to human health.

References

1. AbuQamar, S. F., El-Saadony, M. T., Alkafaas, S. S., Elsalahaty, M. I., Elkafas, S. S., Mathew, B. T., Aljasmi, A. N., Alhammadi, H. S., Salem, H. M., Abd El-Mageed, T. A., Zaghloul, R. A., Mosa, W. F. A., Ahmed, A. E., Elrys, A. S., Saad, A. M., Alsaeed, F. A., & El-Tarabily, K. A. (2024). Ecological impacts and management strategies of pesticide pollution on aquatic life and human beings. *Marine Pollution Bulletin*, 206, 116613. <https://doi.org/10.1016/j.marpolbul.2024.116613>
2. Kumar, P., Kumar, R., Thakur, K., Mahajan, D., Brar, B., Sharma, D., Kumar, S., & Sharma, A. K. (2023). Impact of pesticides application on aquatic ecosystem and biodiversity: A review. *Biology Bulletin*, 50(6), 1362–1375. <https://doi.org/10.1134/S1062359023601386>
3. Saha, R., & Maiti Dutta, S. (2024). Pesticides' mode of action on aquatic life. *Toxicology Reports*, 13, 101780. <https://doi.org/10.1016/j.toxrep.2024.101780>
4. Narayanan, M., Devarayan, K., Verma, M., Selvaraj, M., Ghramh, H. A., & Kandasamy, S. (2024). Assessing the ecological impact of pesticides/herbicides on algal communities: A comprehensive review. *Aquatic Toxicology*, 268, 106851.