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Fate and Transport of Pesticide Residues in Aquatic Environments: A Review

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Abstract: Pesticide contamination in aquatic ecosystems has emerged as a pressing environmental concern, particularly in agricultural catchments. This review synthesizes current research on the fate and transport of pesticide residues in surface and groundwater systems. Pesticides enter water bodies through surface runoff, leaching, atmospheric deposition, and irrigation return flows. Once introduced, their persistence, mobility, and toxicity are influenced by physicochemical properties, environmental conditions, and landscape features. Pesticides such as organophosphates, neonicotinoids, and glyphosate have been detected in varying concentrations in rivers, lakes, and aquifers, posing risks to aquatic organisms and human populations dependent on these waters. Aquatic fauna including fish, amphibians, and invertebrates often exhibit sub-lethal effects such as behavioral changes, endocrine disruption, and reproductive impairments. This review explores pesticide transformation processes including photolysis, hydrolysis, and microbial degradation. Furthermore, models predicting pesticide transport and accumulation are evaluated for accuracy and applicability. Emphasis is placed on the need for integrated watershed management, promotion of environmentally friendly pest control, and strengthened regulatory frameworks to prevent long-term ecological damages.

Keywords: Aquatic Environment, Ecosystem Health, Mechanisms, Pesticides, Pollution.

REVIEW PAPER

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INTRODUCTION

The global demand for food production has necessitated intensive agricultural practices, leading to a substantial increase in pesticide usage worldwide. Between 2000 and 2021, global pesticide use increased by 62 percent, reaching 3.5 million tonnes in 2021, with the American continent accounting for over 1.7 million tonnes of pesticide application annually (Farah *et al*., 2024). The United States and Brazil lead global usage per cultivation area (Farah *et al.,* 2024). Pesticides, classified as insecticides, herbicides, fungicides, rodenticides, and larvicides based on target organisms, have become indispensable in modern agriculture (Farah *et al*., 2024).

The "Green Revolution" of the 1950s marked the beginning of intensive pesticide use, though Rachel Carson's 1962 book *Silent Spring* initiated critical debate about their environmental consequences and inspired the founding of the U.S. Environmental Protection Agency in 1970 (Farah *et al*., 2024). Despite their benefits in pest control, only approximately 1% of applied pesticides reach target organisms; the remainder interacts with environmental compartments through surface runoff, wind drift, infiltration, and volatilization (Farah *et al*., 2024). This dispersion has transformed pesticides into ubiquitous environmental contaminants, with significant implications for aquatic ecosystems (Farah *et al*., 2024).

Neonicotinoid insecticides, introduced in the mid-1990s, represent one of the fastest-growing pesticide classes, comprising approximately one-quarter of the global insecticide market with sales exceeding $3.5 billion (Mandal *et al*., 2025). Their water solubility, mobility, and systemic activity facilitate uptake by vascular plants but also promote contamination of adjacent aquatic environments via runoff, leaching, or spray drift (Mandal *et al*., 2025). Similarly, glyphosate-based herbicides have become the most widely used herbicide formulations globally (Farah *et al.,* 2024).

Pesticide contamination of aquatic systems occurs through multiple pathways, including agricultural runoff, groundwater infiltration, and atmospheric deposition (Farah *et al*., 2024). Recent studies have documented 485 occurrences of pesticides in surface

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water globally, with 42% attributable to insecticides, 35% to herbicides, and 23% to fungicides (Farah *et al*., 2024). Of these, 112 pesticides have been identified as posing significant environmental risks, with 49 compounds regulated in some regions but presenting high risks elsewhere (Farah *et al*., 2024).

The persistence of pesticides in aquatic environments is governed by complex interplay between physicochemical properties, environmental conditions, and biological processes (Farah *et al*., 2024). Hydrolysis, photolysis, and microbial degradation constitute primary transformation pathways, though degradation kinetics vary substantially among compounds (Farah *et al*., 2024). Some pesticides degrade within hours, while others, such as atrazine and paraquat, exhibit half-lives exceeding one year (Farah *et al*., 2024).

Global Use of Pesticides and Aquatic Contamination

Global Pesticide Consumption Trends

Pesticide consumption has increased dramatically over the past several decades. Food and Agriculture Organization data indicate that top five high pesticide use intensity countries for year 2016 are Maldives, Trinidad and Tobago, Costa Rica, Bahamas and Barbados, all above 20 kg/ha per year (Wang *et al*., 2019). The United States accounted for one-fifth of the global pesticide usage, representing 372 and 389 million kg as active ingredient in 2006 and 2007 (Wang *et al*., 2019). A continuous increase in global usage of pesticides since 1950 introduces unintended negative environmental impacts (Wang *et al*., 2019).

The agrochemical market, providing essential input for modern agriculture, moved US$234.2 billion in 2019 and is estimated to exceed US$300 billion by 2025 (Mamboungou *et al*., 2025). Global agrochemical production has experienced significant growth due to its diverse applications in activities including controlling unwanted herbs, fungi, and animals such as insects, mites, molluscs and rodents (Mamboungou *et al*., 2025).

Nature and Extent of Aquatic Contamination

The irresponsible use of pesticides can lead to several negative impacts through contamination of soils, surface and underground waters, air and food (Farah *et al*., 2024). Pesticide contamination has become one of the most important environmental hazards due to their bio-persistence and bioaccumulation in the environs (Mandal *et al.*, 2022). Pesticide pollution of surface waters has received widespread attention around the world and is a major source of worry on a local, state, national, and global basis (Mandal *et al.*, 2022).

In the United States, monitoring studies have reported exceedance of ambient pesticide concentrations over water quality recommendations. Stone *et al*. (2014) examined national pesticide monitoring data in 39 major U.S. rivers from 1992 to 2011 and found that 45%–69% of assessed rivers in agricultural areas had one or more pesticides exceeding the aquatic-life benchmark (Wang *et al*., 2019). In the U.S. Corn Belt, frequently detected pesticides in waterways included atrazine, acetochlor, metolachlor, alachlor, and simazine (Wang *et al*., 2019). For rivers in California, 2,4-D, diuron, prometon, chlorpyrifos and diazinon were frequently identified (Wang *et al*., 2019).

In Europe, monitoring programs have demonstrated the presence of various pesticides in rivers, lakes and subsurface waters (Wang *et al*., 2019). Silva *et al*., (2019) analyzed 76 pesticide residues in 317 European topsoils and detected one or more residues in 83% of the soils, with 58% of samples containing two or more mixtures of residues in eleven EU Member states (Wang *et al*., 2019). Glyphosate and its metabolites are the most frequently detected residues at higher concentrations (Wang *et al*., 2019).

Sources and Pathways of Pesticides into Aquatic Environments

Agricultural Runoff

Surface runoff represents the predominant pathway for pesticide transport from agricultural fields to receiving water bodies (Mandal *et al.*, 2022). During rainfall or irrigation events, pesticides adsorbed to soil particles or dissolved in water are mobilized and transported to adjacent streams, rivers, and lakes (Mandal *et al.*, 2022). The magnitude of runoff losses depends on factors including rainfall intensity, soil properties, slope gradient, and the timing of pesticide application relative to precipitation events (Mandal *et al.*, 2022).

Natural water bodies are often contaminated by agricultural runoff that includes these pesticides, raising concerns for fish and other aquatic organisms (Majumder, 2025). Pesticides can contaminate surface and groundwater through different mechanisms: physical-chemical and biological degradation; sorption-desorption on solid particles; surface runoff; soil leaching; infiltration; absorption by plants; volatilization and atmospheric deposition (Farah *et al*., 2024).

Spray Drift

Spray drift occurs when pesticide droplets are carried by wind beyond the intended treatment area. Atmospheric droplets (10-50 µm in size) can be transported between 250 meters and several kilometers from the point of application (Farah *et al*., 2024). This process can transport pesticides to adjacent water bodies and non-target ecosystems, contributing to widespread environmental contamination. The main routes of pesticide transport to surface waters include runoff, precipitation, spray drift, and drainage (Farah *et al.,* 2024).

Atmospheric Deposition

Atmospheric deposition encompasses both wet deposition (rainfall) and dry deposition of pesticide particles, representing a significant entry pathway for aquatic systems, particularly in areas distant from agricultural fields (Farah *et al*., 2024). Adsorption at the air-water interface is a crucial process for aerosol retention and atmospheric transport, as well as accumulation in the atmospheric boundary layer and surface waters (Farah *et al.,* 2024).

Industrial Discharge

Industrial discharge represents a point source of pesticide contamination into aquatic environments. Manufacturing facilities and industrial processes can release pesticides and their intermediates into adjacent water bodies (Mandal *et al.*, 2022). Leaching, direct runoff, inappropriate container disposal, machine cleaning, and other activities all contribute to pesticide contamination in the aquatic environment (Mandal *et al.*, 2022).

3.5 Wastewater Effluents

Wastewater effluents from domestic, agricultural, and industrial sources can introduce pesticides into aquatic environments. Urban wastewater, particularly from areas with intensive pesticide use in gardens and public spaces, represents a significant source of contamination (Farah *et al*., 2024).

Environmental Fate of Pesticides

Adsorption/Desorption

Adsorption is the process by which pesticides bind to soil particles, organic matter, and sediment surfaces. Desorption is the release of adsorbed pesticides back into the aqueous phase (Farah *et al*., 2024). The extent of adsorption depends on the physicochemical properties of the pesticide, soil characteristics, and environmental conditions. Pesticides with high hydrophobicity (Log Kow > 3) tend to adsorb strongly to organic matter and sediments, reducing their mobility but increasing their persistence and bioaccumulation potential (Farah *et al*., 2024).

Leaching

Leaching occurs when pesticides move downward through the soil profile to reach groundwater (Mandal *et al.*, 2022). This pathway is particularly significant for water-soluble compounds such as neonicotinoids and glyphosate (Mandal *et al*., 2025). The vulnerability of aquifers to pesticide contamination depends on soil properties, depth to water table, and the physicochemical characteristics of the pesticide (Farah *et al*., 2024).

Groundwater contamination by pesticides has been documented extensively worldwide (Farah *et al*., 2024). Analysis of literature data indicates that 51% of pesticide occurrences in groundwater relate to insecticides, 27% to herbicides, and 22% to fungicides (Farah *et al*., 2024). The European continent accounts for 67% of reported groundwater detections, followed by Asian countries (31%) and the Americas (2%) (Farah *et al*., 2024).

Volatilization

Volatilization is the process by which pesticides evaporate from soil or water surfaces into the atmosphere. The rate of volatilization depends on the vapor pressure of the pesticide, temperature, wind speed, and the nature of the surface from which volatilization occurs (Farah *et al*., 2024). Once in the atmosphere, pesticides can be transported long distances and deposited in remote areas through wet or dry deposition (Farah *et al*., 2024).

Hydrolysis

Hydrolysis is the chemical breakdown of pesticides in the presence of water. This process is influenced by pH, temperature, and the chemical structure of the pesticide (Farah *et al*., 2024). Hydrolysis can transform parent pesticides into degradation products that may be more or less toxic than the parent compound. The rate of hydrolysis varies among pesticide classes, with organophosphates being particularly susceptible to hydrolysis in alkaline conditions.

Photolysis

Photolysis is the degradation of pesticides driven by ultraviolet (UV) radiation from sunlight (Farah *et al*., 2024). Photodegradation can occur through direct photolysis (absorption of UV light by the pesticide molecule) or indirect photolysis (involving photosensitizers such as dissolved organic matter) (Farah *et al*., 2024). Photolysis is particularly important for pesticides applied to soil surfaces, plant foliage, or shallow water bodies where UV radiation can penetrate.

4.6 Biodegradation

Microbial degradation is a primary transformation pathway for many pesticides in aquatic and terrestrial environments (Farah *et al*., 2024). Bacteria, fungi, and other microorganisms can metabolize pesticides as energy sources or through co-metabolic processes. Biodegradation rates depend on temperature, pH, nutrient availability, and the microbial community composition (Farah *et al*., 2024). Complete mineralization to carbon dioxide, water, and inorganic compounds is the ultimate goal of biodegradation.

Table 1: Pesticide Degradation Pathways and Half-Lives in Aquatic Environments

Degradation Pathway	Mechanism	Factors Influencing Rate	Typical Half-Life Range
Hydrolysis	Chemical breakdown with water	pH, Temperature, Chemical structure	Days to Weeks
Photolysis	UV radiation degradation	Sunlight intensity, Water clarity	Hours to Days
Biodegradation	Microbial metabolism	Temperature, Nutrients, Microbial community	Days to Months
Volatilization	Evaporation to atmosphere	Vapor pressure, Wind speed, Temperature	Hours to Days
Oxidation	Chemical oxidation	Oxidizing agents, pH	Hours to Days

(Data compiled from Farah et al., 2024; Mandal et al., 2025)

Transport Mechanisms

Surface Runoff

Surface runoff is a primary mechanism for pesticide transport from agricultural fields to receiving water bodies (Farah *et al*., 2024). During rainfall or irrigation events, pesticides dissolved in water or adsorbed to soil particles are mobilized and transported across the soil surface. The magnitude of runoff losses depends on rainfall intensity, soil properties, slope gradient, vegetation cover, and the timing of pesticide application (Farah *et al*., 2024). Pesticides such as organophosphates, neonicotinoids and glyphosate have been detected in varying concentrations in rivers, lakes and aquifers (Farah *et al*., 2024).

Groundwater Transport

Groundwater transport occurs when pesticides leach through the soil profile and reach the water table (Mandal *et al*., 2022). The vulnerability of aquifers to pesticide contamination depends on soil properties, depth to water table, and the physicochemical characteristics of the pesticide (Farah *et al*., 2024). Globally, 7.2% of pesticide input leaches below the root zone, potentially reaching groundwater (Farah *et al*., 2024). Pesticides can also contaminate groundwater through recharge and leaching from surface waters, creating interconnected pathways that affect drinking water quality (Farah *et al*., 2024).

Sediment Transport

Sediment transport is an important mechanism for transporting hydrophobic pesticides that adsorb strongly to soil particles and sediments (Farah *et al*., 2024). During erosion events, pesticide-laden sediments are transported to rivers, lakes, and reservoirs, where they can accumulate in bottom sediments and serve as a long-term source of contamination (Farah *et al*., 2024).

Bioaccumulation

Bioaccumulation is the retention or accumulation of a substance over time in an organism (Farah *et al*., 2024). Bioaccumulation processes in aquatic organisms depend on biological and environmental factors including species, body size, and age of organisms, as well as pH, salinity, temperature, and solubility (Farah *et a*l., 2024). The most concerning pesticide bioaccumulation processes include absorption, assimilation, biotransformation, biomagnification, and elimination (Farah *et al*., 2024).

Certain pesticides, such as cyhalothrin, aldrin, DDT, dieldrin, permethrin, bifenthrin, transfluthrin, fenpropathrin, and heptachlor epoxide, have a log Kow > 5 and are classified as highly bioaccumulative under the Stockholm Convention (Farah *et al*., 2024). Through the biomagnification process, the quantity of pesticides increases in higher organisms through the food chain, which plays a significant role in the health of organisms at higher trophic levels (Farah *et al*., 2024).

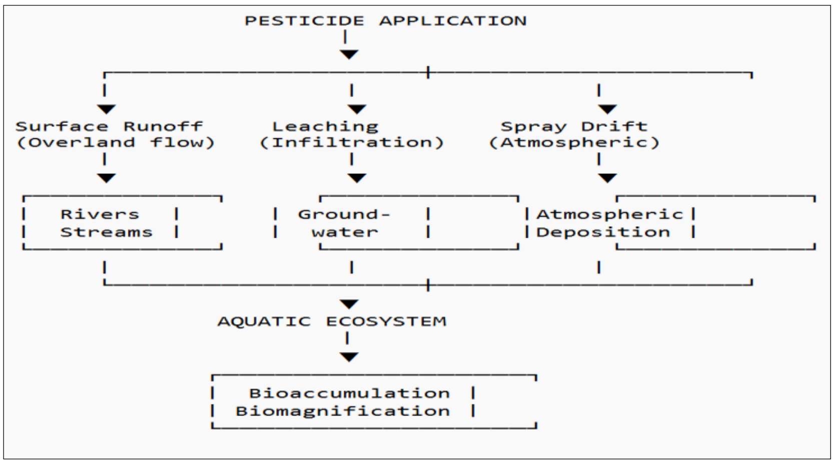

Figure 1: Conceptual Diagram of Pesticide Transport Mechanisms in Aquatic Environments

(Conceptual diagram developed from Farah et al., 2024)

Occurrence of Major Pesticides in Surface and Groundwater

Surface Water Contamination

Pesticides have been detected in varying concentrations in rivers, lakes, and reservoirs worldwide (Farah *et al*., 2024). Herbicides, fungicides and insecticides are present in surface and groundwaters worldwide (Farah *et al*., 2024). Organophosphate, neonicotinoid, and glyphosate compounds are among the most frequently detected, with concentrations ranging from ng/L to µg/L depending on proximity to agricultural areas and hydrological conditions (Farah *et al*., 2024).

Literature data reveal 485 occurrences of pesticides in surface water, with 42% attributable to insecticides, 35% to herbicides, and 23% to fungicides (Farah *et al*., 2024). Neonicotinoids have been detected in rivers and streams across the world, with their water solubility, mobility, and moderate persistence facilitating contamination of adjacent aquatic environments (Borsuah *et al*., 2024; Mandal *et al*., 2025).

Table 2: Occurrence of Pesticides in Surface Waters by Region

Region	Pesticide Types Detected	Concentration Range (µg/L)	Dominant Sources	Selected References
North America	Glyphosate, Atrazine, Neonicotinoids	0.01-10.0	Corn/soybean agriculture	Wang *et al*., 2019; Borsuah *et al*., 2024
Europe	Herbicides, Fungicides	0.001-5.0	Intensive agriculture	Farah *et al*., 2024; Wang *et al*., 2019
Asia	Organophosphates, Neonicotinoids	0.01-15.0	Rice cultivation, horticulture	Farah *et al.,* 2024
Africa	Organochlorines, Organophosphates	0.1-20.0	Subsistence agriculture	Farah *et al*., 2024
South America	Glyphosate, Pyrethroids	0.05-8.0	Soybean, sugarcane	Farah *et al.,* 2024

(Data compiled from Farah et al., 2024; Wang et al., 2019; Borsuah et al., 2024)

Groundwater Contamination

Considering the literature data, 55 data points on pesticide occurrence in groundwater were identified (Farah *et al*., 2024). Of these, 51% of the concentrations are related to insecticides, 27% to herbicides, 22% to fungicides, and none to algicides (Farah *et al*., 2024). The highest frequency of results was for the European continent (67%), followed by Asian countries (31%) and American countries (2%) (Farah *et al*., 2024).

Neonicotinoids are very frequently detected in soils and in freshwater, and they are also found in the air (Mamy *et al*., 2025). They have only been recently monitored in coastal and marine environments, but some studies already reported the presence of imidacloprid and thiamethoxam in transitional or semi-enclosed ecosystems (lagoons, bays, and estuaries) (Mamy *et al*., 2025).

Ecotoxicological Effects

Fish

Fish serve as ideal model organisms in ecotoxicology since they show high susceptibility to contaminants in the aquatic environment, even at extremely minute concentrations, and are a good source of protein-rich food (Majumder, 2025). Pesticides pose a risk to fish and humans because of their high persistence, tendency to bioaccumulate, and detrimental effects on the organisms linked to the food chain (Majumder, 2025).

Pesticides can cause a range of toxic effects in fish, including neurotoxicity, nephrotoxicity, cytotoxicity, genotoxicity, immunotoxicity, hepatotoxicity, endocrine disruption, and reproductive malformations (Mandal *et al*., 2025; Majumder, 2025). The mechanisms of toxicity primarily involve the generation of reactive oxygen species (ROS), leading to oxidative stress, lipid peroxidation, protein oxidation, and DNA damage (Mandal *et al*., 2025; Majumder, 2025).

In modern aquatic toxicology, one reliable method for assessing fish health and stress responses is the analysis of multiple biomarkers in fish exposed to pesticides (Majumder, 2025). A comprehensive approach is used to aggregate all the detected biomarker responses into a single "Integrated Biomarker Response" (IBR) stress score (Majumder, 2025). Moreover, the analysis of adverse outcome pathways (AOP) is a helpful method to interpret the dose-response effects of toxicants (Majumder, 2025).

Amphibians

Amphibians are particularly vulnerable to pesticide contamination due to their permeable skin, aquatic life stages, and dependence on aquatic habitats for reproduction (Mandal *et al*., 2025). Pesticides have been shown to cause developmental abnormalities, endocrine disruption, reduced survival, and population declines in amphibian species (Mamy *et al*., 2025). Neonicotinoids have been found to negatively impact amphibians, fish, mammals and monocotyledonous plants despite being formulated to target insects (Wan *et al*., 2025).

Aquatic Insects

Aquatic insects are among the most sensitive taxa to pesticide contamination, particularly neonicotinoids and pyrethroids (Mamy *et al*., 2025). Direct impacts of neonicotinoids are mainly reported on aquatic invertebrates such as arthropods (Mamy *et al*., 2025). Fipronil has been found to be highly toxic to several aquatic invertebrates, with median lethal concentrations (LC50) in vertebrates being higher compared to invertebrates (Mamboungou *et al*., 2025).

Zooplankton

Zooplankton play a critical role in aquatic food webs and are highly sensitive to pesticide contamination (Farah *et al*., 2024). The toxicity of pesticides to zooplankton affects the entire aquatic food web, as they are primary consumers that support fish populations (Mamy *et al*., 2025). Neonicotinoids have been shown to induce indirect effects via trophic cascades in several species (Mamy *et al*., 2025).

Algae

Algae are primary producers in aquatic ecosystems and are susceptible to herbicide contamination (Farah *et al*., 2024). Herbicides can inhibit photosynthesis and growth of algae and aquatic plants, leading to reduced primary production and ecosystem function (Farah *et al*., 2024). The toxicity of pesticides to algae is an important consideration in environmental risk assessment.

Aquatic Plants

Aquatic plants, including vascular plants and macrophytes, are important components of aquatic ecosystems that can be affected by pesticide contamination (Farah *et al*., 2024). Herbicides are specifically designed to control plants and can have significant negative effects on non-target aquatic vegetation (Wan *et al*., 2025). The loss of aquatic plants can reduce habitat complexity, oxygen production, and nutrient cycling in aquatic ecosystems.

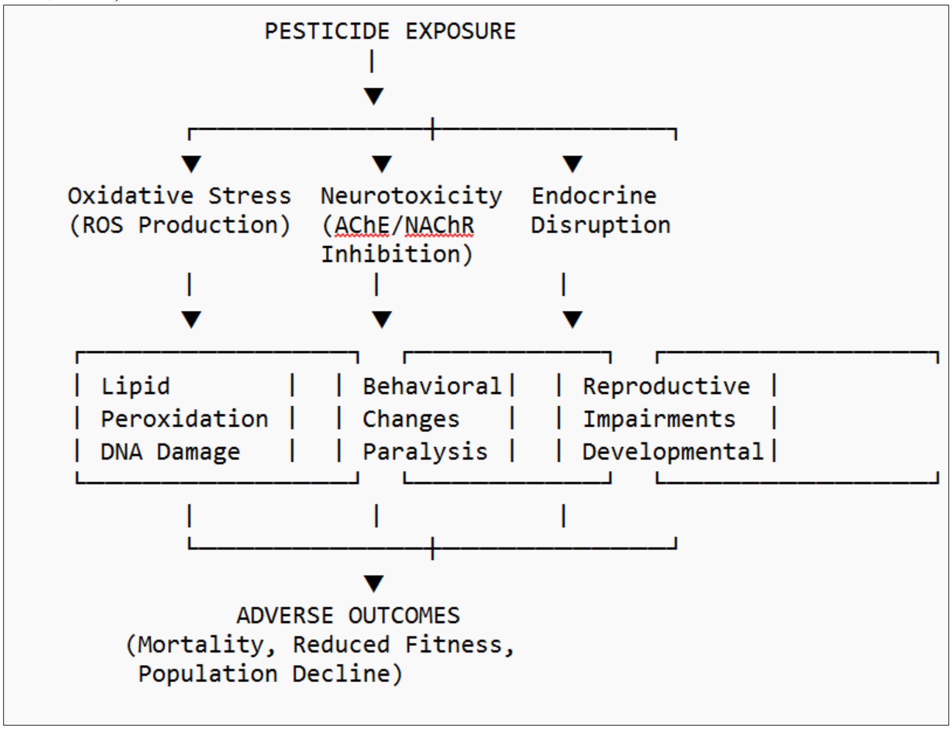

Figure 2: Mechanisms of Pesticide-Induced Toxicity in Aquatic Organisms

Developed from Mandal et al., 2025; Majumder, 2025)

Human Health Implications

Pesticide contamination of aquatic environments has significant implications for human health, particularly through the consumption of contaminated drinking water and aquatic foods (Farah *et al*., 2024). Direct contact with pesticides during application, or indirect contact/intake from pesticide residues in water and food may result in acute or chronic toxic effects on human health (Wang *et al*., 2019). Fantke *et al*. (2012) quantified the health impacts from pesticide exposure in 24 European countries and concluded that 2.6 hours of lifetime is lost per person due to pesticide exposure (Wang *et al*., 2019).

Pesticides have the potential to disrupt the endocrine, immunological, reproductive, and neurological systems and can induce oxidative stress, a key mechanism linked to various diseases such as Parkinson's and Alzheimer's (Farah *et al*., 2024). The bioaccumulation and biomagnification of pesticides in aquatic food chains can lead to human exposure through the consumption of contaminated fish and seafood (Farah *et al*., 2024).

Pesticide residues have been found in freshwater bodies, sediments, and in fish samples, posing risks to both animals and humans because of their high persistence, tendency to bioaccumulate, and detrimental effects on the organisms linked to the food chain (Majumder, 2025). Fipronil identification in the eggs and meat of chicken bred in some European Union countries highlights the likelihood of having this chemical introduced in the food chain and posing risks to human health (Mamboungou *et al*., 2025).

Analytical Methods for Monitoring Pesticides

Sample Preparation Techniques

Sample preparation accounts for approximately 70-90% of the total analysis time, making method optimization critical for efficient pesticide monitoring (Datta *et al*., 2025). Recent research highlights notable advancements in conventional pesticide extraction methods, aiming to develop eco-friendly and cost-effective techniques with high enrichment and recovery rates (Datta *et al*., 2025).

Among liquid-phase microextraction (LPME) techniques, methods such as ionic liquid-based extraction, deep eutectic solvent-based extraction, air-assisted extraction, solidification of a floating organic drop, and ultrasound-assisted LPME are gaining attention due to their ease of handling, operational simplicity, and environmental sustainability (Datta *et al*., 2025). Deep eutectic solvents have emerged as eco-friendly alternatives to conventional solvents in pesticide extraction (Datta *et al*., 2025).

In the solid-phase extraction (SPE) field, researchers have increasingly utilized approaches like magnetic solid-phase extraction, green sorbents, metal-organic framework (MOF) based extraction, cartridge-based SPE, and carbon nanotube-based SPE (Datta *et al*., 2025). The QuEChERS method (quick, easy, cheap, effective, rugged, and safe) is also employed to significantly reduce sample preparation time (Datta *et al*., 2025).

Detection and Quantification

The United States Environmental Protection Agency (USEPA) published Method 1699 in 2007, detailing technical procedures for identifying various pesticide types (Farah *et al*., 2024). Advanced analytical techniques including liquid chromatography-mass spectrometry (LC-MS), gas chromatography-mass spectrometry (GC-MS), and tandem mass spectrometry (MS/MS) are commonly used for pesticide detection and quantification.

Models Used in Fate and Transport Prediction

Soil and Water Assessment Tool (SWAT)

SWAT is an ecohydrological model used in over 3000 published studies, including about 50 for simulating pesticide fate and transport at the watershed scale (Wang *et al*., 2019). Payraudeau and Gregoire (2012) compared the ability of model components to capture 42 critical hydrological and pesticide processes and found that SWAT covered the widest range of processes and was deemed the most comprehensive model for representing relevant hydrological and pesticide cycles (Wang *et al*., 2019).

Quilbé *et al*. (2006) reviewed 36 widely used pesticide models based on a pragmatic approach, and SWAT was deemed one of the best for modeling pesticide contamination under a wide variety of conditions (Wang *et al*., 2019). However, researchers recommend future improvement to fill research gaps in developing modularized field level simulation, improved BMPs, new in-pond and in-stream modules, and the incorporation of soft data (Wang *et al*., 2019).

PRZM (Pesticide Root Zone Model)

PRZM is a one-dimensional model used to simulate pesticide leaching to groundwater and runoff transport (Callaghan *et al*., 2024). The model has been widely used in regulatory assessments and was used as a reference model for validating new modeling approaches (Callaghan *et al*., 2024).

PEARL (Pesticide Emission Assessment at Regional and Local scales)

PEARL is a one-dimensional model used for simulating pesticide fate in soil, including leaching to groundwater (Gassmann, 2021; Callaghan *et al*., 2024). It has been used in the registration process for plant protection products in the European Union (Gassmann, 2021). PEARL was used as a reference model for validating the HydroGeoSphere model (Callaghan *et al*., 2024).

HYDRUS

HYDRUS is a suite of models used for simulating water flow and solute transport in variably saturated porous media (Gassmann, 2021; Callaghan *et al*., 2024). The models are widely used for simulating pesticide transport in soils and have been validated against several other recognized models (Callaghan *et al*., 2024).

PCPF-1

PCPF-1 is a model used for simulating pesticide fate and transport in paddy fields. The model accounts for the unique hydrological conditions of paddy fields, including ponded water, flood irrigation, and preferential flow.

Table 3: Comparison of Pesticide Fate and Transport Models

Model	Scale	Type	Key Features	Regulatory Use	Selected References
SWAT	Watershed	Distributed	Comprehensive hydrological & pesticide processes; GIS integration	US EPA, EU	Wang *et al*., 2019
PRZM	Field	1-D	Leaching, runoff, plant uptake	US EPA	Callaghan *et al.,* 2024
PEARL	Field	1-D	Leaching to groundwater	EU	Gassmann, 2021; Callaghan *et al*., 2024
HYDRUS	Field	1-D/2-D/3-D	Variably saturated flow, solute transport	Research	Gassmann, 2021; Callaghan *et al*., 2024
HydroGeoSphere	Field/Watershed	3-D	Fully integrated surface-subsurface	Research	Callaghan *et al*., 2024

(Data compiled from Wang et al., 2019; Gassmann, 2021; Callaghan et al., 2024)

Mitigation and Remediation Strategies

Best Management Practices (BMPs)

Best Management Practices (BMPs) are strategies designed to reduce pesticide contamination of aquatic environments (Wang *et al*., 2019). BMPs include conservation tillage, buffer strips, constructed wetlands, cover crops, and integrated pest management (IPM) (Wang *et al*., 2019). The effectiveness of BMPs depends on local conditions and the specific pesticides of concern.

Constructed Wetlands

Constructed wetlands can effectively remove pesticides from agricultural runoff through various mechanisms including adsorption, sedimentation, plant uptake, and microbial degradation (Farah *et al*., 2024). These systems are increasingly used as a cost-effective approach to mitigate pesticide contamination of receiving water bodies.

Advanced Water Treatment Methods

Advanced water treatment methods, including adsorption, photocatalysis, membrane filtration, and ozonation, can effectively remove pesticides from water (Farah *et al*., 2024). The adoption of green pesticides and advanced water treatment methods is advocated to mitigate the environmental impact of pesticide contamination (Farah *et al*., 2024).

Integrated Pest Management (IPM)

Integrated Pest Management (IPM) is a sustainable approach to pest control that reduces reliance on chemical pesticides through the use of biological control, cultural practices, and other non-chemical methods (Wan *et al*., 2025). Adoption of sustainable management practices including agricultural ecological intensification and non-pesticide control may help balance food security alongside reducing dependencies on pesticides with their associated risks to nature (Wan *et al*., 2025).

Regulatory Frameworks

International Regulations

In 2001, the Stockholm Convention in Sweden saw participating countries agree to eliminate or reduce 12 persistent organic pollutants (POPs), nine of which are used as pesticides (Farah *et al*., 2024). These include Aldrin, Chlordane, Dieldrin, Endrin, Heptachlor, Hexachlorobenzene, Mirex, Toxaphene, and DDT. However, more than 20 years later, several of these pesticides, such as Aldrin, Dieldrin, Endrin, Heptachlor, and DDT, are still identified in surface and groundwater (Farah *et al*., 2024).

Regulation (EC) No. 1107/2009 places strong emphasis on the use of modeling tools to calculate predicted environmental concentrations (PEC), which serve as a fundamental basis for assessing the environmental risks associated with plant protection products and their active ingredients (Farah *et al*., 2024).

National Regulations

In the United States, ecological risk assessment for individual pesticides is evaluated by Aquatic Life Benchmarks assessed by the U.S. Environmental Protection Agency (Wang *et al.,* 2019). These benchmarks are based on toxicity values found in scientific studies and can be used for evaluating acute and chronic risks for fish, invertebrates, vascular and nonvascular plants (Wang *et al*., 2019).

In Europe, the predicted-no-effect concentration (PNEC) is based on the EU Pesticide Directive 91/414/EEC (Wang *et al*., 2019). If pesticide concentrations exceed 1/100 of the acute LC50 of fish or Daphnia, then water quality requires further evaluation (Wang *et al*., 2019).

Gaps in Regulation

A total of 112 pesticides has been identified as posing significant environmental risks, with 63 pesticides identified in various countries presenting high environmental risks and still lacking limits or restrictions on their use and presence in water (Farah *et al*., 2024). Furthermore, 49 pesticides are regulated in specific regions or countries but pose high risks elsewhere, highlighting the need for broader regulatory measures (Farah *et al*., 2024).

Knowledge Gaps and Future Research

Identified Knowledge Gaps

This review has identified several significant knowledge gaps that require further investigation:

1. **Pesticide Transformation Products**: The contribution of transformation product formation processes to simulation uncertainty was not analyzed at all in most of the studies (Gassmann, 2021). Transformation products of pesticides are found everywhere in the aquatic environment, yet their fate and toxicity are poorly understood (Gassmann, 2021).
2. **Effects on Unstudied Taxa**: Impacts on aquatic vertebrate populations and communities, as well as on microorganisms, are less documented (Mamy *et al*., 2025). More data are needed to reach firmer conclusions on the effects of pesticides on non-target species (Mamy *et al*., 2025).
3. **Marine Environments**: Neonicotinoids have only been recently monitored in coastal and marine environments (Mamy *et al*., 2025). Few studies have reported the presence of imidacloprid and thiamethoxam in transitional or semi-enclosed ecosystems (lagoons, bays, and estuaries) (Mamy *et al*., 2025).
4. **Indirect Effects**: In addition to their toxicity to directly exposed organisms, pesticides induce indirect effects via trophic cascades as demonstrated in several species (Mamy *et al*., 2025). However, more data are needed to get a clearer picture of such indirect effects (Mamy *et al*., 2025).
5. **Data Scarcity in the Global South**: There is a need to increase environmental monitoring, especially in the Global South (Farah *et al*., 2024).

13.2 Future Research Priorities

Based on the identified gaps, future research should focus on:

1. Quantifying transboundary pesticide impacts and environmental transport pathways (Farah *et al*., 2024).
2. Developing advanced predictive models for pesticide fate and transport, particularly for transformation products (Gassmann, 2021).
3. Increasing environmental monitoring in the Global South (Farah *et al*., 2024).
4. Assessing the combined effects of multiple pesticide stressors on aquatic ecosystems (Wang *et al*., 2019).
5. Integrating Quantitative Structure Properties Relationship (QSPR) models predicting transformation product fate characteristics, pathway prediction models, and environmental fate models (Gassmann, 2021).

CONCLUSION

The review has provided a comprehensive analysis of the fate and transport of pesticide residues in aquatic environments, drawing on recent research published between 2018 and the present. Pesticides enter aquatic systems through multiple pathways including surface runoff, leaching, atmospheric deposition, and irrigation return flows. Their persistence, mobility, and toxicity are influenced by physicochemical properties, environmental conditions, and landscape features.

Key Findings from this Review Include:

1. **Widespread Contamination**: Pesticides such as organophosphates, neonicotinoids, and glyphosate have been detected in varying concentrations in rivers, lakes, and aquifers worldwide, posing significant risks to aquatic organisms and human populations dependent on these waters (Farah *et al*., 2024).
2. **Significant Environmental Risks**: A total of 112 pesticides have been identified as posing significant environmental risks, with 63 pesticides presenting high risks and lacking limits or restrictions in various countries (Farah *et al*., 2024).
3. **Ecological Effects**: Aquatic fauna including fish, amphibians, and invertebrates exhibit sub-lethal effects including behavioral changes, endocrine disruption, and reproductive impairments (Mandal *et al*., 2025; Majumder, 2025). Neonicotinoids induce neurotoxicity, nephrotoxicity, cytotoxicity, genotoxicity, immunotoxicity, hepatotoxicity, endocrine disruption, and reproductive malformations (Mandal *et al*., 2025).
4. **Bioaccumulation Potential**: Compounds with Log Kow > 5 present significant bioaccumulation and biomagnification concerns for food chain transfer and human health (Farah *et al*., 2024).
5. **Modeling Advances**: Process-based modeling approaches like SWAT, PRZM, PEARL, and HYDRUS provide quantitative information on pesticide exposure, though there are growing requirements for model development and improvement to better represent natural conditions (Wang *et al*., 2019; Gassmann, 2021; Callaghan *et al*., 2024).
6. **Regulatory Gaps**: Despite advances in legislation, 63 pesticides still lack limits or restrictions in various countries, and 49 pesticides regulated in some regions pose high risks elsewhere (Farah *et al*., 2024).

Recommendations:

1. Integrated watershed management approaches should be implemented to reduce pesticide loading.

2. Promotion of environmentally friendly pest control strategies, including integrated pest management (IPM) and biological control methods (Wan *et al*., 2025).
3. Strengthened regulatory frameworks to prevent long-term ecological damages (Farah *et al*., 2024).
4. Enhanced environmental monitoring programs, particularly in the Global South.
5. Adoption of green pesticides and advanced water treatment methods (Farah *et al*., 2024).
6. Further research on pesticide transformation products and their toxicity (Gassmann, 2021).
7. Development of fully integrated hydrological fate and transport models that incorporate groundwater, tile drainage, and runoff pathways (Callaghan *et al*., 2024).

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