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Aquatic Vulnerability: Pyrethroid Pesticides and Their Detrimental Impacts on Fish

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Abstract

Pyrethroid pesticides are crucial for mitigating agricultural losses by controlling pest populations and are also extensively used for domestic insect control and animal care. Pyrethroid pesticides are favored over carbamate and organophosphate compounds due to their enhanced efficacy at lower concentrations. Furthermore, their rapid breakdown in the environment (lack of photostability and persistence) makes them a preferred choice, minimizing long-term environmental accumulation. Despite their effectiveness and apparent decreased toxicity to mammals, synthetic pyrethroid pesticides (SPs) are a major worldwide hazard to aquatic non- target animals, especially fish and invertebrates. This review highlights their detrimental effects on non-target aquatic organisms with particular reference to fish, including behavioral abnormalities, histopathological damage to vital organs, and significant biochemical and hematological changes indicative of severe physiological stress. While research on SP toxicity is substantial in developed nations, critical knowledge gaps persist concerning developing countries. Addressing these gaps, implementing comprehensive control and mitigation strategies are vital for protecting vulnerable aquatic life and ecosystem health from ongoing pyrethroid contamination.

Introduction

Freshwater is vital for life, supporting everything from human consumption and industry to agriculture and biodiversity.

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However, it's highly susceptible to environmental toxins like pesticides, which jeopardize ecosystems by causing significant biodiversity loss. Water contamination is a major global concern, exacerbated by freshwater scarcity and ongoing human-caused pollution. Pesticides are a primary culprit; while intended for crop protection, they unfortunately inflict substantial harm on non-target organisms (Tahir *et al.,* 2021). Despite their application in pest management, approximately 90% of these agrochemicals are not degraded and thus remain unchanged in the environment (Shah and Parveen, 2020). Pesticides are categorized by their origin, either as naturally occurring (biological) or chemically synthesized. They are further classified into different groups based on their chemical structure and intended targets. Chemical classification is the most widely accepted and suitable method, offering insights into their efficacy and specific properties. Common chemical families include organochlorines, organophosphates, carbamates, and pyrethroids, among others (Georgiadis *et al.,* 2018). Pesticides are also categorized by their target organisms: bactericides (bacteria), insecticides (insects), fungicides (fungi), herbicides (weeds), miticides (mites), nematicides (nematodes), rodenticides (rodents), algaecides (algae), piscicides (fish), avicides (birds), molluscicides (snails), and virucides (viruses).

Modern farming methods result in the indiscriminate use of several pesticides, which eventually find their way into the aquatic environments. When these chemicals contaminate water, they can severely harm aquatic life, including algae, aquatic plants, and various fish species (both shellfish and finfish), impacting their growth, reproduction, and survival. Pollution stands as a critical global challenge, exacerbated by rapid human population growth and industrialization (Stehle and Schulz, 2015). Since the release of industrial, commercial, and agricultural chemicals into these waterways impairs the survival, development, and productivity of aquatic creatures, the consequent pollution of aquatic habitats is a serious global problem. Fish are considered excellent indicators of aquatic ecosystem health due to their sensitivity to environmental changes and consistent responses to diluted pollutants. Beyond their socioeconomic importance and vital roles in food webs, nutrient cycling, and production, fish effectively signal alterations in aquatic ecosystem health and function by exhibiting significant physiological and biochemical changes upon exposure to toxins. Fish serve as crucial ecological biomarkers because their lower detoxifying enzyme activity (like mono-oxygenases) compared to humans leads to greater bioaccumulation of toxicants (Monnolo *et al.*, 2023). This makes them ideal indicator species for quickly and simply assessing pollution's impact on aquatic environments. Research on aquatic toxicology has made extensive use of fish species as model organisms to study the toxic effects of different pesticides (Yancheva *et al.*, 2022; Korkmaz *et al.*, 2023).

Synthetic pyrethroids

Since the 1980s, pyrethroid pesticides, a class of synthetic organic insecticides, have gained global popularity. They are highly effective and are considered less toxic than older pesticide groups like organophosphates and carbamates (Yoo *et al.*, 2016). These synthetic pyrethroid insecticides are derived from pyrethrins, which naturally occur in plants such as *Chrysanthemum cinerariifolium* and *Tanacetum cinerariifolium* (Anadon *et al.*, 2009). These insecticides are chemically composed of acids and alcohols from chrysanthemum acid (ethyl 2,2-dimethyl-3-(1- isobutenyl) cyclopropane-1-carboxylate). These insecticides are extensively used in agriculture for insect control and in both human and veterinary medicine to manage ectoparasitic infections. Numerous insect pests, including those from the orders Coleoptera, Diptera, Hemiptera, Hymenoptera, Lepidoptera, Orthoptera, and Thysanoptera, can be effectively controlled with pyrethroid insecticides (Ahamad and Kumar, 2023). Pyrethroid pesticides hold a unique position in malaria control efforts: they are currently the sole class of insecticides approved for use on insecticide-treated nets (ITNs) and are recognized as the most cost-effective option for managing mosquito vectors responsible for malaria transmission (van den Berg *et al.*, 2021). Geographically, the world market for pyrethroid pesticides is divided into Africa, Asia Pacific, Europe, the Middle East, North America, and South America. Because of the widespread use of pesticides in nations like China, India, and Pakistan, Asia Pacific leads the market.

Different Classes of Pyrethroids

Synthetic chemical compounds known as pyrethroid insecticides fall into two primary groups: Type I pyrethroids, which do not include a cyano moiety, and Type II pyrethroids, which are identified by the existence of an alpha-cyano group (Nasuti *et al.*, 2003). Type I pyrethroids include Allethrin, Bifenthrin, Bioresmethrin, Resmethrin, Tefluthrin, Tetramethrin, d-phenothrin, and Permethrin, while Type II pyrethroids consist of Cyfluthrin, Cyhalothrin, Cypermethrin, Deltamethrin, Fenvalerate, Fenpropathrin, Flumethrin, Fluvalinate, and Tralomethrin (Gajendiran and Abraham, 2018).

(Synthetic Pyrethroids)	
Type I pyrethroids	Type II pyrethroids
Allethrin 1st generation	Fenvalerate 3rd generation
Resmethrin 2nd generation	Cyhalothrin 4th generation
Permethrin 3rd generation	Cypermethrin 4th generation
Bifenthrin 4th generation	Deltamethrin 4th generation

Table: Based on classification by Roy (2002).

Mechanism of action of pyrethroids

Pyrethroid pesticides are potent neurotoxins that specifically act on the voltage-gated sodium channels in insects (Valmorbida *et* *al.*, 2022). They kill insects by binding to these sodium channels, leading to excitatory paralysis. Pyrethroids primarily alter the permeability of the nerve cell membrane, resulting in an unusually stable, hyperexcitable condition. This disruption results in a sub-lethal, incapacitating effect known as "knockdown," where insects are temporarily immobilized (Davies *et al.*, 2007). Bradberry *et al*. (2005) found that in insects, pyrethroids are 2250 times more poisonous than in animals. This is probably because insects have lower internal temperatures and more reactive sodium channels.

How pyrethroid insecticides reach aquatic ecosystems

Pyrethroid insecticides frequently enter water bodies through agricultural and urban runoff, washing off treated areas into drains and natural waterways (Hill *et al.*, 2020). The substantial urban utilization of synthetic pyrethroids (SPs) has resulted in their elevated prevalence in urban aquatic environments when contrasted with agricultural streams. Contaminated dust often acts as the primary vehicle for transporting synthetic pyrethroids (SPs) throughout urban landscapes when conditions are dry (Richards *et al.,* 2016). Spray drift during application can directly deposit them into water, while eroded contaminated soil also carries these chemicals into aquatic systems. Less common routes include wastewater discharge, limited soil leaching, and the resuspension of contaminated sediments. Ultimately, improper disposal or even atmospheric transport can contribute to their presence in our water.

Pyrethroid toxicity to non-target aquatic species

Synthetic pyrethroids pose a toxic threat to both aquatic macroinvertebrates (Yang *et al.*, 2018) and fish populations (Kumar *et al.*, 2025). Temperature, duration of exposition, and the level of particles in suspension are among the physical parameters that have a substantial impact on the toxicity of synthetic pyrethroids (SPs) in aquatic settings. For instance, because water temperature and SP toxicity are inversely correlated, pyrethroids tend to be detrimental to aquatic life at lower temperatures. This phenomenon, known as a negative temperature coefficient, implies that aquatic life in cooler water bodies (often below standard laboratory testing temperatures) faces a heightened risk from SP exposure. The availability of suspended sediments also plays a crucial role. Pyrethroids readily bind to organic matter and particles, including suspended sediments in the water column. When SPs are adsorbed to these particles, their bioavailability—the portion that is freely dissolved and thus available for uptake by organisms— can be significantly reduced. Consequently, higher concentrations of suspended sediments can decrease the overall toxicity of pyrethroids in the water phase, although the contaminated sediments themselves can still pose a risk to benthic (bottom-dwelling) organisms.

Synthetic pyrethroids exhibit diverse toxicity levels across various aquatic species. This variability is immediately apparent when comparing the LC_{50} values, which represent the lethal concentration for 50% of a population, across different organisms. For instance, cypermethrin shows extreme toxicity to sensitive invertebrates like shrimp, with a 96-hour water-spiked LC_{50} of a mere 0.01 µg/L (Coats *et al.*, 1989). Similarly, aquatic insects such as mayfly and stonefly nymphs are also exceptionally vulnerable to cypermethrin, with LC_{50} values of 0.08 µg/L and 0.13 µg/L, respectively (Crowley *et al.*, 2021). In contrast, while still toxic, fish like the Asian stinging catfish show a somewhat lower sensitivity to cypermethrin at 0.67 µg/L (96h; Biswas *et al.*, 2019), and amphibian tadpoles (*Quasipaa boulengeri*) have a 96-hour LC_{50} of 0.33 µg/L (Xiaoqin *et al.*, 2021). The difference becomes even more pronounced when examining organisms like freshwater snails or oligochaete worms, where cypermethrin's LC50s are significantly higher at 15.0 µg/L (Pal and Bej, 2019) and 43.39 µg/L (Bej *et al.*, 2015), respectively. Aquatic animals are typically thought to be at little risk of toxicity from synthetic pyrethroids. This reduced susceptibility is attributed to several physiological characteristics of mammals, including their relatively poor absorption through the skin, efficient and rapid metabolism of these compounds, and typically larger body sizes. Once absorbed, pyrethroids are swiftly broken down and transformed into inactive metabolites, which are then readily excreted from the organism, primarily via urine. Consequently, there is limited scientific data available specifically detailing the toxicity of pyrethroids in aquatic mammalian species.

Detrimental effects on fish

Pyrethroid pesticides exhibit a significantly higher toxicity to fish, being up to 1000 times more potent than to mammals and birds (Yang *et al.,* 2020). This extreme vulnerability in fish is attributed to their specialized organs, such as gills, which facilitate direct absorption from water, and their comparatively slower metabolic detoxification processes against these compounds. Pyrethroid pesticides pose a significant threat to fish due to their limited ability to detoxify these synthetic compounds. Unlike humans, fish notably lack efficient hydrolase enzymes, which are crucial for the hydrolytic breakdown of pyrethroids. This metabolic deficiency renders fish highly susceptible to pyrethroid poisoning. Risk assessment of environmental contaminants is best achieved by integrating exposure evaluation with biological indicators. This chapter examines the physiological stress indicators in fish exposed to various pyrethroid insecticides**,** specifically focusing on induced behavioral changes, histopathological alterations, biochemical markers, ultra-structural changes, hematological parameters and genotoxic effects.

Effects on behavior

Behavioral changes are key indicators of harm caused by toxicants in organisms. This is because fish behavior offers a sensitive way to measure the effects of chemical exposure, even at levels that aren't immediately lethal (Sharma *et al.*, 2019). Pesticide exposure can trigger a range of abnormal behaviors in fish, including altered schooling patterns, increased mucus secretion (sliminess), and sudden movements like jumping or jerky swimming. Other observed responses encompass changes in migratory behavior, adopting unusual vertical or inverted positions, sinking to the bottom, and a combination of non-responsiveness with hyperexcitability. Elevated opercular rates (indicating increased respiration) and shifts in body coloration are also common. These behavioral modifications have been documented across various fish species by different researchers (Ogueji *et al.*, 2018; Sharma and Jindal, 2021; Choudhary and Saba, 2025; Cominassi *et al.*, 2025).

Histopathological changes

Histopathological examination is a crucial and sensitive biomonitoring tool for assessing the impact of environmental contaminants, including pesticides, on fish. By analyzing changes in key tissues like the liver, kidney, gills, brain and intestine, it provides early warnings of disease and helps determine the severity of toxicity, especially sub-lethal and chronic effects, offering a comprehensive understanding of aquatic contamination. Pesticide exposure causes significant histopathological damage to fish organs, offering crucial insights for ecotoxicological investigations. Numerous investigations revealed various histological changes in different tissues of different fish species that were brought on by different pyrethroid pesticides (Reddy *et al.*, 2023; Kaval Oğuz *et al.*, 2024; da Silva *et al.*, 2025; Dorlikar and Thengare, 2025).

Biochemical Changes

Biochemical markers are crucial for risk assessment, reflecting an organism's structural and functional status under stress and correlating strongly with detrimental species-level effects (Abdallah *et al.*, 2024). Monitoring oxidative stress markers, enzyme activities, protein levels, and blood biochemical parameters can reveal physiological strain from pollution exposure. These markers are widely used to detect pesticide toxicity across various fish species. Pesticide exposure often depletes protein, carbohydrate, and lipid reserves in fish tissues, as energy is redirected to cope with toxic stress (Elayi and Williams, 2024). Organisms possess antioxidant defense systems, both enzymatic (e.g., SOD, CAT, GPx, GST, GR) and non-enzymatic (e.g., GSH, MDA), to counteract Reactive Oxygen Species (ROS)-mediated damage from pesticides. Various researchers have documented the altered antioxidant defense system of different fish species after exposure to different pesticides (Korkmaz *et al.*, 2023; Reddy *et al.*, 2023; Eli *et al.*, 2025). Additionally, phosphatase enzyme activity (ALP, ACP) serves as an indicator of cellular damage (Kumari and Mishra, 2025). Hemato-biochemical parameters, such as elevated serum urea and creatinine, are also vital indicators of renal dysfunction and overall physiological stress caused by toxicant exposure in fish (Uddin *et al.*, 2022; Javed *et al.*, 2025).

Hematological changes

Hematological parameters are vital, least-invasive biomarkers for assessing fish health, stress, and environmental pollution, offering early insights into physiological alterations (Sinha *et al.*, 2022). These parameters, including total erythrocyte count (TEC), hemoglobin (Hb) levels, packed cell volume (PCV), erythrocyte sedimentation rate (ESR), and total leukocyte count (TLC), are crucial in toxicological studies, though influenced by various intrinsic and extrinsic factors. Pesticide exposure commonly causes erythrocyte damage, leading to anemia due to Reactive Oxygen Species (ROS), evident in reduced TEC, Hb, and altered PCV. Alterations in ESR and absolute red blood cell indices (MCV, MCH, MCHC) also help diagnose anemia and indicate cellular damage. Beyond this, altered erythrocyte morphology and nuclear structure serve as critical indicators of oxidative stress and potential genetic damage. Meanwhile, leukocyte counts (TLC, DLC) reveal immune system responses, and thrombocyte count (ThC) alongside coagulation time offer insights into tissue damage and clotting under pesticide stress, as widely confirmed across various fish species. Numerous studies consistently demonstrated significant alterations in the aforementioned hematological parameters in various fish species following pyrethroid pesticide exposure (Korkmaz *et al.*, 2023; Kawsar *et al.*, 2025; Özok, 2025).

Ultra-structural changes

Electron microscopy (EM), encompassing both Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy

(TEM), is crucial for validating ultra-structural information and offers insights into cellular and sub-cellular changes relevant to toxicity studies (Sinha and Jindal, 2020). SEM excels in visualizing the three-dimensional surface structures of cells, like fish scales, which serve as valuable non-lethal biomarkers for water quality due to their sensitivity to even minute contaminants. TEM, on the other hand, provides high-resolution two- dimensional images, effectively detailing internal cellular damage, such as organelle changes, nuclear degeneration, and cytoplasmic integrity loss. Both techniques are essential in aquatic ecotoxicology, enabling the detection of early impacts of pollutants like pesticides on various fish organs. Various researchers have used the SEM and TEM analysis for the determination of ultrastructural changes in different organs of fish induced by different synthetic pyrethroids (Sharma *et al.,* 2021; Devi and Gupta, 2024).

Genotoxic effects

Genotoxicity, particularly the formation of micronuclei (MN) in fish, serves as a primary indicator of pollution's impact on aquatic ecosystems (Shahjahan *et al.,* 2019). The widely used Micronucleus (MN) assay helps detect this cytogenetic damage, linking contaminant levels to potential long-term health consequences and population decline in fish. Exposure to pyrethroid insecticides causes significant genotoxic effects in fish, primarily identified by the micronucleus (MN) assay (Chaudhary and Saxena, 2016; Sharma and Jindal, 2022; Kumar *et al.*, 2025). Based on the findings of various researchers, we can say that genotoxic damage in fish exposed to type II synthetic pyrethroids can be used as a valuable biomarker in toxicological studies. This manifests as increased micronuclei frequency and other nuclear abnormalities in fish erythrocytes, indicating chromosomal damage.

Research and knowledge gap

Synthetic pyrethroids (SPs) present a substantial risk to non-target organisms, especially fish, which include some endangered species. The way SPs are applied, along with environmental conditions and their physical and chemical characteristics, affects how these compounds spread and settle in sediments. Despite the evident danger, most research on SP toxicity has been concentrated in a few developed countries (e.g., USA, UK, China, Australia). Consequently, there's limited information available from developing nations like India, Pakistan, and Bangladesh, highlighting a critical knowledge gap. There are notable gaps in our understanding of synthetic pyrethroid (SP) toxicity concerning specific animal groups like zooplankton, amphibians, and fish. The majority of the data currently available is derived from toxicity tests conducted in water, which provides little information on how sediment-bound SPs affect a wide variety of aquatic creatures. To obtain an improved comprehension of the effects that SPs in sediment have on aquatic environments, it's crucial to investigate their effects on these less- studied groups. This will provide a more holistic understanding of the broader ecological risks. Synthetic pyrethroids (SPs) pose a significant threat to endangered species and their communities in aquatic environments, making it crucial for data-driven conservation plans to account for SPs' role in extinctions. Bio-monitoring is vital to grasp the full implications of SP exposure, especially sub-lethal effects; for instance, understanding how SPs impact species based on their traits can reveal broader community effects, though this area remains under-researched.

Control and mitigation strategies

Mitigating pyrethroid contamination in aquatic ecosystems demands a comprehensive strategy. Foremost is Integrated Pest Management (IPM), emphasizing minimal pesticide use through monitoring and non-chemical controls. When chemical intervention is unavoidable, responsible product selection (e.g., less toxic alternatives, targeted formulations) and precise application techniques are crucial, including avoiding spraying near water and adhering to buffer zones. Considering weather conditions to prevent drift and runoff, alongside proper equipment calibration, are also vital. Furthermore, site-specific management like establishing vegetated filter strips and riparian buffers can effectively intercept runoff. On the remediation side, bioremediation using microbes or plants offers an eco-friendly approach to break down existing contamination. Lastly, public education on safe use and disposal, combined with improved wastewater treatment, collectively reduces pyrethroid entry into and persistence within aquatic environments.

Conclusion

Freshwater ecosystems globally face severe threats from indiscriminate pesticide use, with synthetic pyrethroids being a significant concern due to their widespread application and environmental persistence. These neurotoxic compounds, while effective against target insect pests, inflict substantial harm on non-target aquatic organisms, particularly fish, which are exceptionally vulnerable due to their unique physiological characteristics and limited detoxification capabilities. Fish serve as critical bioindicators, exhibiting measurable changes in behavior, histopathology, biochemistry, hematology, and ultrastructure, along with genotoxic effects like micronuclei formation, upon exposure. Despite extensive research in some regions, a critical knowledge gap persists regarding pyrethroid toxicity in developing nations and its impact on various lesser-studied aquatic species. Addressing this complex issue necessitates a multi- pronged approach involving robust integrated pest management, responsible application practices, and advanced bio-monitoring techniques to safeguard aquatic biodiversity and human health.

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