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Review Article

TOXIC EFFECTS OF PESTICIDES AND HEAVY METALS IN FISH: MECHANISMS AND REMEDIATION STRATEGIES -A REVIEW

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ABSTRACT

Heavy metals and pesticides are two of the main pollutants endangering aquatic environments worldwide. Natural geochemical processes, mining operations, municipal trash, industrial effluents, and agricultural runoff all contribute to their entry into water bodies. Fish, which serve as crucial indicators of environmental health, are particularly at risk from these pollutants because of their persistence and bioaccumulation. Fish growth, metabolism, immunity, reproduction and early development are all negatively impacted by exposure to these pollutants. They cause oxidative stress, enzyme inhibition, and tissue damage at the cellular level, which leads to notable histopathological alterations in important organs like the liver, kidneys, gonads and gills. Heavy metals and insecticides together may increase toxicity and harm to the environment. Concerns about food safety and human health are also raised by their buildup in edible fish tissues. In addition to highlighting environmentally acceptable remediation techniques, such as plant-based bioactive substances for toxicity mitigation, this review analyzes sources, toxicity mechanisms, and biological effects.

Keywords: Fish toxicity, Pesticides, Heavy metals, Bioaccumulation, Oxidative stress.

INTRODUCTION

Chemical contamination resulting from fast industrialization, urbanization, and intensive agricultural activities is posing a growing threat to aquatic environments. Because of their toxicity, environmental stability, and propensity for bioaccumulation, pesticides and heavy metals are among the many pollutants that are known to be hazardous and persistent (Ali *et al.,* 2019; Kumar *et al.,* 2020). Widespread ecological disruptions result from the introduction of these contaminants into aquatic habitats by mining operations, industrial effluents, agricultural runoff, sewage discharge, and atmospheric deposition (Jaishankar *et al.,* 2014; Singh *et al.,* 2021). Fish are especially susceptible to these pollutants since they are essential parts of aquatic food webs and a significant source of human diet. Fish are useful bioindicators of environmental contamination because of their direct contact to contaminated water and their ability to collect hazardous compounds in their tissues (Authman *et al.,* 2015; Abdel-Tawwab & Hamed, 2020). Fish exposed to pesticides and heavy metals may have altered enzymatic activity, compromised development and reproduction, weakened immunological responses, and disrupted physiological processes (Sarkar *et al.,* 2019; El-Naggar *et al.,* 2020). By producing reactive oxygen species (ROS), these toxicants cause oxidative stress at the cellular level, which results in DNA damage, lipid peroxidation, and protein degradation (Lushchak, 2011; Sharma *et al.,* 2022).

One of the most obvious effects of fish exposure to toxins is histopathological changes. When exposed to pollutants, vital organs including the gills, liver, kidneys, and gonads show structural damage that includes necrosis, cellular degeneration, and tissue disarray (Hadi & Alwan, 2012; Velmurugan *et al.,* 2009). Furthermore, pesticides and heavy metals may intensify toxicity through synergistic or combination interactions, leading to more serious biological and ecological effects (Farombi *et al.,* 2007; Rajkumar *et al.,* 2018). The buildup of these harmful compounds in edible fish tissues presents significant health hazards to humans in addition to ecological ramifications. Chronic health problems, such as neurological, renal, and carcinogenic impacts, can result from eating contaminated fish (Jaishankar *et al.,* 2014; Tchounwou *et al.,* 2012).

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Thus, it is essential to comprehend the processes of toxicity and create efficient remediation techniques.

In order to lessen the effects of these pollutants, recent research has concentrated on environmentally friendly and sustainable repair techniques. Among these, the utilization of medicinal herbs and plant-based bioactive chemicals has drawn interest because of its detoxifying, chelating, and antioxidant qualities (Abdel-Daim *et al.,* 2019; Gupta *et al.,* 2021). These organic substances can improve fish's physiological resistance to harmful shocks and lessen oxidative stress. With a focus on phytoremediation and herbal therapies, the current study attempts to give a thorough understanding of the sources, mechanisms, and harmful consequences of pesticides and heavy metals in fish as well as developing remediation techniques.

Pesticide Toxicity

Although pesticides are widely used in agriculture to manage pests and increase crop yield, aquaculture systems are increasingly concerned about their accidental introduction into aquatic habitats. The main ways that pesticides contaminate ponds, rivers, and reservoirs used for fish farming are through runoff from agricultural fields, spray drift, and inappropriate disposal (Singh *et al.,* 2021; Kumar *et al.,* 2020). These substances include pyrethroids, carbamates, organochlorines, and organophosphates, many of which are extremely dangerous even at low doses. Fish exposed to pesticides in aquaculture may have both acute and long-term harmful consequences. Behavioral abnormalities include erratic swimming, loss of balance, increased mucus secretion, and respiratory discomfort due to gill injury are frequently caused by acute poisoning (Velisek *et al.,* 2011). Conversely, long-term exposure reduces fish production and survival rates by affecting growth, feed efficiency, and metabolic processes (Sarkar *et al.,* 2019). Pesticides disturb normal neural transmission at the physiological level by interfering with enzymatic systems, namely by decreasing acetylcholinesterase activity in nerve tissues (Lionetto *et al.,* 2013). Furthermore, they cause oxidative stress by producing reactive oxygen species (ROS), which result in DNA damage, lipid peroxidation, and protein denaturation (Lushchak, 2011). Fish antioxidant defense systems are weakened by this oxidative imbalance, which also leads to cellular malfunction.

There are numerous reports of histopathological changes in fish exposed to pesticides. Lesions in organs like the gills, liver, kidneys, and gonads include tissue degradation, vacuolation, necrosis, and epithelial lifting (Hadi & Alwan, 2012). According to Scholz *et al.,* (2008), pesticides have a considerable negative impact on gametogenesis, lower fertility, and cause developmental defects in embryos and larvae. Additionally, fish tissues may store pesticide residues, which can cause bioaccumulation and biomagnification throughout the food chain. Because eating tainted fish may have neurological, endocrine, and cancer-causing consequences, this poses major health risks to people (Aktar *et al.,* 2009). Improved farming methods, the use of biopesticides, water quality control, and the application of natural antioxidants such plant extracts have all been suggested as ways to reduce pesticide toxicity in aquaculture. Fish resistance to pesticide-induced stress has been improved through phytoremediation and dietary supplementation with medicinal herbs (Abdel-Daim *et al.,* 2019). In therefore, fish health, food safety and aquaculture viability are all seriously threatened by pesticide toxicity. Therefore, to reduce its influence, ongoing monitoring, regulation, and the development of eco-friendly alternatives are crucial.

Pesticides and Heavy Metals in Fish, mechanisms, effects and mirtigation.

A variety of chemical pollutants are becoming more prevalent in aquatic ecosystems as a result of increased urbanization, industrialization, and agricultural intensification. Because of their persistence, non-biodegradability, and significant potential for bioaccumulation in aquatic organisms, pesticides and heavy metals are among the most dangerous of these (Ali *et al.,* 2019; Kumar *et al.,* 2020). These pollutants pose serious dangers to aquatic life and ecosystem stability because they reach water bodies through a variety of routes, such as industrial effluents, mining operations, agricultural runoff, sewage discharge, and atmospheric deposition (Singh *et al.,* 2021; Tchounwou *et al.,* 2012).

Due to their direct and ongoing exposure to contaminated water and their capacity to collect harmful compounds in their tissues, fish are particularly vulnerable to these toxins. Fish are therefore frequently employed as bioindicators to evaluate the condition of aquatic ecosystems (Authman *et al.,* 2015; Abdel-Tawwab *et al.,* 2021). Fish that are exposed to pesticides and heavy metals may experience negative effects on their physiological, biochemical, and molecular functions, among other biological levels. According to El-Naggar *et al.,* (2020) and Sharma *et al.,* (2022), these toxicants affect enzyme activity, interfere with growth and reproduction, disturb normal metabolic processes, and weaken immunological responses. Both heavy metals and pesticides are known to cause oxidative stress at the molecular level by producing too many reactive oxygen species (ROS), which can result in DNA damage, lipid peroxidation, and protein oxidation (Lushchak, 2011; Sinha *et al.,* 2022). Furthermore, heavy metals disrupt fundamental physiological pathways by attaching to proteins and displacing necessary metal ions, while pesticides like organophosphates inhibit important enzymes like acetylcholinesterase, causing neurotoxicity (Lionetto *et al.,* 2013; Jaishankar *et al.,* 2014). Important organs like the gills, liver, kidneys, and gonads frequently have significant histopathological alterations as a result of these molecular abnormalities.

These pollutants have harmful effects not only on aquatic life but also on people who eat tainted fish. Because long-term exposure can result in neurological disorders, endocrine disruption, and carcinogenic outcomes, bioaccumulation and biomagnification of pesticides and heavy metals in edible fish tissues raise serious concerns about food safety and public health (Tchounwou *et al.,* 2012; Kumar *et al.,* 2020). The creation of practical mitigation techniques has been a top priority in environmental and aquaculture research due to these difficulties. Recent research has demonstrated the promise of environmentally friendly methods to lower pollutant levels and lessen toxicity in fish, including phytoremediation, bioremediation, and the utilization of bioactive chemicals obtained from plants (Abdel-Daim *et al.,* 2019; Gupta *et al.,* 2021). These natural remedies have detoxifying, metal-chelating, and antioxidant qualities, providing long-term substitutes for traditional remediation techniques. In light of this, the current study attempts to give a thorough overview of pesticides and heavy metals in fish, emphasizing their sources, toxicity mechanisms, biological consequences, and new mitigation techniques.

Water Pollutants

Rapid urbanization, industrialization, and increased agricultural production have made water contamination a major worldwide environmental concern. Because of their persistence, toxicity, and bioaccumulative nature, water pollutants have been highlighted by numerous studies as significant hazards to aquatic ecosystems and human health (Ali et al., 2019; Kumar *et al.,* 2020). Heavy metals, pesticides, fertilizers, medicines, and microplastics are just a few of the many compounds that make up these pollutants, and they all contribute in different ways to the deterioration of the ecosystem. Because of their long-term persistence in aquatic habitats and lack of biodegradability, heavy metals are among the water contaminants that have been investigated the most. Even at low quantities, metals like lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) can build up in sediments and biota and cause harmful effects (Ali *et al.,* 2019).

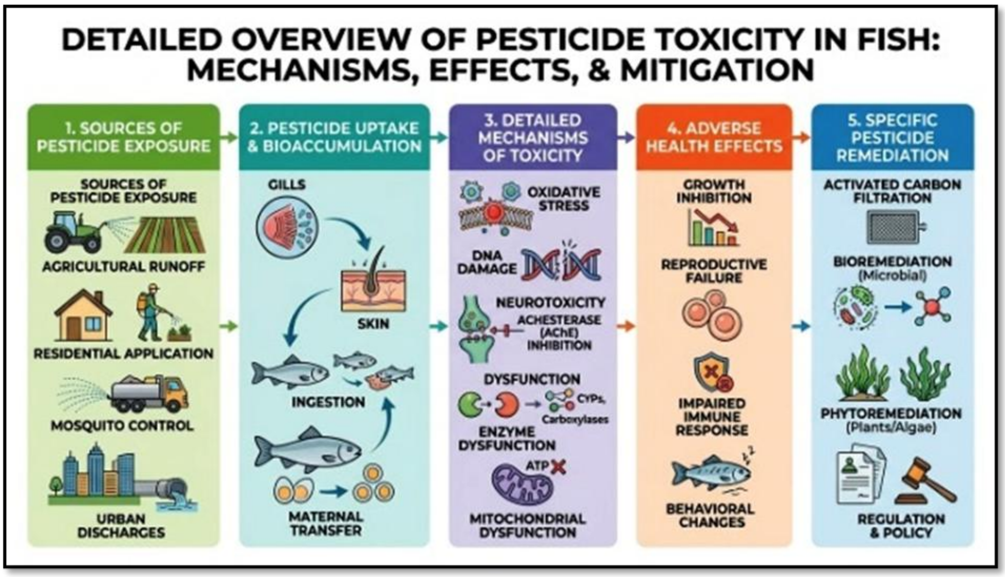

Figure 1. Various forms of Pesticide toxicity.

According to studies, these metals seriously change aquatic creatures' physiology and biochemistry, create oxidative stress, and interfere with cellular processes (Sharma *et al.,* 2022). Additionally, heavy metals pose serious health hazards to humans since they can biomagnify through the food chain. Another significant category of water contaminants are pesticides, which are frequently employed in agriculture yet find their way into water bodies through leaching and runoff. According to research, organophosphates, carbamates, and pyrethroids are among the pesticides that can harm aquatic creatures both acutely and over time (Singh *et al.,* 2021). These substances cause oxidative damage and compromised physiological functioning by interfering with enzymatic activities, including acetylcholinesterase inhibition, and producing reactive oxygen species (ROS) (Lushchak, 2011).

Eutrophication in aquatic systems is a result of nutrient contamination, which is mostly brought on by excess nitrogen and phosphorus from fertilizers and sewage. Fish kills follow from this mechanism, which causes excessive algal growth and decreased dissolved oxygen levels (Kumar *et al.,* 2020). Eutrophication-related cyanobacterial blooms can also release toxins that are dangerous to humans and aquatic life. Due to their ubiquitous presence and possible ecological effects, new pollutants such medicines, personal care products (PPCPs) and microplastics have drawn attention in recent years. Conventional wastewater treatment methods frequently fail to eliminate these pollutants, which cause them to build up in aquatic habitats (Rochman *et al.,* 2016). It has been demonstrated that microplastics in particular serve as transporters for other harmful compounds, increasing their toxicity and bioavailability.

A complex mixture of toxins is introduced into aquatic systems by urban wastewater and industrial effluents, which are significant contributors to water pollution.

Research highlights how untreated or insufficiently treated wastewater can drastically change water quality, impacting ecosystem functioning and biodiversity (Singh *et al.,* 2021). The burden on aquatic creatures is further increased by pH shifts and heat pollution. Many remediation techniques have been investigated to alleviate water pollution. Both phytoremediation, which uses plants, and bioremediation, which uses microorganisms, have demonstrated encouraging outcomes in eliminating or purifying contaminants from water bodies (Gupta *et al.,* 2021). For effective pollution removal, cutting-edge treatment technologies are also being developed, including as membrane filtration and nanotechnology-based methods. The literature as a whole emphasizes that water contaminants present complex issues that need for integrated management techniques. To lessen the negative consequences of water pollution on ecosystems and human health, stringent regulations, ongoing monitoring, and the adoption of sustainable practices are crucial.

Pesticides in Aquatic Environments

Chemicals used extensively in agricultural and pest management, pesticides frequently find their way into aquatic environments through runoff, leaching, and inappropriate disposal. Fungicides, herbicides, insecticides, and rodenticides are major classes with different modes of action and ecological effects (Singh *et al.,* 2021; Ali *et al.,* 2019).

Fungicides

Compared to other pesticides, fungicides are typically thought to be less harmful to aquatic life; yet, some compounds have shown serious ecological hazards. In the past, fish were severely contaminated and bioaccumulated by mercury-based fungicides, which resulted in widespread fish mortality and ultimately led to regulatory prohibitions (Raeeszadeh *et al.,* 2022). Even though they are generally safer, modern fungicides can still harm fish and aquatic invertebrates if they are used incorrectly close to bodies of water. Therefore, in order to reduce their impact, limited usage and environmental monitoring are crucial.

Herbicides

Herbicides are widely utilized in aquatic systems and agricultural areas to manage undesirable plants. They are used to get rid of emergent, floating, and submerged weeds as well as bothersome algae. However, by giving fish food, shelter, and oxygen, these plants are essential to the upkeep of aquatic ecosystems. Fish growth and reproduction are adversely affected by their removal, which also upsets ecological balance and lowers dissolved oxygen levels (Kumar *et al.,* 2020). Therefore, overuse of herbicides might result in decreased fish productivity and habitat deterioration.

Insecticides

Among the most harmful classes of pesticides that influence aquatic life are insecticides. They include both natural (like *Azadirachta indica*) and manufactured (such organochlorines, organophosphates, carbamates, and pyrethroids) substances that work by ingestion, direct contact, or fumigation (Sharma *et al.,* 2022). These substances cause neurotoxicity by blocking enzymes like acetylcholinesterase, which impairs nervous system function. Fish are a prominent problem in aquatic toxicology because pesticide exposure produces physiological malfunction, oxidative stress, and behavioral abnormalities.

Rodenticides

Rodenticides may inadvertently find their way into aquatic habitats and are used to manage rodent populations. Common substances like sodium fluoroacetate, zinc phosphide, and warfarin interfere with essential physiological functions like blood coagulation and metabolic control. Fish and aquatic invertebrates are among the non-target creatures that can be impacted by their contamination in water bodies, despite the fact that their primary target is terrestrial pests (Gupta *et al.,* 2021). The risk of aquatic toxicity is increased by improper disposal and discharge.

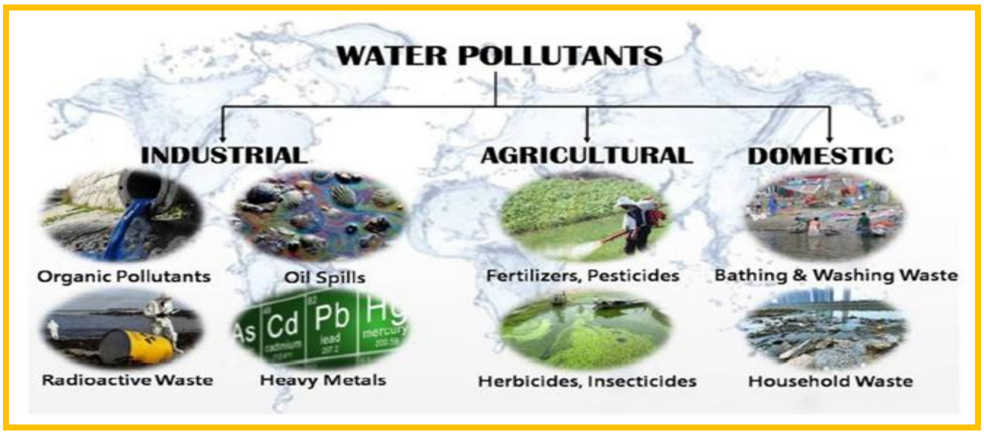

Figure 2. Various kinds and sources of water pollutants. Source. Yadav *et al.,* 2019.

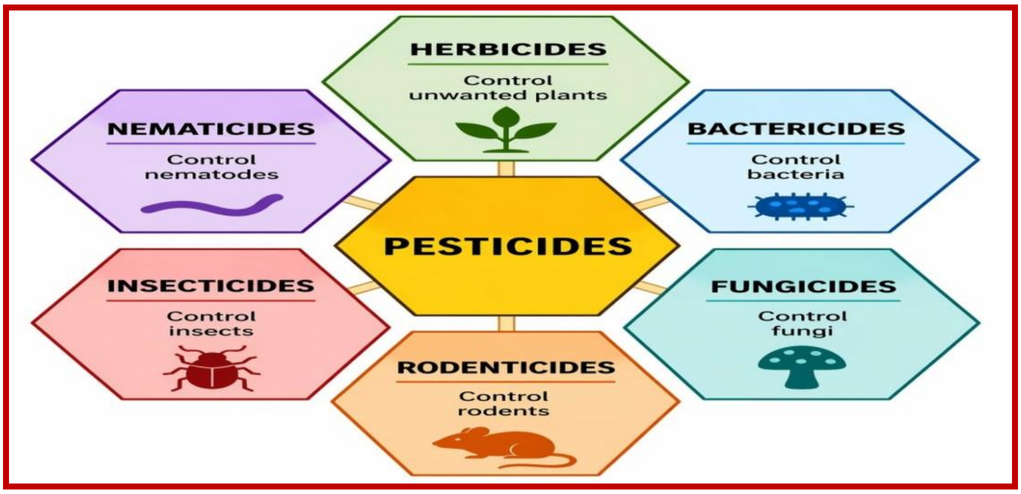

Figure 3. Various types Pesticides in Environment. Source: V. R. Remya *et al.,*2019.

Table 1. Guideline Values of Heavy Metals (According to WHO, 2004).

Heavy Metal	Symbol	Guideline Value (mg/L)
Antimony	Sb	0.02
Arsenic	As	0.01
Barium	Ba	0.7
Cadmium	Cd	0.003
Chromium	Cr	0.05
Copper	Cu	2.0
Lead	Pb	0.01
Manganese	Mn	0.4
Mercury	Hg	0.006
Molybdenum	Mo	0.07
Nickel	Ni	0.07
Selenium	Se	0.01
Uranium	U	0.015

Effects of Pesticides on Fish

Fish health and survival are seriously threatened by pesticides, which are one of the biggest pollutants in aquatic habitats. These substances accumulate in aquatic ecosystems after entering water bodies by atmospheric deposition, industrial discharge, and agricultural runoff (Moezzi *et al.,* 2025; Singh *et al.,* 2021). Pesticides can negatively impact fish at several biological levels, including physiological, biochemical, and molecular processes, because of their persistence and bioaccumulative nature. The production of oxidative stress is one of the main mechanisms of pesticide toxicity in fish. Reactive oxygen species (ROS), which upset cellular equilibrium and harm lipids, proteins, and DNA, are produced in excess by pesticides (Moezzi *et al.,* 2025).

Fish exposed to organophosphates and herbicides have been shown to have increased lipid peroxidation, as seen by raised levels of malondialdehyde (MDA), especially in organs including the liver, gills, and kidneys (Rossi *et al.,* 2022). Cellular dysfunction eventually results from these oxidative alterations that compromise enzyme activities and membrane integrity. By blocking important enzymes like acetylcholinesterase (AChE), which is essential for nerve impulse transmission, pesticides also cause neurotoxic effects in fish. Fish exhibit aberrant neuronal signaling, altered behavior, and decreased locomotor activity as a result of organophosphate pesticides, such as malathion and chlorpyrifos, which suppress AChE activity (Khan *et al.,* 2024). Fish survival and ecological fitness are severely impacted by this neurotoxicity.

Pesticides affect fish metabolism and physiology in addition to having oxidative and neurotoxic effects. Pesticide exposure changes energy metabolism, ammonia excretion and oxygen use, all of which are signs of metabolic stress (Khan *et al.,* 2024). Fish populations' general fitness is lowered as a result of these disruptions, which also impede feed utilization and growth performance. Another significant effect of pesticide exposure is histopathological changes. Research has shown that important organs like the kidneys, liver, gills and brain tissues undergo structural damage. Normal organ function is hampered by these alterations, which include tissue degeneration, necrosis, vacuolation, and epithelial lifting (Rahman *et al.,* 2023). Due to their direct exposure to the aquatic environment, gills are especially susceptible to respiratory and osmoregulation problems. Fish reproductive systems are similarly impacted by pesticides, which can lead to endocrine disruption and decreased fertility. They cause developmental defects in embryos and larvae, disrupt gametogenesis, and interfere with hormone control (Moezzi *et al.,* 2025). Fish population sustainability may eventually be diminished by such reproductive deficiencies. Pesticide residues can pose serious health hazards to humans since they build up in fish tissues and biomagnify along the food chain. Eating tainted fish can cause long-term health problems, such as neurological and cancerous repercussions (Rahman *et al.,* 2023). Overall, the research makes it abundantly evident that fish exposed to pesticides suffer from a variety of harmful consequences, such as oxidative stress, neurotoxicity, metabolic disturbance, histopathological damage, and reproductive impairment. These consequences raise severe issues about food safety and ecosystem stability in addition to endangering fish health and aquaculture output. Therefore, to reduce pesticide toxicity in aquatic environments, efficient monitoring and the use of environmentally suitable substitutes are crucial.

Table 2. Effects of Different Pesticides on Various Fish Species.

S. No.	Species	Pesticide	Dose	Exposure Time (Days)	Effects	References
1	*Oreochromis niloticus*	Chlorpyrifos	0.05 mg/L	15	Reduced growth, oxidative stress, liver damage	Khan *et al.,* 2024
2	*Cyprinus carpio*	Malathion	0.1 mg/L	10	AChE inhibition, behavioral abnormalities	Sharma *et al.,* 2022
3	*Labeo rohita*	Endosulfan	0.01 mg/L	20	Gill damage, respiratory distress	Singh *et al.,* 2021
4	*Clarias batrachus*	Carbaryl	0.2 mg/L	12	Hematological changes, reduced immunity	Kumar *et al.,* 2020
5	*Danio rerio*	Atrazine	2 mg/L	7	Developmental toxicity, endocrine disruption	Rossi *et al.,* 2022
6	*Channa punctatus*	Cypermethrin	0.02 mg/L	14	Neurotoxicity, erratic swimming behavior	Rahman *et al.,* 2023
7	*Heteropneustes fossilis*	Glyphosate	5 mg/L	21	Histopathological changes in liver and kidney	Abdel-Daim *et al.,* 2019
8	*Oncorhynchus mykiss*	Diazinon	0.03 mg/L	10	Enzyme inhibition, oxidative stress	Ali *et al.,* 2019

Table 3. Effects of Heavy Metals on Different Aspects of Fish.

S. No.	Species	Heavy Metal (Dose)	Exposure Period	Effects	References
1	*Oreochromis niloticus*	Cadmium (0.05 mg/L)	21 days	Oxidative stress, liver damage, reduced growth	Abdel-Tawwab *et al.,* 2021
2	*Cyprinus carpio*	Lead (0.1 mg/L)	15 days	Hematological changes, increased glucose levels	Vinodhini *et al.,* 2009
3	*Labeo rohita*	Mercury (0.01 mg/L)	20 days	Neurotoxicity, behavioral abnormalities	Sharma *et al.,* 2022
4	*Clarias batrachus*	Chromium (0.2 mg/L)	10 days	Gill damage, respiratory distress	Kumar *et al.,* 2020
5	*Channa punctatus*	Arsenic (0.05 mg/L)	30 days	Histopathological changes in liver and kidney	Ali *et al.,* 2019
6	*Heteropneustes fossilis*	Nickel (0.1 mg/L)	14 days	Enzyme inhibition, metabolic stress	Gupta *et al.,* 2021
7	*Danio rerio*	Copper (0.03 mg/L)	7 days	Developmental toxicity, oxidative stress	El-Naggar *et al.,* 2020
8	*Oncorhynchus mykiss*	Zinc (0.5 mg/L)	12 days	Growth retardation, ion imbalance	Authman *et al.,* 2015

Due to their bioaccumulation and durability in water bodies, pesticides are significant aquatic pollutants that negatively impact fish health (Singh *et al.,* 2021). Many fish species experience oxidative stress, enzymatic inhibition, and metabolic disruptions when exposed to various pesticides, including organophosphates, carbamates, and pyrethroids (Ali *et al*., 2019; Sharma *et al.,* 2022). Acetylcholinesterase inhibition-induced neurotoxicity is a typical mechanism that results in aberrant behavior and decreased lifespan (Khan *et al.,* 2024). Physiological functions are often compromised by histopathological changes in the kidneys, liver, and gills (El-Naggar *et al.,* 2020). Additionally, pesticide residues bioaccumulate in fish tissues, endangering human health and aquatic ecosystems (Kumar *et al.,* 2020). According to Ali *et al.,* (2019), heavy metals are persistent aquatic contaminants that build up in fish tissues and have serious toxicological effects. Fish exposed to metals including cadmium, lead, and mercury experience oxidative stress, which results in DNA changes, protein degradation, and lipid peroxidation (Sharma *et al.,* 2022). Fish survival and fitness are eventually decreased by these pollutants because they interfere with physiological processes as metabolism, development, and immunological function (Abdel-Tawwab *et al.,* 2021). Important organs like the liver, kidneys, and gills frequently have histopathological alterations that compromise normal organ function (El-Naggar *et al.,* 2020). Additionally, through the food chain, heavy metal bioaccumulation and biomagnification in fish offer major health concerns to humans (Kumar *et al.,* 2020).

Table 4. Remediation Strategies for Pesticide and Heavy Metal Effects in Fishes.

Strategy	Description	References
Physical Methods	Water and sediments are directly cleaned of pollutants. While filtering and adsorption (such as activated carbon) lower pesticide and metal levels, dredging eliminates polluted materials. Fish survival is aided by aeration and water exchange, which also improve water quality and dilute harmful compounds.	Ali H, Khan, E., & Sajad M. A (2013).
Chemical Methods	Substances that are toxic are transformed into less dangerous versions. While chelating agents bind metals and lessen toxicity, precipitation and coagulation eliminate heavy metals by creating insoluble molecules. Pesticide residues are broken down by sophisticated oxidation processes (ozone, hydrogen peroxide).	Javed M, & Usmani N (2016).
Biological Methods (Bioremediation)	Pollutants are detoxified using living organisms. Bacteria and fungus are microorganisms that break down pesticides and change metals. Water is naturally cleaned by aquatic plants like Lemna minor and Eichhornia crassipes, which absorb and collect pollutants.	Varol M, & Sünbül M. R (2019).
Nutritional Support in Fish	Fish with diets high in antioxidants are better able to withstand harmful impacts. Vitamins C and E, selenium, and plant-based substances are examples of nutrients that strengthen immunity and lessen oxidative stress brought on by pollution.	Ahmad I *et al.,* (2022).
Environmental Management	Pollution is decreased by preventive actions. These include controlling the use of pesticides, cleaning up industrial waste before it is released, and keeping an eye on the quality of the water. Aquatic ecosystems are safeguarded by sustainable farming methods and environmentally friendly biopesticides.	Zahran E *et al.,* (2025).
Integrated Approaches	Pollutant removal is improved when physical, chemical, and biological approaches are combined. Constructed wetlands successfully minimize pesticide and heavy metal contamination by utilizing bacteria, plants, and natural processes.	Javed M, & Usmani N (2016).

CONCLUSION

Heavy metals and pesticides are two of the main aquatic pollutants that, through bioaccumulation and persistence, have extremely harmful impacts on fish. In critical organs like the liver, kidneys, and gills, these pollutants cause oxidative stress, enzymatic inhibition, and histological damage. Their combined effects can increase toxicity even more, impairing fish survival, development, and reproduction. Through biomagnification, the buildup of these toxins in edible fish also poses serious health concerns to people. Therefore, maintaining aquatic ecosystems require efficient monitoring and environmentally friendly remediation techniques including bioremediation and phytoremediation.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

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AI TOOL DECLARATION

The authors declare that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

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