International Journal of Environmental and Ecology Research
www.environmentaljournal.in
Online ISSN: 2664-7117
Received: 13-02-2026, Accepted: 16-03-2026, Published: 31-03-2026
Volume 8, Issue 1, 2026, Page No. 68-74

Ecotoxicological impacts of pesticides on freshwater fish in India: A contemporary review

Anand Kumar, Veena P Swami
Department of Zoology, B.S.N.V.P.G. College, University of Lucknow, Lucknow, Uttar Pradesh, India

Abstract

The extensive use of pesticides to improve agricultural yield has raised serious environmental concerns, particularly in aquatic ecosystems. Pesticides comprise a wide range of chemical substances applied to control pests in agricultural and domestic settings; however, only a minimal proportion reaches the intended targets, while the majority is dispersed into the surrounding environment. Owing to their chemical stability and resistance to degradation, these compounds persist for extended periods and accumulate in soil and water bodies.

Aquatic environments receive pesticide inputs mainly through surface runoff, leaching, and drift, leading to contamination of freshwater systems. Fish are highly sensitive to such pollutants and are widely recognized as reliable bioindicators of water quality. Exposure to pesticide residues results in their accumulation within fish tissues, producing multiple adverse effects. These include disruptions in physiological processes, altered behaviour, changes in haematological and biochemical parameters, tissue damage, immune suppression, endocrine imbalance, reproductive impairment, and genetic damage.

In addition, the presence of pesticide residues in fish represents a potential risk to human health through food chain transfer. This review therefore focuses on evaluating the ecological risks associated with pesticide contamination in freshwater ecosystems, emphasizing its impact on fish health and highlighting the current status and implications of pesticide usage in India.

Keywords: pesticide toxicity, pesticide status in india, fish health, behavioural and haematological responses, histopathology, genotoxicity

Introduction

Pesticides constitute a diverse class of chemical compounds widely utilized for the control of agricultural and domestic pests, thereby playing a critical role in enhancing crop productivity and safeguarding public health. Over recent decades, the global consumption of pesticides has increased dramatically, not only in intensive agricultural systems but also in household environments for controlling vectors such as mosquitoes, cockroaches, ticks, and other pests. Despite their undeniable benefits, the excessive and indiscriminate application of pesticides has raised serious environmental and toxicological concerns.

It is well established that only a negligible fraction—approximately 1%—of applied pesticides reaches the intended target organisms, while the remaining proportion is dispersed into environmental matrices such as soil, water, and air (Mahmood *et al*., 2016) [28]. These contaminants enter aquatic ecosystems through multiple pathways, including agricultural runoff, leaching, spray drift, and subsurface drainage, ultimately accumulating in freshwater bodies such as rivers, lakes, and streams (Cosgrove *et al*., 2019) [12]. Recent studies have emphasized that such environmental dispersion leads to persistent contamination and long-term ecological risks (Sharma *et al*., 2024; Adams *et al*., 2025) [1, 36].

Aquatic organisms, particularly fish, are highly vulnerable to pesticide exposure due to their continuous interaction with contaminated water. Fish serve as vital components of aquatic food webs and are widely recognized as bioindicators of environmental pollution. Contemporary research has highlighted that pesticide residues, especially organochlorines and other persistent compounds, bioaccumulate in fish tissues and may reach concentrations exceeding permissible safety limits (Ghafarifarsani *et al*., 2024) [17]. Earlier investigations in Indian river systems, including the Ganga and its tributaries, reported significant accumulation of pesticides such as DDT, HCH, aldrin, and endosulfan in fish tissues, often exceeding FAO tolerance limits (Kumari *et al*., 2001a, 2001b; Singh *et al*., 2008). These findings continue to be supported by recent assessments indicating persistent contamination in freshwater ecosystems.

Chronic exposure to pesticides induces a wide spectrum of toxicological effects in fish. These include physiological dysfunction, behavioral alterations, hematological and biochemical disturbances, histopathological lesions, immunosuppression, endocrine disruption, reproductive impairments, and genotoxic effects (Ullah *et al*., 2014; Pandey *et al*., 2014; Ghafarifarsani *et al*., 2024; Moezzi *et al*., 2025) [17, 31, 39]. Mechanistically, many pesticides exert toxicity through the induction of oxidative stress, disruption of enzymatic activities, and interference with hormonal regulation, ultimately impairing growth, survival, and reproductive success in fish populations (Moezzi *et al*., 2025; Burch *et al*., 2025) [8, 31].

In addition to physiological impacts, pesticide exposure significantly alters fish behavior, including feeding patterns, locomotion, predator avoidance, and social interactions. Such behavioural modifications can reduce fitness and survival, thereby affecting population dynamics and ecosystem stability (Saaristo *et al*., 2020; Morrison *et al*., 2025) [30, 35]. Furthermore, prolonged exposure to sublethal concentrations of pesticides has been shown to compromise immune responses, increasing susceptibility to diseases and environmental stressors (Burch *et al*., 2025) [8].

The ecological consequences of pesticide contamination extend beyond individual organisms to entire aquatic communities. Disruption of trophic interactions and ecological balance may lead to biodiversity loss and long-term ecosystem degradation. Moreover, the bioaccumulation and biomagnification of pesticide residues in fish pose significant risks to human health through dietary exposure. Consumption of contaminated fish has been associated with various adverse health outcomes, including endocrine disruption, neurotoxicity, and carcinogenic effects (Gerber *et al*., 2016; Sharma *et al*., 2024) [16, 36].

Given these concerns, there is an urgent need for comprehensive risk assessment and monitoring of pesticide contamination in freshwater ecosystems, particularly in developing countries like India, where agricultural intensification continues to rise. Therefore, the present manuscript aims to evaluate the current status of pesticide contamination, assess its toxicological impacts on freshwater fish, and highlight the associated ecological and human health risks.

Present Scenario of Pesticides in India

The use of pesticides in India dates back to 1948, when dichlorodiphenyltrichloroethane (DDT) was introduced for malaria control and benzene hexachloride (BHC) for locust management. Subsequently, India established its first pesticide manufacturing facility in 1952 for the production of DDT and BHC. By 1958, domestic pesticide production had already exceeded 5,000 metric tonnes (Gupta, 2004) [20]. Since then, the pesticide industry has expanded substantially, making India one of the leading producers globally.

As of 2025, approximately 295–300 pesticides (including insecticides, herbicides, fungicides, and biopesticides) are registered for use in India under the Central Insecticides Board and Registration Committee (CIBRC). The total annual production of technical-grade pesticides has increased to around 320,000–330,000 metric tonnes, reflecting the growing demand driven by agricultural intensification (Government of India, 2024 [19]; FAO, 2023). India currently ranks among the top pesticide-producing nations, holding approximately the 4th position globally (Table-1), while its consumption ranks around 12th–13th worldwide, indicating relatively lower per hectare usage compared to many developed and developing countries.

Despite relatively low pesticide consumption in India—estimated at approximately 0.6 kg/ha in 2024 [19]–2025, compared to significantly higher usage in countries such as China (~13 kg/ha) and Brazil (~10–12 kg/ha)—the environmental burden remains substantial due to improper application practices, lack of awareness, and inadequate regulatory enforcement (FAO, 2023; Sharma *et al*., 2024) [36]. Recent global estimates indicate that countries such as Maldives (~50 kg/ha), Trinidad and Tobago (~25 kg/ha), and Costa Rica (~22 kg/ha) exhibit the highest pesticide consumption per hectare, highlighting stark global disparities.

Historically, pesticide-related poisoning incidents have posed serious public health challenges in India. The first reported case occurred in 1958 in Kerala, where over 100 individuals died after consuming parathion-contaminated wheat flour. One of the most catastrophic industrial disasters in history, the Bhopal Gas Tragedy, occurred on the night of December 2–3, 1984, when methyl isocyanate (MIC) leaked from a pesticide plant owned by Union Carbide India Limited. This incident resulted in more than 15,000 deaths and affected over 500,000 people, leaving long-term environmental and health consequences.

At the national level, pesticide consumption patterns show significant regional variation. According to recent agricultural statistics (2024–2025), Uttar Pradesh remains the highest pesticide-consuming state, contributing approximately 20–22% of total usage, followed by Maharashtra (~17–19%), Telangana (~8–9%), Punjab (~7–8%), and Haryana (~6–7%) (table- 2). In contrast, northeastern states such as Arunachal Pradesh and Nagaland exhibit minimal pesticide consumption, largely due to lower agricultural intensification (Government of India, 2024) [19]. However, in terms of pesticide use intensity (kg/ha), Jammu & Kashmir (~2.3 kg/ha), Punjab (~1.4 kg/ha), and Haryana (~1.2 kg/ha) rank among the highest.

Although India falls within the lower pesticide consumption category globally (table-3), residues of various pesticides have been consistently reported in major river systems (table-4), including the Ganga and its tributaries (Singh *et al*., 2013; Chakraborty *et al*., 2016; Mondal *et al*., 2018; Khuman *et al*., 2019) [11, 23, 29].

Recent monitoring studies (2020–2024) [2] further confirm the presence of both legacy organochlorine pesticides (OCPs) and newer-generation pesticides in Indian freshwater ecosystems, indicating their persistence and widespread distribution (Sharma *et al*., 2024; Ghafarifarsani *et al*., 2024) [17, 36].

Extensive application of pesticides in agricultural fields along river basins facilitates their transport into aquatic environments through runoff, leaching, and atmospheric deposition. This leads to bioaccumulation of pesticide residues in water, sediments, and aquatic organisms (Holvoet *et al*., 2007 [21]; Takatori *et al*., 2008). Such accumulation poses significant risks to non-target organisms, including fish, invertebrates, and aquatic plants, ultimately disrupting ecological balance (Carriquiriborde *et al*., 2014) [9]. According to reports from the Pesticide Quantification and Risk Surveillance (PQRS, 2017), approximately 72,741 metric tonnes of pesticides were used in the Ganga basin between 2012 and 2017, accounting for nearly 27% of the country's total pesticide consumption.

Historically, organochlorine pesticides were extensively used in India for crop protection, resulting in their long-term persistence in the environment. Despite regulatory restrictions and bans on several such compounds, their residues continue to be detected in aquatic ecosystems due to their high stability and bioaccumulative nature (Singh *et al*., 2012; Chakraborty *et al*., 2016; Mondal *et al*., 2018) [11, 29]. Recent studies highlight that even newer classes of pesticides, including organophosphates and pyrethroids, contribute to aquatic toxicity, raising concerns about sustainable agricultural practices and environmental safety (Sharma *et al*., 2024) [36].

Overall, the current scenario underscores a paradox wherein India's relatively low pesticide consumption per unit area coexists with significant environmental contamination, necessitating improved regulatory frameworks, sustainable pest management strategies, and continuous environmental monitoring.

Table 1: Top pesticide producing and consuming countries in the world

Country	Production (MT/year)	Consumption (MT/year)	Remarks
China	1,600,000–1,800,000	200,000–1,700,000	Largest global producer and major consumer
United States	400,000–450,000	~429,500	Advanced agrochemical industry
Brazil	250,000–300,000	~800,650	Highest consumption globally
India	200,000–250,000	~50,000–60,000	Major producer, moderate consumption
Japan	150,000–180,000	~50,000	High pesticide intensity
Germany	100,000–120,000	~48,000	Strong chemical industry
France	80,000–100,000	~70,500	Leading EU consumer
United Kingdom	60,000–80,000	~20,000	Moderate usage
Italy	70,000–90,000	~56,000	Horticulture-driven demand
South Korea	40,000–60,000	~20,000	High per hectare usage

Table 2: State wise pesticide production and consumption in India

State	Production (MT/year)	Consumption (MT/year)	Status Category	Remarks
Gujarat	120,000–150,000	1,800–2,000	**Production Hub**	Largest agrochemical manufacturing center
Maharashtra	70,000–90,000	6,500–7,000	Production + High Consumption	Cotton belt, strong industry
Telangana	40,000–60,000	4,800–5,000	Production + High Consumption	Cotton & chilli crops
Andhra Pradesh	30,000–50,000	~2,000	Production + Moderate Consumption	Irrigated agriculture
Tamil Nadu	25,000–40,000	~1,500	Production + Moderate Consumption	Diverse cropping
Karnataka	20,000–30,000	~1,800	Emerging Producer	Plantation crops
Uttar Pradesh	15,000–25,000	11,000–12,000	**Highest Consumption**	Largest agricultural state
Punjab	10,000–15,000	~5,100	High Consumption	Intensive rice–wheat system
Haryana	10,000–15,000	~4,000	High Consumption	High input farming
West Bengal	8,000–12,000	~4,000	Moderate Consumption	Humid, pest-prone region
Rajasthan	—	1,800–2,000	Low Production	Arid agriculture
Madhya Pradesh	—	1,200–1,500	Low–Moderate	Expanding soybean cultivation

Table 3: Comparative scenario of pesticide production and consumption in India and world

Parameter	India	Global Scenario	Remarks
Production (MT/year)	200,000–250,000	~3,500,000–4,000,000	India is among top 4 producers globally
Consumption (MT/year)	50,000–60,000	~3,500,000–3,700,000	India contributes ~1–2% of global use
Consumption per hectare (kg/ha)	~0.6	~2.5–3.0	Much lower than global average
Major pesticide type used	Insecticides (~50–60%)	Herbicides dominate globally	Reflects tropical pest pressure
Key crops	Rice, cotton, vegetables	Cereals, soybean, maize	Crop pattern influences usage
Growth trend	Increasing (due to intensification)	Stable to moderately increasing	Shift toward modern agrochemicals
Export status	Major exporter	China dominates global export	India is a leading generic pesticide exporter

Table 4: Use of pesticide, agricultural Drivers, and associated fish toxicity risk zones in India

State	Consumption (MT/year)	Production Status	Major Crops	Associated River Basin / Water Body	Fish Toxicity Risk
Uttar Pradesh	11,000–13,000	Moderate	Rice, wheat, sugarcane	Ganga River basin	Very High (runoff, industrial + agricultural load)
Maharashtra	6,500–8,700	High	Cotton, soybean, fruits	Godavari River basin	High (cotton pesticide runoff)
Punjab	5,000–5,200	Moderate	Rice, wheat	Sutlej River basin	Very High (intensive pesticide use)
Telangana	4,800–5,000	High	Cotton, chilli	Krishna River basin	High (agrochemical runoff)
Haryana	~4,000	Moderate	Rice, wheat	Yamuna River basin	Very High (urban + agricultural pollution)
West Bengal	~4,000	Moderate	Rice, jute, vegetables	Hooghly River	High (deltaic accumulation, runoff)
Andhra Pradesh	~2,000	High	Rice, chilli, cotton	Godavari River & Krishna River deltas	High (aquaculture + agriculture exposure)
Gujarat	~1,800–2,000	Very High	Cotton, groundnut	Gulf of Khambhat	Moderate–High (industrial discharge + runoff)
Rajasthan	~1,800–2,000	Moderate	Mustard, pulses	Chambal River basin	Moderate (lower water availability, dilution effect)
Karnataka	~1,800	Moderate	Coffee, cotton	Cauvery River basin	Moderate–High (plantation runoff)
Tamil Nadu	~1,500	Moderate	Rice, sugarcane	Cauvery River delta	High (irrigation return flow contamination)

Adverse Effects of Pesticide on Fish Health

Pesticides are among the most pervasive contaminants in aquatic ecosystems and pose significant risks to fish health. Their toxicity depends on chemical composition, concentration, persistence, and exposure duration. A positive correlation generally exists between pesticide dose and fish mortality; however, toxicity is also influenced by factors such as uptake rate, environmental conditions, and species-specific sensitivity (Nwani *et al*., 2010; Banaee, 2013; Kumar *et al*., 2023) [5, 25, 32].

Acute Toxicity of Pesticide

Acute toxicity is commonly expressed as LC_{50}, representing the concentration causing 50% mortality in a test population. Several studies have demonstrated variation in LC_{50} values among fish species exposed to pesticides such as cypermethrin, chlorpyrifos, and malathion (Nwani *et al*., 2010; Velisek *et al*., 2011; Kumar *et al*., 2022) [4, 32, 40]. Recent studies highlight that even low concentrations of neonicotinoids and pyrethroids can induce significant mortality in fish (Rashid *et al*., 2022; Ahmad *et al*., 2024) [2, 34].

Behavioural Alterations

Behavioural responses are among the earliest and most sensitive indicators of pesticide toxicity. Fish exposed to pesticides exhibit abnormal swimming, loss of equilibrium, reduced feeding, and erratic movements due to neurotoxicity and acetylcholinesterase (AChE) inhibition (Scott & Sloman, 2004; Nwani *et al*., 2010; Banaee, 2013) [5, 32].

Sublethal exposure to pesticides such as cypermethrin, chlorpyrifos, and dimethoate causes hyperactivity, increased opercular movement, excessive mucus secretion, and surfacing behaviour (Ullah *et al*., 2014 [39]; Nagaraju *et al*., 2011). For example, *Cyprinus carpio* exposed to chlorpyrifos exhibited erratic swimming and respiratory distress (Singh *et al*., 2021) [38]. Similarly, *Oreochromis niloticus* exposed to imidacloprid showed reduced locomotion and stress-induced behavioural changes (Ahmad *et al*., 2024) [2]. These behavioural disruptions increase vulnerability to predation and disease (Gill & Raine, 2014; Kaur *et al*., 2023) [18, 22].

Biochemical and Physiological Changes

Pesticides interfere with metabolic and enzymatic pathways, leading to physiological dysfunction. They impair oxygen consumption either by affecting gill function or altering water quality (Shereena *et al*., 2009; Banaee, 2013) [5].

Enzymatic alterations include inhibition of AChE and changes in metabolic enzymes such as LDH, SDH, and ATPases (Das & Mukherjee, 2003; Velmurugan *et al*., 2007). Elevated levels of liver enzymes (AST, ALT, ALP) indicate hepatotoxicity (Ogueji & Auta, 2007; Banaee *et al*., 2011) [6].

Recent studies emphasize oxidative stress as a key mechanism of toxicity. Increased activities of antioxidant enzymes (SOD, CAT) and lipid peroxidation (LPO) have been reported in fish exposed to pesticides like malathion and glyphosate (Bharti & Rasool, 2021; Zhang *et al*., 2023; Verma *et al*., 2025) [7, 41, 42].

Carbohydrate Metabolism

Glycogen depletion is a common response to pesticide-induced stress, reflecting increased energy demand and hypoxic conditions. Fish utilize glycogen reserves through anaerobic metabolism, resulting in elevated blood glucose levels (Sepici-Dincel *et al*., 2009; Banaee, 2013) [5].

Studies have shown that pesticides such as cypermethrin and dichlorvos significantly alter carbohydrate metabolism in fish species like *Labeo rohita* and *Oreochromis mossambicus* (Das & Mukherjee, 2003; Lakshmanan *et al*., 2013) [27]. Recent findings confirm that pesticide exposure disrupts glucose homeostasis and stress hormone regulation (Patel *et al*., 2022; Singh & Chandra, 2024) [33, 37].

Protein Metabolism

Protein depletion in pesticide-exposed fish indicates increased proteolysis and impaired protein synthesis due to toxic stress. Reduced protein levels in tissues such as liver, muscle, and gills have been widely reported (Muley *et al*., 2007; Banaee, 2013) [5].

Exposure to pesticides such as cypermethrin, endosulfan, and malathion significantly decreases protein content in fish (Ullah *et al*., 2014 [39]; Thenmozhi *et al*., 2011). Recent studies (Kaur *et al*., 2023; Das *et al*., 2025) [13, 22] demonstrate that pesticide-induced proteotoxicity affects cellular integrity and physiological performance.

Haematological Changes

Haematological parameters are reliable indicators of fish health and environmental stress. Pesticide exposure often leads to decreased RBC count, haemoglobin concentration, and packed cell volume, indicating anaemia (Talas & Gulhan, 2009; Banaee *et al*., 2011) [6].

Leucocytosis (increased WBC count) is commonly observed as an adaptive immune response (Joshi & Deep, 2002). Alterations in blood indices such as MCV, MCH, and MCHC reflect disruptions in haematopoiesis (Kumar *et al*., 2004).

Recent studies have reported significant haematological changes in fish exposed to chlorpyrifos, lambda-cyhalothrin, and imidacloprid, confirming immunotoxic effects (Ali *et al*., 2022; Kumar *et al*., 2024) [4, 26].

Histopathological Alterations

Histopathological examination is a reliable and widely used approach for assessing the toxic effects of environmental contaminants in aquatic organisms. Structural alterations in tissues provide clear evidence of cellular damage and help evaluate the severity and chronicity of pesticide exposure. In fish, such alterations can impair vital physiological functions, including growth, metabolism, reproduction, and immune competence (Banaee, 2013; Kaur *et al*., 2023) [5, 22].

Pesticide exposure has been strongly associated with the generation of reactive oxygen species (ROS) and other free radicals, leading to oxidative stress. These reactive molecules disrupt cellular integrity by damaging lipids, proteins, and nucleic acids, ultimately resulting in tissue degeneration and necrosis (Zhang *et al*., 2023; Verma *et al*., 2025) [41, 42]. Organophosphate pesticides, in particular, interfere with cellular proteins through phosphorylation reactions, thereby limiting tissue repair and recovery processes (Ali *et al*., 2022) [4]. Numerous studies have documented pesticide-induced histopathological lesions in various fish organs following exposure to compounds such as diazinon, deltamethrin, fenitrothion, chlorpyrifos, and glyphosate (Velmurugan *et al*., 2017; Rashid *et al*., 2022; Ahmad *et al*., 2024) [2, 34].

These tissue-level changes disrupt physiological homeostasis and may lead to severe health consequences. The major histopathological alterations observed in different fish organs are described below-

Gills: Fish gills are highly specialized organs responsible for respiration, osmoregulation, and excretion. Due to their large surface area and direct contact with water, gills are particularly sensitive to environmental pollutants and are considered effective biomarkers of aquatic toxicity (Mallatt, 1985; Banaee, 2013) [5]. Exposure to pesticides commonly results in structural damage to gill tissues, including epithelial hyperplasia, lamellar fusion, edema, aneurysms, hemorrhages, and necrosis. These alterations impair gas exchange and ionic balance. For instance, deltamethrin exposure has been shown to induce edema, epithelial lifting, and fusion of secondary lamellae in *Cyprinus carpio* (Cengiz *et al*., 2017) [10]. Similarly, chlorpyrifos and glyphosate exposure in *Oreochromis niloticus* leads to mucus hypersecretion, lamellar disorganization, and vascular congestion (Subburaj *et al*., 2015; Zhang *et al*., 2023) [42].

Recent studies (Kumar *et al*., 2022; Ahmad *et al*., 2024) [2, 4] further confirm that pesticide-induced gill damage significantly reduces respiratory efficiency, thereby causing hypoxia and physiological stress in fish.

Liver: The liver is the primary organ for detoxification and metabolism in fish and is highly vulnerable to chemical toxicity. Pesticide exposure often leads to severe hepatic damage, depending on the type and concentration of the toxicant (Banaee, 2013) [5].

Common histopathological changes in the liver include hepatocyte degeneration, cytoplasmic vacuolation, necrosis, hemorrhage, and nuclear abnormalities such as pyknosis and karyolysis. Exposure to pesticides like chlorpyrifos, carbofuran, and cypermethrin has been reported to cause ruptured hepatocytes, cirrhosis-like conditions, and hydropic degeneration in species such as *Oreochromis niloticus* and *Cyprinus carpio* (Velmurugan *et al*., 2017; Rashid *et al*., 2022) [34].

Recent findings (Kaur *et al*., 2023; Verma *et al*., 2025) [22, 41] highlight that pesticide-induced oxidative stress is a major contributor to hepatocellular damage, resulting in impaired detoxification and metabolic dysfunction.

Kidney: The kidney plays a crucial role in osmoregulation, excretion, and maintenance of internal homeostasis. Histopathological examination of renal tissues provides valuable insights into environmental contamination and toxic stress (Ali *et al*., 2022) [4].

Pesticide exposure induces a range of pathological changes in the kidney, including glomerular hypertrophy, tubular degeneration, necrosis, hemorrhage, and vacuolation. For example, diazinon exposure has been reported to cause glomerular damage and renal hemorrhage in *Clarias gariepinus* (Al-Otaibi *et al*., 2019) [3]. Similarly, cypermethrin exposure leads to degeneration of renal tubules and nuclear disintegration in freshwater fish (Velmurugan *et al*., 2017).

Recent studies (Kumar *et al*., 2024; Ahmad *et al*., 2024) [2, 26] demonstrate that chronic pesticide exposure severely impairs renal function, affecting osmoregulation and waste elimination.

Intestine: The intestine is essential for digestion and nutrient absorption, and its structural integrity is critical for fish health. Pesticides can disrupt intestinal architecture, leading to impaired digestive efficiency.

Histological alterations in the intestine include degeneration of epithelial cells, disruption of mucosal layers, villi deformation, necrosis, and inflammatory infiltration. Exposure to pesticides such as fenvalerate, lindane, and chlorpyrifos has been shown to cause villi fusion, epithelial erosion, and hemorrhage in species like *Cirrhinus mrigala* and *Channa punctatus* (Velmurugan *et al*., 2017; Rashid *et al*., 2022) [34].

Recent investigations (Singh & Chandra, 2024; Das *et al*., 2025) [13, 37] indicate that these structural changes significantly reduce nutrient absorption, leading to poor growth and weakened physiological performance.

Gonads: Pesticide toxicity has profound effects on fish reproductive systems, leading to impaired fertility and population decline. Both male and female gonads exhibit significant histopathological alterations under pesticide exposure.

In testes, common abnormalities include reduced sperm count, degeneration of spermatocytes, vacuolation, and structural disruption of seminiferous tubules. In ovaries, pesticide exposure leads to oocyte degeneration, irregular yolk formation, follicular atresia, and cytoplasmic disorganization (Banaee *et al*., 2011; Ullah *et al*., 2014) [6, 39].

Recent studies (Kaur *et al*., 2023; Verma *et al*., 2025) [22, 41] have demonstrated that pesticides such as cypermethrin and diazinon cause severe reproductive toxicity, including disruption of gametogenesis and hormonal imbalance. These alterations ultimately result in reduced fecundity, poor egg quality, and decreased survival of embryos and larvae.

Genotoxic Effects

Pesticides constitute a significant class of environmental genotoxins capable of compromising genomic stability in aquatic organisms. In fish, exposure to these chemicals induces a spectrum of genetic alterations, including DNA strand breaks, chromosomal aberrations, point mutations, and carcinogenic transformations, ultimately impairing physiological performance, reproductive success, and survival. A central mechanism driving these effects is the excessive generation of reactive oxygen species (ROS), which leads to oxidative damage of nucleic acids, proteins, and cellular membranes (Banaee, 2013; Zhang *et al*., 2023; Verma *et al*., 2025) [5, 41, 42].

Among the available biomarkers, the micronucleus (MN) assay is extensively utilized due to its sensitivity and reliability in detecting chromosomal damage. Micronuclei originate from acentric chromosomal fragments or lagging chromosomes that fail to be incorporated into daughter nuclei during mitosis. The occurrence of additional nuclear abnormalities, such as nucleoplasmic bridges and nuclear buds, further reflects chromosomal instability and defective DNA repair processes (Fenech *et al*., 2011; Ali *et al*., 2022) [4, 14].

Complementary approaches, including comet assay and chromosomal aberration analysis, provide insights into DNA strand breaks and mutagenic potential. Recent investigations have demonstrated that pesticides such as chlorpyrifos, cypermethrin, and imidacloprid significantly elevate genotoxic damage in fish species like Cyprinus carpio and Oreochromis niloticus, indicating impaired DNA repair capacity and increased genomic instability (Ahmad *et al*., 2024; Kumar *et al*., 2024) [2, 26]. Collectively, these findings underscore the utility of fish as sentinel organisms for assessing pesticide-induced genetic hazards in aquatic ecosystems.

Conclusion

Pesticide pollution represents a significant hazard to aquatic ecosystems, particularly affecting fish as sensitive non-target organisms. These chemicals enter water bodies mainly through runoff and leaching, where they accumulate in fish tissues and produce a range of toxic effects. Exposure can lead to alterations in behavior, physiology, biochemical processes, blood parameters, tissue structure, reproduction, and genetic integrity. Even at low concentrations, pesticides can disrupt essential biological functions, reducing fish survival and threatening ecological stability.

In addition, the movement of pesticide residues through the food chain poses potential risks to human health. Therefore, it is crucial to implement strict regulatory measures, ensure regular environmental monitoring, and promote the use of safer, environmentally friendly alternatives to reduce the harmful impacts of pesticides and protect aquatic life.

References

1. Adams E, Smith J, Clarke R. Acute fish toxicity testing in pesticide risk assessment: Relevance and future perspectives. Environmental Sciences Europe,2025:37:117.
2. Ahmad Z, Khan MA, Ali S. Genotoxic and physiological responses of freshwater fish to imidacloprid exposure. Environmental Toxicology and Pharmacology,2024:102:104243. https://doi.org/10.1016/j.etap.2024.104243
3. Al-Otaibi AM, Al-Balawi HF, Ahmad Z. Toxicological impact of diazinon on fish kidney. Saudi Journal of Biological Sciences,2019:26:146–152.
4. Ali D, Nagpure NS, Kumar S, Kumar R, Kushwaha B. Genotoxicity assessment of chlorpyrifos in freshwater fish using micronucleus and comet assay. Chemosphere,2022:287:132263. https://doi.org/10.1016/j.chemosphere.2021.132263
5. Banaee M. Physiological dysfunction in fish after exposure to pesticides. Ecotoxicology,2013:22(1):132–141. https://doi.org/10.1007/s10646-012-1020-1
6. Banaee M, Sureda A, Mirvaghefi AR, Ahmadi K. Effects of diazinon on biochemical parameters of fish. Pesticide Biochemistry and Physiology,2011:99:1–6. https://doi.org/10.1016/j.pestbp.2010.09.001
7. Bharti S, Rasool F. Analysis of oxidative stress biomarkers in fish exposed to malathion. Environmental Science and Pollution Research,2021:28:12345–12354.
8. Burch E, Johnson M, Patel D. Assessing the effects of pesticides on aquacultured fish: Mechanisms and ecological implications. Fishes,2025:10(5):223. https://doi.org/10.3390/fishes10050223
9. Carriquiriborde P, Díaz J, Mugni H, Bonetto C, Ronco A. Impact of pesticides on aquatic ecosystems. Ecotoxicology,2014:23(5):811–828. https://doi.org/10.1007/s10646-014-1234-9
10. Cengiz EI, Unlu E, Balci K. Histopathological changes in fish exposed to deltamethrin. Environmental Toxicology,2017:32:120–128.
11. Chakraborty P, Sarkar A, Vudamala K, Naik R, Nath BN. Organic pesticide residues in Ganga river water. Environmental Monitoring and Assessment,2016:188:1–12.
12. Cosgrove S, Jefferson B, Jarvis P, Parsons SA. Pesticide removal from drinking water sources: A review. Water Research,2019:139:294–305. https://doi.org/10.1016/j.watres.2018.12.048
13. Das S, Gupta R, Singh A. Tissue-level toxicity of pesticides in freshwater fish. Aquatic Toxicology,2025:267:106789.
14. Fenech M, Kirsch-Volders M, Natarajan AT, Surrallés J, Crott JW, Parry J, et al. Molecular mechanisms of micronucleus formation and application in genotoxicity testing. Mutation Research,2011:705(2):71–97. https://doi.org/10.1016/j.mrrev.2010.07.001
15. Food and Agriculture Organization. FAOSTAT statistical database: Pesticides use. Food and Agriculture Organization, 2023. https://www.fao.org/faostat/
16. Gerber R, Ngidi M, Mthembu S. Human health risks associated with pesticide residues in food. Food Control,2016:70:1–8.
17. Ghafarifarsani H, Rahimi R, Karimi A. Pesticides and heavy metal toxicity in fish and possible mitigation strategies: A review. Archives of Animal Breeding and Sciences,2024:68:1–18.
18. Gill TS, Raine JC. Pesticide-induced immunotoxicity in fish. Fish Physiology and Biochemistry,2014:40:123–134.
19. Government of India. Agricultural statistics at a glance 2024. Ministry of Agriculture & Farmers Welfare, 2024.
20. Gupta PK. Pesticide exposure—Indian scene. Toxicology,2004:198(1–3):83–90.
21. Holvoet KMA, Seuntjens P, Vanrolleghem PA. Monitoring and modeling pesticide fate in surface waters. Agricultural Water Management,2007:86:1–10.
22. Kaur R, Kaur M, Singh H. Pesticide-induced genotoxicity and oxidative stress in freshwater fish: A review. Ecotoxicology and Environmental Safety,2023:252:114560.
23. Khuman SN, Chakraborty P, Cincinelli A. Pesticide contamination in Indian rivers. Environmental Science and Pollution Research,2019:26:1–15.
24. Kumar A, Singh V, Pandey A. Acute toxicity of pesticides on freshwater fish. Journal of Environmental Biology,2022:43:567–574.
25. Kumar R, Sharma P, Gupta N. Ecotoxicological effects of pesticide residues in aquatic systems. Environmental Monitoring and Assessment,2023:195:876.
26. Kumar S, Verma A, Tripathi M. Evaluation of DNA damage and haematological alterations in fish exposed to pesticide mixtures. Environmental Toxicology,2024:39:1123–1132.
27. Lakshmanan S, Rajendran K, Krishnan M. Effect of dichlorvos on biochemical changes in fish. International Journal of Fisheries and Aquatic Studies,2013:1:45–49.
28. Mahmood I, Imadi SR, Shazadi K, Gul A, Hakeem KR. Effects of pesticides on environment. Plant, soil and microbes, 2016, 253–269.

29. Mondal R, Das S, Mukherjee A. Organochlorine pesticide residues in aquatic ecosystems. Environmental Science and Pollution Research,2018:25:1–12.
30. Morrison K, Lee C, Brown P. Effects of pesticide exposure on fish social behaviour: A meta-analysis. Environmental Pollution, 2025.
31. Moezzi SA, Hosseini SM, Rezaei M. Mechanisms of pesticide toxicity in fish: Insights into oxidative stress and mitigation strategies. Aquatic Toxicology Reports, 2025.
32. Nwani CD, Lakra WS, Nagpure NS, Kumar R, Kushwaha B, Srivastava SK. Toxicity of cypermethrin in fish. Toxicology and Industrial Health,2010:26:215–221.
33. Patel V, Shah D, Patel H. Metabolic stress responses in fish under pesticide exposure. Environmental Science and Pollution Research,2022:29:44567–44578.
34. Rashid M, Ahmad I, Khan M. Toxic effects of neonicotinoids on freshwater fish. Chemosphere,2022:287:132345.
35. Saaristo M, et al. Behavioural and ecological consequences of pesticide exposure in aquatic organisms. Biological Reviews,2020:95:1605–1624.
36. Sharma AK, Verma P, Singh R. Advances in aquatic toxicology. Science of the Total Environment,2024:907:167789.
37. Singh A, Chandra R. Endocrine disruption in fish under pesticide stress. Aquatic Toxicology,2024:260:106567.
38. Singh R, Kumar P, Singh S. Behavioural toxicity of chlorpyrifos in fish. Journal of Applied Ichthyology,2021:37:789–795.
39. Ullah S, Li Z, Hassan W, Zorriehzahra MJ. Pesticides induced oxidative stress in fish. Environmental Science and Pollution Research,2014:21:256–265.
40. Velisek J, Svobodova Z, Piackova V. Effects of pesticides on fish. Acta Veterinaria Brno,2011:80:221–227.
41. Verma P, Singh D, Yadav K. Oxidative stress-mediated genotoxic effects in fish. Environmental Research,2025:245:117123.
42. Zhang Y, Liu X, Wang J. Oxidative DNA damage in fish exposed to pesticides. Science of the Total Environment,2023:857:159456.