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(Review Article)

Mercury (Hg) induced toxicity in freshwater fish: A comprehensive review

Anand Kumar * and Veena P. Swami

Department of Zoology, B.S.N.V.P.G. College (Lucknow University), Lucknow-226001, (U.P.), India

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Abstract

Mercury (Hg) is a persistent pollutant in aquatic environments that poses severe risks to freshwater fish. Among its various forms, methylmercury (MeHg) is the most toxic, highly bioavailable, and prone to bioaccumulation. Exposure to mercury alters antioxidant enzyme function, elevates lipid peroxidation, and disrupts metabolic processes, ultimately impairing growth and immunity. At the behavioural level, affected fish display changes in locomotion, feeding, predator evasion, and reproductive activity. Histopathological investigations reveal significant tissue damage in the gills, liver, kidney, and gonads, compromising organ functionality. Additionally, mercury interferes with endocrine regulation, causing hormonal imbalance, reduced gamete quality, diminished fertility, and abnormalities in offspring development. Collectively, these toxic effects threaten individual health, population stability, and ecosystem resilience. Current studies (2020–2025) emphasize the urgent need for systematic monitoring of mercury contamination and mechanistic understanding of its toxic impacts to safeguard freshwater biodiversity.

Keywords: Mercury Toxicity; Oxidative Stress; Behavioural Disruption; Haematology Histopathology; Reproductive and Genetic Effects

1. Introduction

Mercury (Hg) is a naturally occurring heavy metal with long environmental persistence and high toxicity. Human activities such as industrial discharges, coal combustion, mining, agriculture, and poor waste management have significantly increased mercury loading in aquatic systems (Zulkipli et al., 2021). In freshwater environments, mercury occurs in several chemical forms, but inorganic mercury (Hg^{2+}) and methylmercury (MeHg) are particularly relevant due to their high toxicity and ecological mobility. Microbial conversion of inorganic Hg into MeHg makes the latter especially dangerous, as it readily accumulates and magnifies through aquatic food webs (Jeong et al., 2024).

Fish are highly vulnerable to Hg because of their direct interaction with contaminated sediments, water, and prey. Sublethal exposure impairs metabolic pathways, induces oxidative stress, and weakens immune responses (Chen et al., 2022). At higher concentrations, mercury damages essential organs such as the liver, kidney, gills, and gonads, resulting in functional impairments. Beyond physiology, mercury targets the nervous system, altering locomotion, foraging, social behaviour, and predator evasion (Vieira et al., 2023). Reproductive disruption is another critical outcome, involving hormonal changes, poor gametogenesis, reduced fertility, and abnormal reproductive behaviour (Mishra et al., 2023).

Given these complex and multi-level impacts, mercury is considered a major ecological stressor. Understanding how Hg affects biochemical, behavioural, histological, and reproductive endpoints in fish is essential for environmental monitoring and ecological risk assessment. Recent findings (2020–2025) have expanded our knowledge of mercury's mechanistic toxicity, underscoring the importance of integrated approaches to conserve freshwater biodiversity.

* Corresponding author: Anand Kumar.

This review synthesizes current evidence on mercury's impact on fish health, focusing on biochemical responses, behavioural impairments, tissue pathology, and reproductive consequences. It also highlights genotoxicity, ecological risks, and mitigation strategies to provide a comprehensive perspective on mercury toxicity in freshwater ecosystems.

1.1. Sources of Mercury Exposure in Fish

Mercury enters aquatic ecosystems from natural sources such as volcanic activity and weathering of rocks, and predominantly from anthropogenic sources including coal-fired power plants, mining, industrial effluents, waste incineration, and improper disposal of mercury-containing products (Tchounwou et al., 2012; Driscoll et al., 2013). The various sources of mercury pollution is briefly presented in figure-1.

Atmospheric deposition is a major pathway by which mercury reaches water bodies. In aquatic environments, inorganic mercury is converted by microorganisms into methylmercury, a highly toxic form that bioaccumulates plankton and biomagnifies in fish through the food chain (Clarkson & Magos, 2006; Wiener et al., 2003).

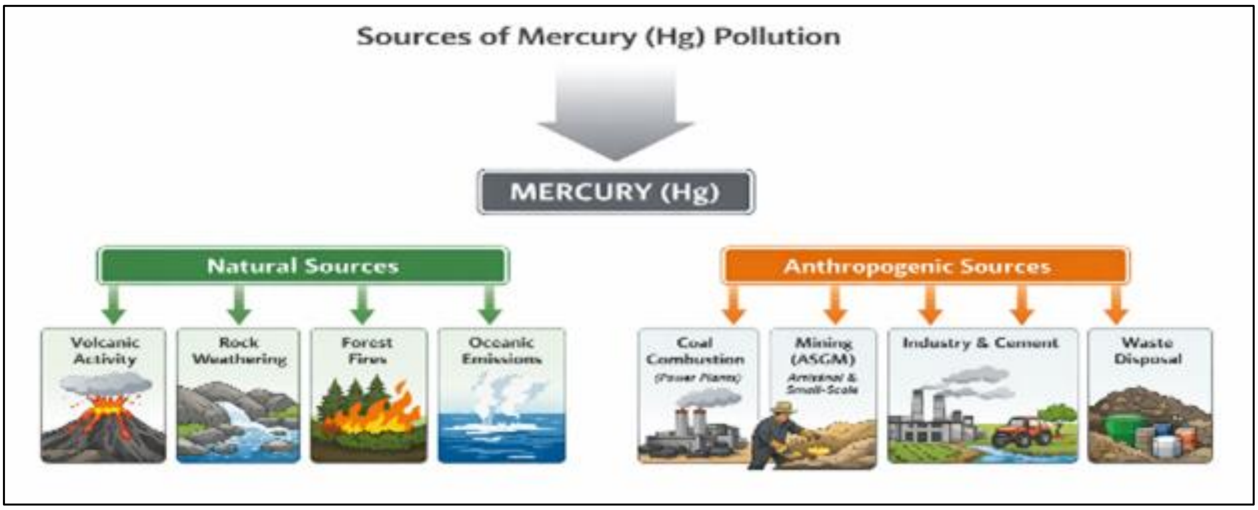

Figure 1 Sources of Hg pollution in aquatic ecosystem

1.2. Bioaccumulation and Food Web Transfer

Mercury enters fish primarily through gill absorption, sediment ingestion, and consumption of contaminated prey. Concentrations of Hg in tissues rise with age, size, and trophic status. Predators at higher trophic levels show the greatest mercury burdens, highlighting the role of biomagnification in aquatic food webs (Sinclair et al., 2024). The bioaccumulation and food web transfer of Hg illustrated in figure - 2.

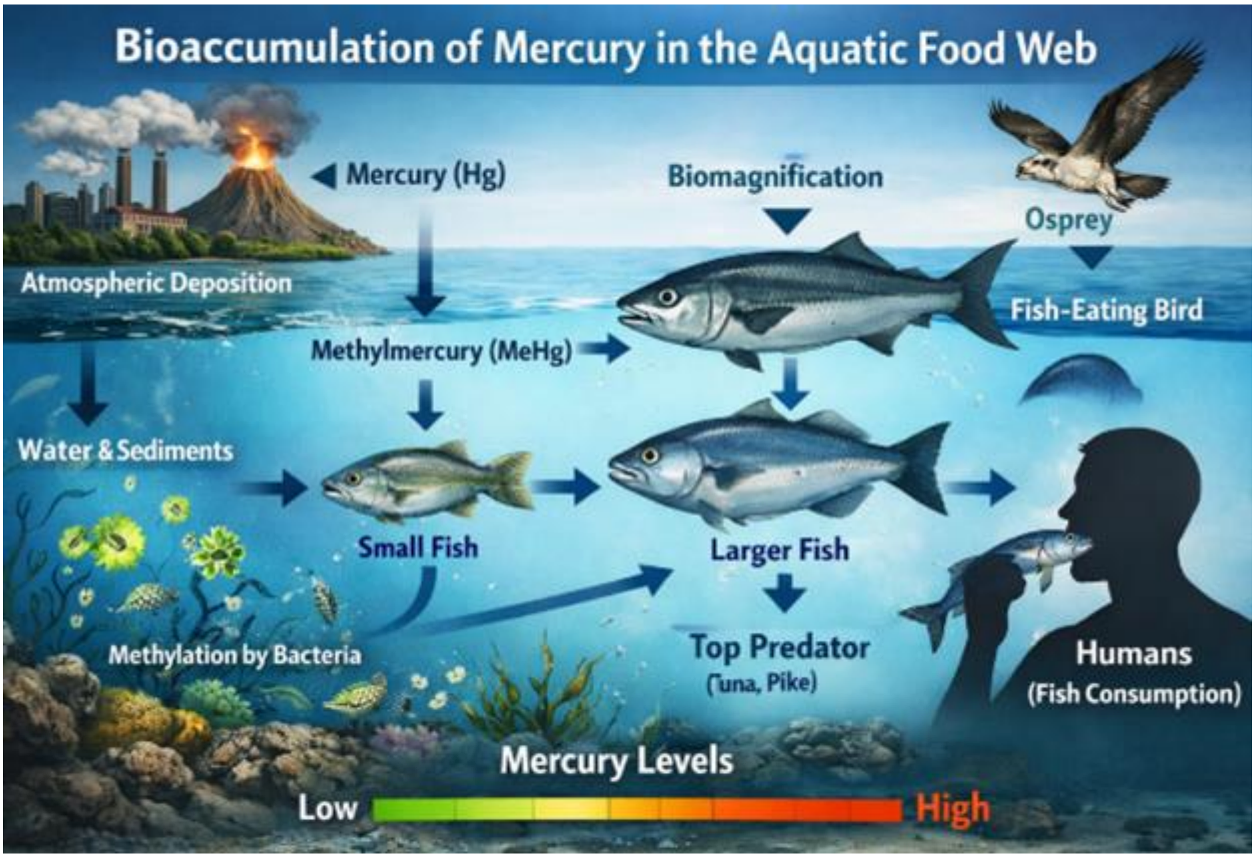

Figure 2 Bioaccumulation of Hg in different trophic levels

1.3. Toxicological Mechanisms

The toxic action of mercury involves several interconnected processes:

- ***Enzyme inhibition:*** Hg binds to sulfhydryl groups, altering protein conformation and enzymatic activity.
- ***Oxidative stress:*** Excess reactive oxygen species (ROS) trigger lipid peroxidation, DNA injury, and protein oxidation (Chen et al., 2022).
- ***Mitochondrial dysfunction:*** Mercury impairs ATP synthesis, disrupting cellular energy metabolism.
- ***Neurotoxicity***: MeHg interferes with neurotransmitter systems, leading to motor deficits and behavioural changes (Jeong et al., 2024). The overall toxicological mechanisms illustrated in figure 3.

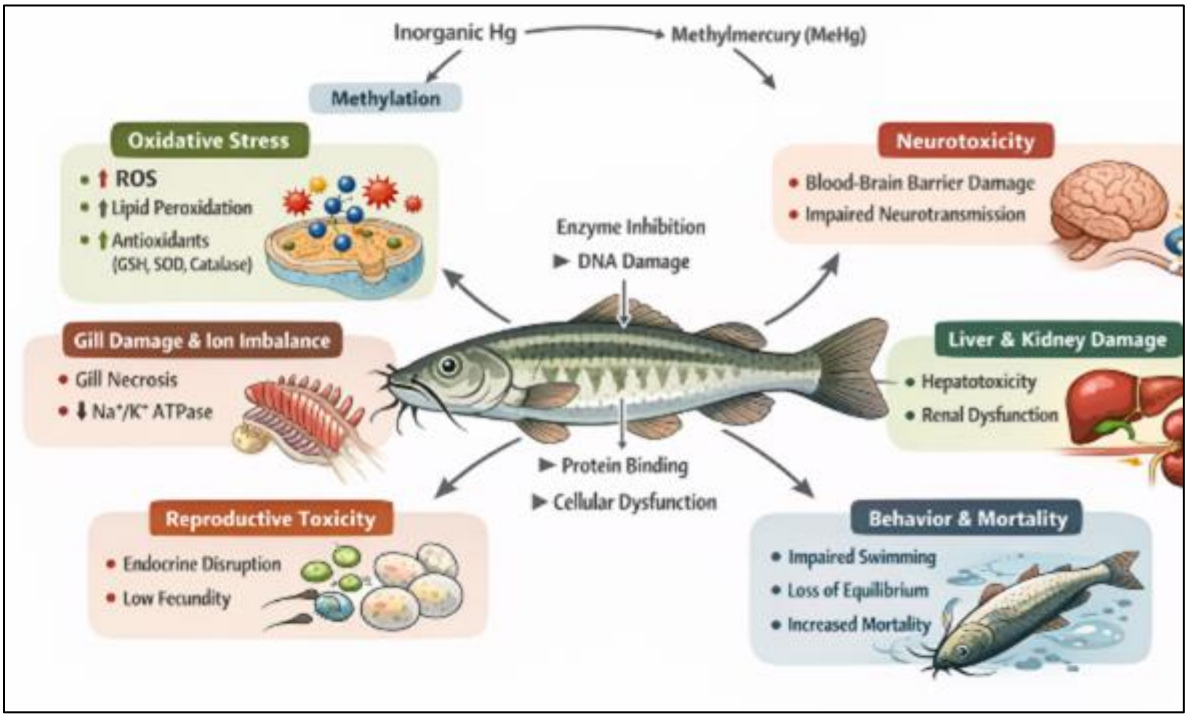

Figure 3 Toxicological Mechanisms of Hg in Fish

1.4. Behavioural Alterations

Mercury exposure alters multiple behavioural endpoints critical for fish survival and reproduction.

- Locomotion: Fish often show erratic swimming, loss of balance, and reduced exploratory behaviour. Glazer et al. (2021) reported impaired coordination in fish exposed to MeHg during early development.
- Feeding: Hg impairs sensory and neuromuscular functions, reducing prey capture and feeding efficiency (Ye et al., 2021).
- Predator avoidance: Hg-exposed fish react more slowly to threats and have reduced escape capacity, increasing predation risk (Vieira et al., 2023).
- Social behaviour: Chronic Hg contamination disrupts schooling and group interactions, affecting foraging and defense strategies (Vieira et al., 2023).
- Reproductive behaviour: Courtship, nest building, and parental care are diminished, reducing reproductive success (Blanchfield et al., 2022).

1.5. Biochemical Disruptions

Oxidative stress is a hallmark of mercury exposure in fish. Enzymatic antioxidants such as superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx) decline, while malondialdehyde (MDA) levels increase (Chen et al., 2022).

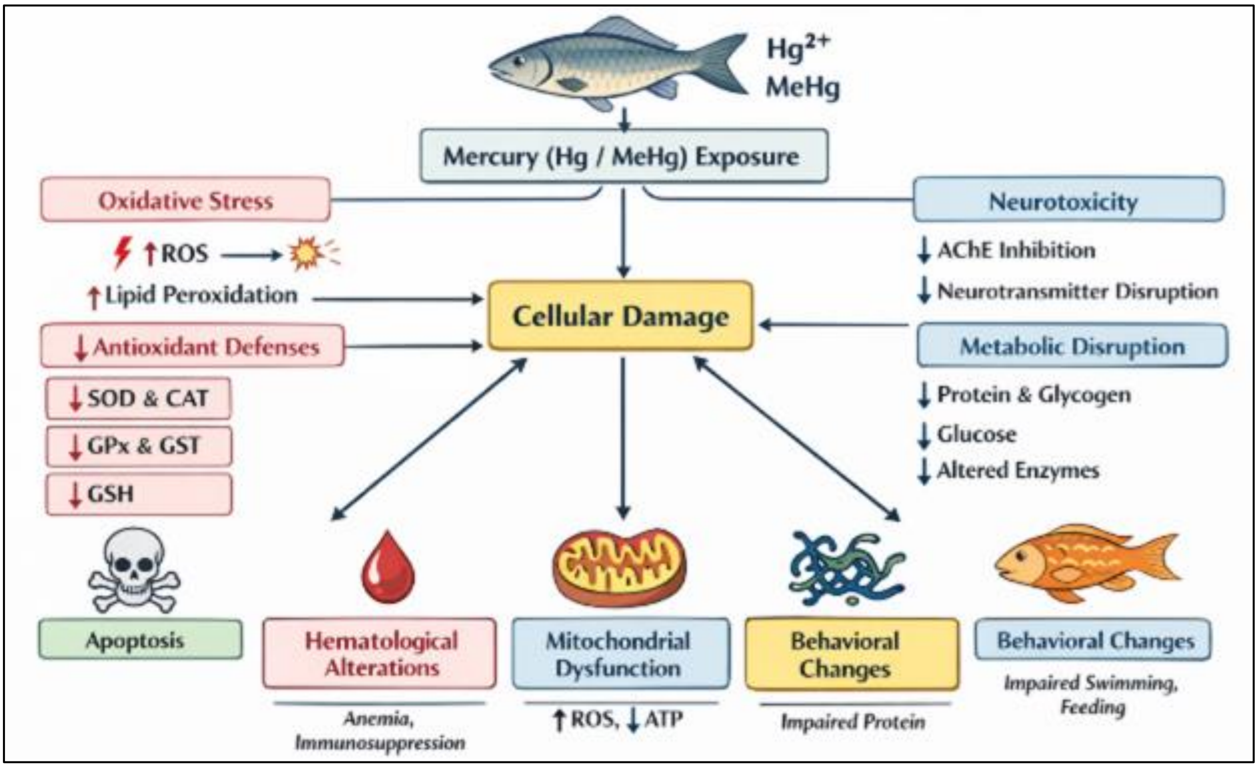

Figure 4 Effects of Hg on fish biochemical

Hg also interferes with energy metabolism, alter glucose and glycogen profiles in *Clarias batrachus* suggest disrupted carbohydrate utilization (Mishra et al., 2023). Sultana et al. (2022) reported abnormal protein and cholesterol levels indicate liver dysfunction. Jeong et al. (2024) suggested that the MeHg inhibits acetylcholinesterase (AChE) which leading to impaired neurotransmission and behaviour (Fig. 4)

1.6. Hematological alterations

Mercury (Hg) exposure induces profound and consistent alterations in the hematological profile of fish (fig. 5), reflecting systemic toxicity and physiological stress. Sublethal and chronic Hg exposure typically results in a significant reduction in red blood cell (RBC) count, hemoglobin (Hb) concentration, and hematocrit (Hct), indicating the development of anemia due to oxidative damage–mediated hemolysis, inhibition of erythropoiesis in hematopoietic tissues, and interference with haemoglobin synthesis through Hg binding to sulfhydryl groups (–SH) (Shaw & Handy, 2011; Mishra et al., 2023). Mercury-generated reactive oxygen species compromise erythrocyte membrane integrity, leading to increased fragility and morphological abnormalities such as echinocytes, spherocytes, nuclear degeneration, and cellular lysis (Jeong et al., 2024). Alterations in erythrocyte indices, including decreased mean corpuscular haemoglobin (MCH) and mean corpuscular haemoglobin concentration (MCHC), along with variable changes in mean corpuscular volume (MCV), further suggest the occurrence of hypochromic and macrocytic or microcytic anemia depending on exposure duration and concentration (Zulkipli et al., 2021). White blood cell (WBC) counts often increase during acute Hg exposure as part of an inflammatory and stress-induced immune response, characterized by elevated neutrophils and monocytes, while prolonged exposure may lead to leukopenia and lymphopenia due to immunosuppression and damage to hematopoietic organs such as the kidney and spleen (Sultana et al., 2022). Collectively, these haematological disturbances impair oxygen transport, immune competence, and overall physiological performance, establishing blood parameters as sensitive and reliable biomarkers for assessing mercury toxicity in fish under laboratory and field conditions (Shaw & Handy, 2011; Jeong et al., 2024).

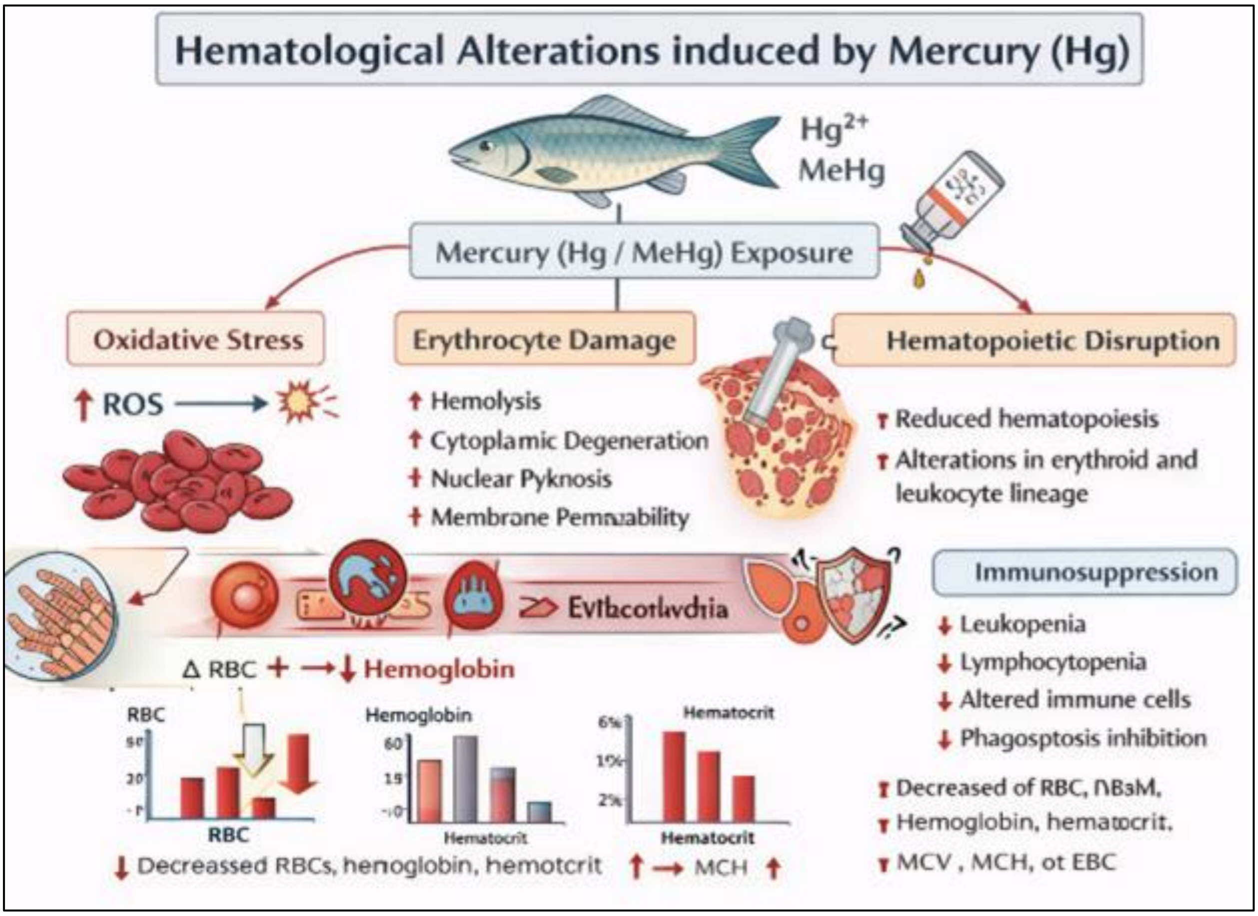

Figure 5 Exposure of Hg alters blood profile of fish

1.7. Histopathological Alterations

Hg exposure causes characteristic lesions across vital fish organs discuss below and illustrated in figure 6.

- ***Gills***: Hyperplasia, lamellar fusion, necrosis, and aneurysms impair respiration and osmoregulation (Mishra et al., 2023).
- ***Liver***: Vacuolization, nuclear degeneration, lipid build-up, and necrosis weaken detoxification capacity (Zulkipli et al., 2021)
- ***Kidney***: Renal tubule damage, glomerular shrinkage, and inflammation reduce excretory efficiency (Sultana et al., 2022).
- ***Muscle and brain***: Muscle fibre degeneration and brain vacuolization correlate with poor growth and neurobehavioral deficits (Jeong et al., 2024).

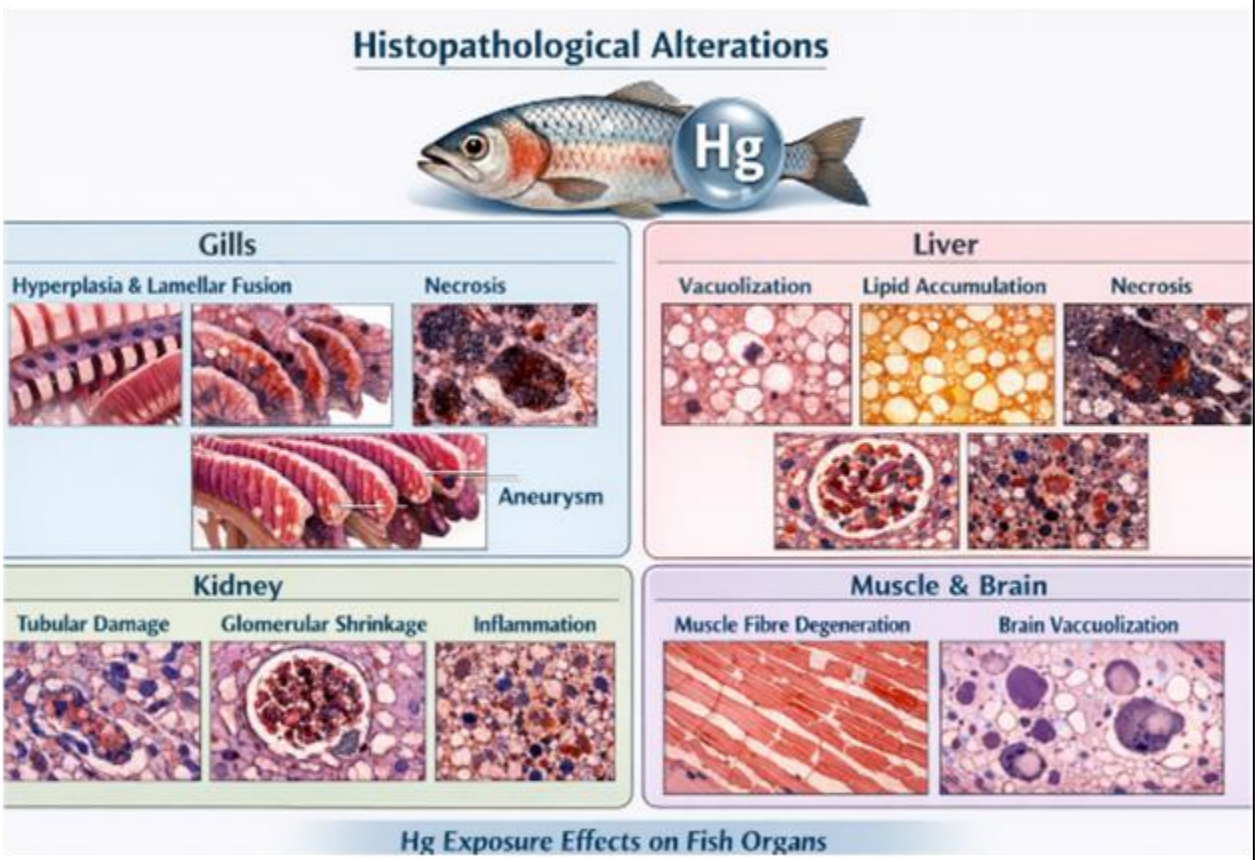

Figure 6 Hg exposure induces histopathological changes in fish

1.8. Genotoxicity

Mercury is strongly genotoxic, producing DNA strand breaks, chromosomal aberrations, and micronuclei formation. Comet assays and micronucleus tests in *Clarias batrachus, Oreochromis niloticus*, and *Danio rerio* confirm elevated DNA fragmentation in Hg-exposed fish (Patil et al., 2021; Singh et al., 2022). The genotoxic effects of Hg exposure are briefly summarize in figure 7.

Oxidative stress amplifies DNA injury through base modifications and crosslinking (Zulkipli et al., 2021). Genetic damage in germ cells threatens reproductive success and reduces population fitness (Jeong et al., 2024).

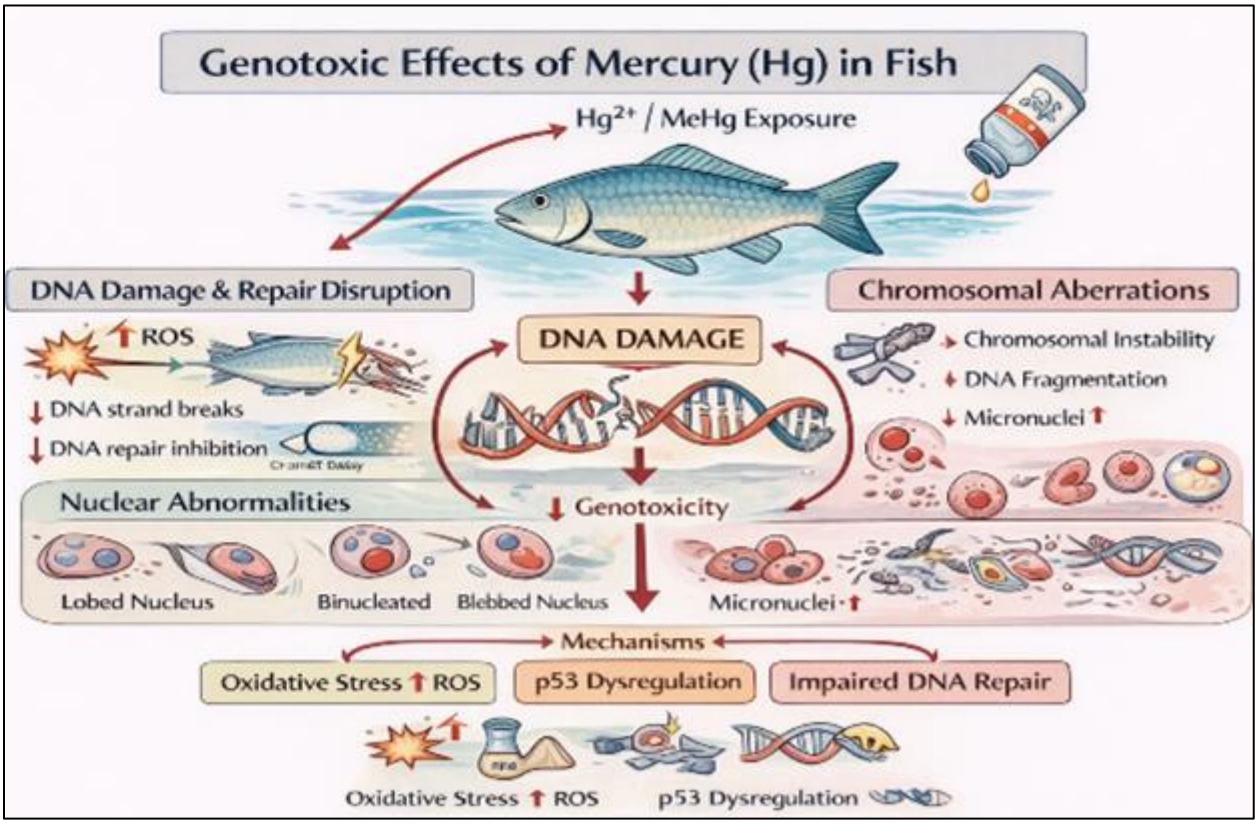

Figure 7 Hg pollution induced genotoxic effects in fish

1.9. Reproductive and Developmental Effects

Mercury severely compromises fish reproduction:

- ***Males***: Testes show vacuolization, necrosis, and disrupted spermatogenesis, leading to reduced sperm density and motility (Mishra et al., 2023).
- ***Females***: Oocytes undergo degeneration, atresia, and irregular follicular development. Vitellogenin synthesis is reduced, producing smaller, less viable eggs (Jeong et al., 2024).
- ***Hormonal disruption****:* Altered plasma testosterone and estradiol levels interfere with sexual maturation and spawning.
- ***Transgenerational effects****:* Poor gamete quality leads to low hatching success, deformities, and juvenile mortality (Patil et al., 2021). All affected reproductive parameters are summarized in figure 8.

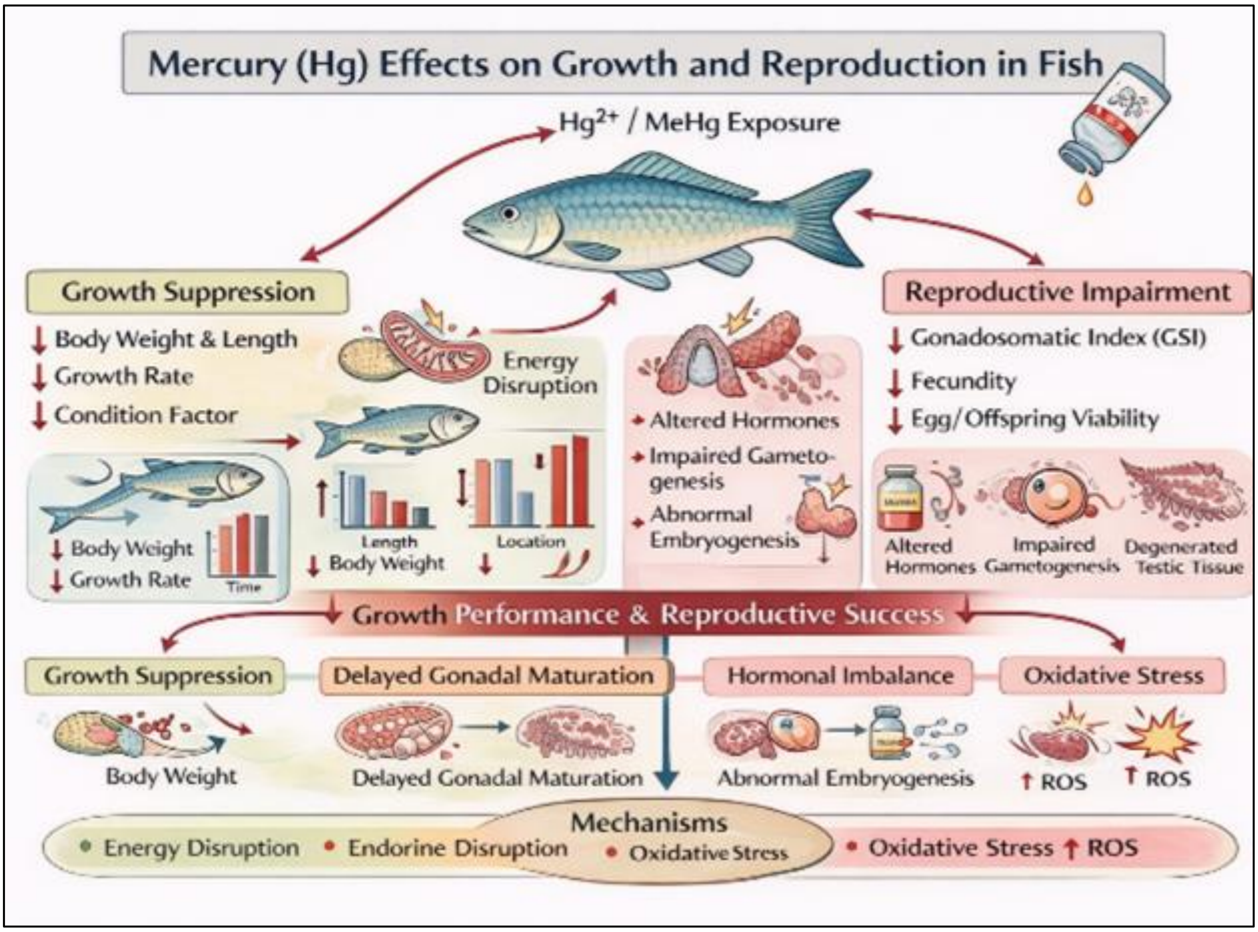

Figure 8 Adverse effects of Hg pollution on fish reproduction

Table 1 Summary of Effects of Mercury (Hg) on Fish at Multiple Biological Levels

Toxicity Level	Fish Species	Hg Exposure	Observed Effects / Parameters	References
Behavioral	*Clarias batrachus*, *Oreochromis niloticus*, *Danio rerio*	0.01–0.5 mg/L (waterborne)	Erratic swimming, loss of equilibrium, reduced feeding, increased surface gulping, hypoactivity, impaired predator avoidance	Shaw & Handy (2011); Mishra et al. (2023)
Biochemical	*Cyprinus carpio*, *Labeo rohita*, *Oreochromis mossambicus*	0.05–1.0 mg/L	Increased lipid peroxidation (MDA), decreased antioxidant enzymes (SOD, CAT, GPx), altered glucose, protein and lipid metabolism, elevated cortisol	Zulkipli et al. (2021); Sultana et al. (2022)
Hematological	*Clarias gariepinus*, *Channa punctatus*, *Danio rerio*	0.01–0.3 mg/L	Decreased RBC, Hb, Hct; altered MCV, MCH, MCHC; leukocytosis or leukopenia; lymphopenia; erythrocyte deformities	Shaw & Handy (2011); Jeong et al. (2024)
Histopathological	*Labeo rohita*, *Oreochromis niloticus*, *Clarias batrachus*	0.05–1.0 mg/L	**Gills:** lamellar fusion, hyperplasia, necrosis, aneurysm; **Liver:** vacuolization, lipid accumulation, nuclear degeneration, necrosis; **Kidney:** tubular degeneration, glomerular shrinkage;	Zulkipli et al. (2021); Mishra et al. (2023); Sultana et al. (2022)

			Brain/Muscle: vacuolization, fiber degeneration	
Genotoxicity	*Danio rerio*, *Channa punctatus*, *Cyprinus carpio*	0.005–0.2 mg/L	DNA strand breaks (comet assay), micronuclei formation, nuclear abnormalities, chromosomal aberrations, oxidative DNA damage	Jeong et al. (2024); Witeska et al. (2014)

1.10. Ecological and Human Health Risks

Mercury contamination alters aquatic food webs and reduces biodiversity. For humans, consumption of contaminated fish poses risks of neurological damage, cardiovascular problems, and immune suppression (Sinclair et al., 2024).

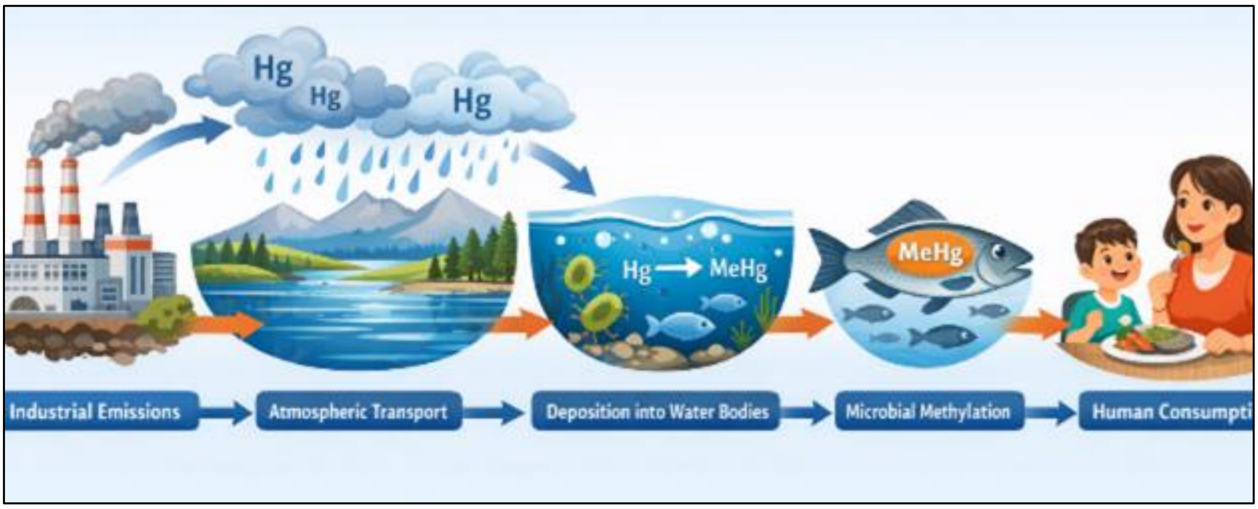

Figure 9 Transfer of Hg via aquatic food chain to human beings

1.11. Biomarkers and Monitoring

A combination of biochemical, histological, and ecological markers provides effective monitoring tools. Antioxidant enzyme activity, lipid peroxidation levels, histopathological lesions, and stable isotope analysis can together assess Hg exposure and ecological risks (Sinclair et al., 2024).

2. Conclusion

Mercury contamination remains a pressing challenge to freshwater ecosystems. Its toxicological impacts span from biochemical disruptions and organ damage to impaired reproduction and genetic alterations. These effects not only reduce fish health but also threaten biodiversity and human well-being. Effective management requires integrating biomarker-based monitoring with strict regulatory measures, emission reduction, and ecological restoration to protect aquatic systems and public health.

Compliance with ethical standards

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Disclosure of conflict of interest

There is no conflicts of interest

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