Genotoxic Effects of Pollution on Different Fish Species

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Abstract

Aquatic ecosystems are critical indicators of environmental health, yet they are increasingly threatened by anthropogenic pollution. Industrial discharges, agricultural runoff, urbanization, and improper waste management introduce pollutants such as heavy metals, pesticides, polycyclic aromatic hydrocarbons (PAHs), pharmaceuticals, and microplastics into water bodies. These contaminants induce genotoxic effects in fish, key bioindicators of aquatic health, leading to DNA damage, oxidative stress, and chromosomal abnormalities. Such effects compromise fish reproduction, growth, and population sustainability, posing significant ecological risks. This mini-review explores the primary sources of aquatic pollutants, their mechanisms of genotoxicity, and documented impacts on fish species. Understanding the interplay between pollution and genotoxicity is essential for safeguarding aquatic biodiversity and ensuring the resilience of freshwater ecosystems.

Key Words: Genetic damage, Pollution, Aquatic environment, Fish

Introduction

The health of aquatic habitat is intrinsically connected to environmental quality, serving as a critical indicator of the pollution in natural water bodies. With the intensification of manmade activities, i.e., industrial discharge, urban expansion, and improper waste management, a varied array of chemical pollutants is being released into air water and soil (Rana et al., 2023). These contaminants include heavy metals like mercury, cadmium, and lead, pesticides and herbicides such as organophosphates and carbamates, polycyclic aromatic hydrocarbons (PAHs) from oil spills and combustion processes, pharmaceuticals, endocrine-disrupting compounds, and microplastics derived from plastic waste. Once in aquatic ecosystems, these pollutants persist, bioaccumulate, and often exhibit toxic effects on resident organisms, disrupting the delicate balance of these ecosystems.

Fish, as key bioindicators, provide vital insights into water quality and the ecological health of aquatic systems. Their sensitivity to pollutants makes them especially vulnerable to environmental stressors, which can result in physiological, biochemical, and genetic damage

(Satkar et al., 2024). Among these, genotoxicity—defined as damage to an organism's genetic material—has emerged as a critical area of concern. Genotoxic effects in fish are associated with adverse outcomes such as impaired reproductive performance, reduced growth rates, developmental abnormalities, and increased susceptibility to diseases (Taslima et al., 2022). These effects threaten not only the sustainability of fish populations but also the overall biodiversity and stability of aquatic ecosystems.

This mini-review aims to synthesize current knowledge on the sources and types of chemical pollutants affecting aquatic systems, elucidate the mechanisms through which these pollutants induce genotoxicity, and document their impacts on various fish species. Furthermore, it explores sustainable strategies for pollution control, emphasizing the need for integrated approaches to mitigate the genotoxic and ecological risks posed by these contaminants.

Sources of Pollution and Genotoxic Agents

Industrial effluents, agricultural runoff, urban wastewater, microplastics, and oil spills significantly threaten freshwater ecosystems through genotoxic effects. Heavy metals released from mining and industrial processes, are potent genotoxic agents, forming reactive oxygen species (ROS) that directly damage DNA (Balali-Mood et al., 2021). Similarly, agricultural runoff carries pesticides and herbicides, such as organophosphates and carbamates, which interact with DNA, causing mutations and strand breaks. Urban wastewater introduces pharmaceuticals, personal care products, and endocrine-disrupting compounds into aquatic systems, often resulting in chromosomal aberrations and altered genetic material. Microplastics exacerbate the issue by adsorbing toxic chemicals and acting as vectors, delivering these pollutants to aquatic organisms, where they induce oxidative stress and DNA damage (Goswami et al., 2024). Moreover, oil spills release polycyclic aromatic hydrocarbons (PAHs), which are hydrophobic and interact with cellular components to form DNA adducts, leading to mutations. Together, these pollutants disrupt the genetic integrity of aquatic life, posing severe risks to freshwater biodiversity.

Mechanisms of Genotoxicity in Fish

Pollutants induce genotoxic effects through multiple mechanisms, significantly compromising the genetic integrity of organisms. Heavy metals and PAHs can directly bind to DNA, causing structural damage such as single- and double-strand breaks (Kushwaha et al., 2024). Many pollutants further exacerbate genetic harm by inhibiting DNA repair enzymes, preventing the correction of DNA lesions. Beyond direct damage, certain pollutants cause epigenetic modifications, such as DNA methylation and histone modifications, altering gene expression patterns without directly damaging the DNA structure (Chatterjee and Walker, 2017). These combined mechanisms heighten the risk of mutations and chromosomal aberrations, posing severe threats to organismal health and biodiversity.

Biomarker Assays for Detecting Genotoxicity

Biomarker assays are crucial tools for detecting genotoxicity in aquatic organisms. Techniques such as the Comet assay and micronucleus test assess DNA strand breaks and chromosomal aberrations, respectively, while molecular biomarkers like qPCR evaluate gene expression changes. These assays provide sensitive, reliable insights into pollutant-induced genetic damage.

Table 1: Different types of biomarkers for detection of genotoxicity

Technique	Purpose	Key Features	References
Comet Assay	Measures DNA strand breaks at the single-cell level.	High sensitivity and simplicity.	Dwivedi et al., (2024)
Micronucleus Test	Detects chromosomal fragments or whole chromosomes that fail to segregate.	Useful for identifying segregation errors.	Jain et al., (2024)
Chromosomal Aberration Assay	Identifies structural changes in chromosomes due to clastogenic agents.	Detects clastogenic-induced changes.	Tripathi (2020)
Molecular Biomarkers	Assesses gene expression and DNA sequence integrity using qPCR and NGS.	Advanced techniques for molecular-level analysis.	Sarhadi & Armengol (2022)
Histopathological Studies	Examines tissue-level changes, like nuclear anomalies in fish cells.	Provides insight into cellular genotoxic effects.	Karim et al., (2022)

Documented Genotoxic Effects on Fish Species

Aquatic organisms are highly vulnerable to genotoxic effects induced by various pollutants. Heavy metal pollution, such as cadmium exposure in *Oreochromis niloticus* (Nile tilapia) (Almeida et al., 2001), increases micronucleus frequency and DNA strand breaks, while mercury exposure in *Channa punctatus* leads to oxidative DNA damage and impaired reproductive performance (Ratn et al., 2018). Pesticide exposure also poses significant threats, with atrazine causing elevated chromosomal aberrations and reduced antioxidant enzyme activity in *Cyprinus carpio* (Common carp), and organophosphate pesticides inducing oxidative stress and DNA fragmentation in *Catla catla*. Microplastic ingestion further exacerbates genotoxicity, as observed in *Danio rerio* (zebrafish), where histological changes in gills and liver were coupled with DNA strand breaks. Additionally, prolonged exposure to polycyclic aromatic hydrocarbons (PAHs) in *Clarias gariepinus* (African catfish) results in DNA adduct formation and hepatocyte apoptosis, highlighting the pervasive impact of hydrocarbon pollution. Together, these studies underscore the diverse and severe genetic damage pollutants inflict on aquatic species.

Conclusion

The genotoxic effects of pollution on fish species underscore the urgency of addressing aquatic pollution. Advancements in biomarker technologies offer robust tools for early detection of genotoxicity, aiding in the conservation of aquatic ecosystems. Multidisciplinary approaches integrating ecological, molecular, and policy-driven strategies are essential for mitigating pollution and preserving fish biodiversity.

Efforts to reduce anthropogenic pollution, combined with community involvement and scientific innovation, will be pivotal in safeguarding aquatic life from genotoxic threats.

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