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Ecotoxicological Impacts and Biotransformation of Xenobiotic Pollutants in Aquatic Ecosystems: Implications for Fish Bioindicators and Environmental Remediation

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Abstract The persistence of biologically active xenobiotic compounds in aquatic environments poses a significant threat to ecosystem health and human safety. This review synthesizes current knowledge on the interactions and ecological impacts of xenobiotics in aquatic systems, with particular emphasis on fish as sensitive bioindicators of environmental contamination. Xenobiotics, including heavy metals and synthetic chemicals, induce a wide spectrum of biological responses in fish, ranging from synergistic or antagonistic interactions to alterations in mortality, behaviour, physiology, and cellular integrity. Bioaccumulation of these contaminants in fish tissues not only disrupts aquatic biodiversity but also facilitates their transfer through trophic levels into the human food chain, thereby posing serious public health concerns. Recent investigations highlight the significance of cellular-level xenobiotic interactions in processes such as carcinogenesis and chronic toxicity. Freshwater fish species are therefore increasingly employed as ecological sentinels for early detection of environmental contamination. In addition, this review discusses emerging remediation strategies, including bacterial bioremediation and phytoremediation, which utilize natural biological processes to degrade xenobiotic compounds. Advancements in the understanding of xenobiotic biotransformation pathways provide promising opportunities for mitigating environmental pollution and protecting aquatic ecosystems.

Keywords Xenobiotic contamination; Biotransformation pathways; Aquatic biomarkers; Fish ecotoxicology; Pollution remediation

1 Introduction

Environmental pollution affecting aquatic and terrestrial ecosystems represents one of the most significant global environmental challenges. Contaminants released from both natural and anthropogenic activities accumulate in environmental compartments and frequently enter food chains, where they exert harmful effects on plants, animals, and human populations. Aquatic ecosystems are particularly vulnerable to contamination by xenobiotic compounds originating from agricultural runoff, industrial effluents, pharmaceutical residues, and municipal wastewater discharges (Gavrilescu et al., 2015; Richardson and Kimura, 2017). Through processes such as bioaccumulation and biomagnification, these pollutants progressively concentrate within higher trophic levels, leading to serious ecological and toxicological consequences (Schwarzenbach et al., 2006; Kumar et al., 2023).

The term xenobiotic is derived from the Greek words *xenos* meaning "foreign" and *bios* meaning "life," referring to chemical substances that are not naturally synthesized or expected to occur within biological systems. Xenobiotics encompass a broad spectrum of compounds including agrochemicals, pharmaceuticals, petrochemicals, dyes, preservatives, adhesives, and personal care products (Daughton and Ternes, 1999; Fent et al., 2006; Aus der Beek et al., 2016; Wilkinson et al., 2022). The extensive global production and use of these compounds have resulted in widespread contamination of aquatic environments.

Among these pollutants, heavy metals represent a particularly hazardous group because of their persistence, toxicity, and ability to accumulate within biological tissues. Heavy metals such as lead, cadmium, mercury, and arsenic are among the most hazardous environmental pollutants due to their persistence, bioaccumulation, and toxic effects on aquatic organisms and human health (Tchounwou et al., 2012; Jaishankar et al., 2014; Ali et al., 2019). These metals accumulate in fish tissues and may threaten aquatic biodiversity while posing potential health risks to humans through seafood consumption (Kumar et al., 2023).

Fish species are widely recognized as valuable model organisms in ecotoxicological research because their physiological and biochemical responses often reflect the overall health status of aquatic ecosystems. Exposure to xenobiotic pollutants can induce biochemical, physiological, and metabolic disturbances in fish, including oxidative stress, enzyme induction, cellular damage, and disruption of metabolic pathways (Authman et al., 2015; Rai et al., 2021).

Various strategies have been developed to remove xenobiotic contaminants from aquatic environments. Conventional physicochemical treatment methods, including precipitation, adsorption, and advanced oxidation processes, are often costly and may generate secondary pollutants. Consequently, environmentally sustainable approaches such as microbial bioremediation and phytoremediation are increasingly explored because of their ecological compatibility and cost effectiveness (Varjani et al., 2020; Sharma et al., 2022).

Despite extensive research on xenobiotic contamination and its ecological impacts, existing reviews often address these aspects in isolation, focusing either on environmental occurrence, toxicological mechanisms, or remediation technologies. There remains a critical lack of integrated perspectives that connect xenobiotic biotransformation processes with ecotoxicological responses in aquatic organisms, particularly fish, and their application as bioindicators in environmental monitoring. Furthermore, limited attention has been given to linking biomarker responses with emerging remediation strategies in a unified framework. This review aims to bridge these gaps by providing a comprehensive synthesis of xenobiotic distribution, bioaccumulation, and biotransformation pathways alongside fish-based ecotoxicological responses, while also highlighting the role of bioindicators in assessing environmental health and guiding sustainable remediation approaches.

2 Classification and Environmental Distribution of Xenobiotic Pollutants

Xenobiotic compounds present in aquatic environments can be categorized based on their origin, chemical composition, and environmental behavior. These substances include both naturally occurring bioactive compounds synthesized by living organisms and synthetic chemicals produced through industrial and agricultural activities (Richardson and Kimura, 2017; Wilkinson et al., 2022).

2.1 Natural and anthropogenic xenobiotic compounds

Xenobiotic substances can broadly be classified into natural and synthetic categories depending on their origin. Synthetic xenobiotics are artificially produced chemicals associated primarily with anthropogenic activities such as industrial manufacturing, agricultural practices, and pharmaceutical production. Examples include pesticides, industrial solvents, pharmaceutical residues, synthetic dyes, preservatives, and plastic additives (Schwarzenbach et al., 2006; Aus der Beek et al., 2016).

Natural xenobiotics, on the other hand, are compounds synthesized by plants, microorganisms, or animals as part of their chemical defense systems. These compounds include plant-derived alkaloids, microbial toxins, and naturally occurring antibiotics. Examples include pyrethrins produced by *Chrysanthemum* species and nicotine synthesized by plants belonging to the *Solanaceae* family (Rai et al., 2021; Wilkinson et al., 2022).

2.2 Biochemical classification of xenobiotic substances

Xenobiotic compounds may also be categorized according to their biochemical origin and metabolic behavior within biological systems.

2.2.1 Externally introduced xenobiotic chemicals

Exogenous xenobiotics are foreign chemical substances introduced into biological systems from external environmental sources. These compounds may enter organisms through contaminated food, water, inhalation, or pharmaceutical administration. Examples include pesticides, pharmaceutical residues, food additives, industrial chemicals, and emerging contaminants such as microplastics and personal care products. Because these substances are foreign to the body, they are typically subjected to detoxification processes mediated by metabolic enzymes, particularly cytochrome P450 monooxygenases, which play a central role in the biotransformation and elimination of xenobiotics (Varjani et al., 2020; Rai et al., 2021; Wilkinson et al., 2022).

2.2.2 Endogenously generated toxic metabolites

Endogenous compounds are substances naturally synthesized within living organisms during metabolic processes but may exhibit toxic properties when accumulated at elevated concentrations. Examples include bile acids, steroid hormones, bilirubin, eicosanoids, and certain fatty acids. Although these compounds are physiologically produced, excessive accumulation can lead to toxic effects similar to those produced by external xenobiotic substances (Rai et al., 2021).

2.3 Major environmental seources and transport pathways of xenobiotics

Anthropogenic activities represent the principal sources of xenobiotic contaminants in aquatic ecosystems. Industrial activities such as pharmaceutical manufacturing, chemical processing, mining operations, and petroleum refining contribute substantially to environmental pollution. Agricultural practices involving intensive application of pesticides, herbicides, and fertilizers also introduce large quantities of xenobiotic compounds into aquatic systems through surface runoff (Varjani et al., 2020; Sharma et al., 2022).

Persistent organic pollutants such as polychlorinated biphenyls and pharmaceutical residues have been widely detected in aquatic ecosystems worldwide (Aus der Beek et al., 2016; Wilkinson et al., 2022). These compounds can be absorbed by primary producers such as algae and plankton and subsequently transferred through aquatic food webs, eventually accumulating in higher organisms including fish and aquatic mammals (Richardson and Kimura, 2017). Microbial degradation processes play a crucial role in the transformation and detoxification of xenobiotic compounds in the environment. Through biodegradation and biotransformation reactions, microorganisms convert toxic chemicals into intermediate metabolites that may eventually be mineralized into inorganic products (Varjani et al., 2020; Singh et al., 2021).

3 Bioaccumulation and Toxicological Impacts of Xenobiotics in Fish

Aquatic ecosystems frequently receive a wide range of xenobiotic pollutants, including heavy metals, pharmaceuticals, pesticides, and endocrine-disrupting compounds, originating from industrial discharges, agricultural runoff, atmospheric deposition, and natural geological processes. Once introduced into aquatic systems, these contaminants can be absorbed by aquatic organisms and progressively accumulate in biological tissues through bioaccumulation and biomagnification processes (Luoma and Rainbow, 2015; Kumar et al., 2019; Kumar et al., 2023). In addition to heavy metals, emerging contaminants such as pharmaceutical residues and personal care products are increasingly detected in aquatic environments and are known to persist and exert chronic toxic effects on aquatic biota.

Fish absorb xenobiotic contaminants primarily through their gills, digestive system, and skin. After entering the bloodstream, these substances may accumulate in vital organs such as the liver, kidney, and muscle tissues. The extent of accumulation depends on species-specific traits, environmental conditions, exposure duration, and pollutant concentration (Authman et al., 2015; Luoma and Rainbow, 2015; Kumar et al., 2023). While heavy metals remain a major concern, organic xenobiotics such as pesticides and pharmaceuticals can also bioaccumulate and interfere with metabolic and physiological processes in fish.

Chromium represents one of the most extensively studied heavy metals due to its widespread industrial application and high toxicity. Exposure to chromium can induce physiological, biochemical, histological, enzymatic, and genetic alterations in fish species (Jaishankar et al., 2014; Rai et al., 2021). Similarly, arsenic contamination is a major environmental concern, typically occurring in aquatic environments as arsenate or arsenite ions, which can disrupt metabolic processes and accumulate in aquatic organisms (Ali et al., 2019).

Beyond heavy metals, pesticides and their degradation products persist in aquatic environments and accumulate within sediments and food chains, thereby threatening aquatic biodiversity and human health (Sarkar et al., 2019; Sharma et al., 2022). In addition, endocrine-disrupting chemicals such as synthetic hormones and industrial compounds can interfere with hormonal regulation in fish, leading to reproductive abnormalities, altered growth patterns, and population-level effects. Pharmaceutical contaminants, including antibiotics and analgesics, have also been shown to induce sub-lethal toxicity, behavioral changes, and antimicrobial resistance in aquatic organisms, further highlighting the complexity of xenobiotic pollution in aquatic ecosystems.

4 Biomarkers and Receptor-Mediated Toxicological Responses in Fish

Exposure to xenobiotic compounds can trigger a wide range of molecular and physiological responses in aquatic organisms. Many xenobiotics interact with intracellular receptor proteins that function as ligand-activated transcription factors, resulting in altered gene expression and metabolic activity (Whyte et al., 2000; Wilkinson et al., 2022). One of the most extensively studied receptor systems involved in xenobiotic toxicity is the aryl hydrocarbon receptor signaling pathway. Activation of this receptor leads to the induction of detoxification enzymes and plays an important role in mediating toxicity associated with polycyclic aromatic hydrocarbons and related compounds (Whyte et al., 2000).

Fish species are widely used as bioindicators of environmental pollution because biochemical changes within their tissues provide early warning signals of ecosystem contamination (Moore et al., 2004; Authman et al., 2015; Rai et al., 2021). Biochemical biomarkers such as cytochrome P450 enzymes, particularly ethoxyresorufin-O-deethylase (EROD) activity, serve as important indicators of xenobiotic exposure. Changes in enzyme activity levels are widely used in environmental monitoring programs to assess pollution levels in aquatic ecosystems (Whyte et al., 2000; Wilkinson et al., 2022).

In practical applications, biomarker-based monitoring has been incorporated into several environmental assessment programs worldwide. For example, EROD activity and other biochemical biomarkers have been used in river monitoring studies to evaluate contamination from industrial effluents and urban wastewater discharges. Similarly, integrated biomarker responses in fish have been applied in ecological risk assessment frameworks to assess the impact of complex pollutant mixtures in aquatic environments. Monitoring programs in contaminated rivers and coastal ecosystems have demonstrated that biomarker responses in fish can provide early detection of sub-lethal toxicity before visible ecological damage occurs, thereby supporting timely environmental management and remediation strategies.

5 Metabolic Biotransformation and Microbial Degradation of Xenobiotics

Xenobiotic compounds undergo metabolic transformation within living organisms through complex detoxification pathways that are critical for detoxification and elimination. In aquatic organisms such as fish, xenobiotic biotransformation primarily occurs in the liver, which serves as the major detoxification organ, but is also significantly influenced by gill uptake and direct exposure to contaminants in water. Unlike terrestrial organisms, fish are continuously exposed to dissolved pollutants, making gill tissues an important site for both uptake and initial metabolic processing.

Phase I reactions involve oxidation, reduction, and hydrolysis processes that introduce reactive functional groups into xenobiotic molecules, primarily mediated by cytochrome P450 monooxygenases. However, compared with mammals, fish often exhibit lower activity and diversity of certain cytochrome P450 isoforms, which may result in slower metabolic transformation and prolonged persistence of xenobiotics in tissues. Phase II reactions involve conjugation processes such as glucuronidation, sulfation, methylation, glutathione conjugation, and amino acid conjugation, which enhance the water solubility of xenobiotics and facilitate their excretion (Wilkinson et al., 2022).

The efficiency of these biotransformation processes in fish is influenced by environmental factors such as temperature, dissolved oxygen, and pollutant concentration, which can further modulate enzymatic activity and detoxification capacity. For example, polycyclic aromatic hydrocarbons (PAHs) are metabolized in fish through

Phase I oxidation to reactive intermediates, which can bind to cellular macromolecules and induce toxic effects if not effectively conjugated during Phase II reactions. This incomplete detoxification can lead to oxidative stress, DNA damage, and carcinogenic outcomes in aquatic organisms.

In addition to organism-level metabolism, microbial biodegradation plays a crucial role in the environmental transformation of xenobiotics. Microorganisms in aquatic systems can metabolize a wide range of pollutants, including hydrocarbons, pesticides, and pharmaceutical residues, thereby contributing to the natural attenuation of contaminants (Wang and Wang, 2016; Varjani et al., 2020; Singh et al., 2021). The interaction between microbial processes and fish metabolism ultimately determines the persistence, bioavailability, and ecological impact of xenobiotic compounds in aquatic ecosystems.

6 Oxidative Stress and Cellular Damage Induced by Xenobiotics

One of the most significant mechanisms through which xenobiotics exert toxic effects in aquatic organisms is the induction of oxidative stress. Xenobiotic compounds such as heavy metals, pesticides, and pharmaceutical residues can stimulate the excessive production of reactive oxygen species (ROS) including superoxide radicals, hydrogen peroxide, and hydroxyl radicals. These reactive molecules can damage cellular macromolecules such as proteins, lipids, and nucleic acids, ultimately leading to impaired physiological functions in aquatic organisms (Livingstone, 2001; Valavanidis et al., 2006). Fish exposed to xenobiotic pollutants frequently exhibit increased lipid peroxidation, DNA damage, and enzyme inhibition due to oxidative stress. Antioxidant defense systems such as superoxide dismutase, catalase, glutathione peroxidase, and glutathione-S-transferase play essential roles in mitigating oxidative damage. However, prolonged exposure to pollutants can overwhelm these defense mechanisms, resulting in cellular dysfunction and tissue damage (Monteiro et al., 2010; Lushchak, 2011). Recent studies have demonstrated that oxidative stress biomarkers in fish can be used as sensitive indicators of environmental contamination. Monitoring antioxidant enzyme activity and oxidative damage products therefore provides valuable information for assessing the ecological impact of xenobiotic pollutants in aquatic ecosystems (Valavanidis et al., 2006).

7 Endocrine Disruption and Reproductive Toxicity in Aquatic Organisms

Certain xenobiotic pollutants function as endocrine-disrupting chemicals (EDCs) that interfere with hormonal signaling pathways in aquatic organisms. These substances can mimic, block, or alter the synthesis, transport, and metabolism of natural hormones, resulting in disturbances in growth, reproduction, and development. Endocrine-disrupting compounds commonly detected in aquatic environments include industrial chemicals, pesticides, plasticizers, and pharmaceutical residues (Sumpter and Johnson, 2005; Diamanti-Kandarakis et al., 2009).

At the molecular level, many EDCs exert their effects by binding to nuclear hormone receptors such as estrogen receptors (ERs), androgen receptors (ARs), and thyroid hormone receptors, thereby altering transcriptional regulation of target genes involved in reproductive and developmental processes. This receptor-mediated interaction can lead to changes in gene expression, protein synthesis, and endocrine feedback mechanisms, ultimately disrupting physiological homeostasis. In fish populations, exposure to endocrine-disrupting xenobiotics has been associated with abnormalities such as reduced fertility, altered sex ratios, intersex conditions, and impaired reproductive behavior. Synthetic estrogens, for example, have been shown to induce feminization of male fish in contaminated aquatic environments (Jobling et al., 2003).

Recent studies have highlighted the growing significance of emerging endocrine disruptors, including pharmaceutical residues and microplastics, in aquatic ecosystems. Pharmaceutical compounds such as synthetic hormones and antidepressants can interact with endocrine signaling pathways even at low concentrations, while microplastics may act as carriers for adsorbed EDCs or directly interfere with endocrine function. These contaminants have been shown to modulate gene expression related to reproductive development and endocrine regulation, leading to sublethal but ecologically significant effects in fish populations (Sharma et al., 2022; Wilkinson et al., 2022).

The increasing detection of endocrine disruptors in rivers and lakes worldwide has raised serious concerns regarding the long-term sustainability of aquatic ecosystems. Consequently, monitoring endocrine biomarkers such as vitellogenin expression in fish has become an important tool in environmental toxicology and ecological risk assessment (Sumpter and Johnson, 2005). Advances in molecular biomarkers, including gene expression profiling and omics-based approaches, are further enhancing the sensitivity and specificity of detecting endocrine disruption in aquatic environments.

8 Role of Nanotechnology in Xenobiotic Remediation

Nanotechnology has recently emerged as a promising approach for the remediation of xenobiotic pollutants in aquatic environments. Nanomaterials such as metal nanoparticles, carbon nanotubes, and nano-adsorbents possess unique physicochemical properties including high surface area and enhanced catalytic activity, making them highly effective for pollutant removal (Qu et al., 2013).

Nanoparticles can facilitate the adsorption, degradation, or transformation of xenobiotic compounds including pesticides, dyes, pharmaceuticals, and heavy metals. For instance, nano-scale zero-valent iron has been widely studied for its ability to degrade chlorinated organic pollutants in contaminated water systems (Zhang, 2003).

Despite their promising applications, the environmental safety of nanomaterials remains an important concern. Further research is required to evaluate the ecological risks associated with nanoparticle release into aquatic ecosystems while optimizing their use in environmental remediation technologies (Qu et al., 2013).

9 Climate Change and Its Influence on Xenobiotic Toxicity

Climate change is increasingly recognized as an important factor influencing the environmental behavior and toxicity of xenobiotic pollutants. Rising water temperatures, changes in pH, and altered hydrological cycles can significantly modify the transport, transformation, and bioavailability of contaminants in aquatic ecosystems (Noyes et al., 2009).

Elevated temperatures can increase metabolic rates in aquatic organisms, which may enhance the uptake and toxicity of xenobiotic compounds. In addition, climate-driven changes in precipitation patterns may increase the transport of agricultural pesticides and industrial pollutants into aquatic environments (Noyes et al., 2009).

Understanding the combined effects of climate change and chemical pollution is therefore essential for predicting future environmental risks and developing effective strategies for aquatic ecosystem protection.

10 Concluding Perspectives and Future Research Directions

Xenobiotic contamination of aquatic ecosystems remains a critical global environmental challenge driven by the persistence, toxicity, and bioaccumulative nature of anthropogenic pollutants. The continuous release of complex mixtures of chemicals—including heavy metals, pesticides, pharmaceuticals, and industrial compounds—has significantly impacted aquatic biodiversity and poses risks to human health through trophic transfer. Fish serve as sensitive and reliable bioindicators of environmental contamination, reflecting the integrated effects of xenobiotic exposure at biochemical, physiological, and molecular levels, with key mechanisms of toxicity including oxidative stress and endocrine disruption that impair cellular function, reproduction, and overall organismal health. While advances in bioremediation and emerging technologies such as nanomaterials offer promising strategies for mitigating xenobiotic pollution, their long-term ecological safety requires careful evaluation, particularly under the influence of climate change, which can alter pollutant distribution, bioavailability, and toxicity in aquatic systems. Moving forward, research should prioritize the development of species-specific biomarker systems for early detection of xenobiotic exposure in fish, alongside the integration of omics-based approaches with ecological modeling to better predict long-term ecosystem responses. Greater emphasis is also needed on understanding the environmental fate and toxicological impacts of emerging contaminants such as pharmaceutical residues and microplastics, as well as elucidating species-specific biotransformation pathways and their implications for ecological risk and trophic transfer. In addition, evaluating the combined effects of xenobiotics under changing climate conditions and optimizing sustainable remediation strategies—including microbial, phytoremediation, and nanotechnology-assisted approaches—will be essential. Finally, strengthening the linkage between scientific research and environmental policy through standardized monitoring frameworks and risk assessment tools will be critical for effective management and long-term protection of aquatic ecosystems.

Conflict of Interest

Author declares that there is no conflict of interest.

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