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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