

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