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