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