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).