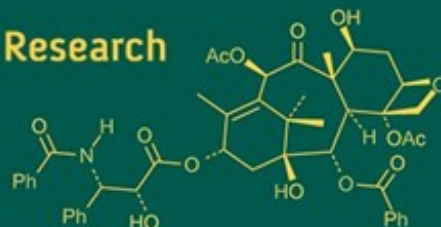
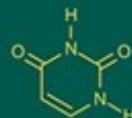
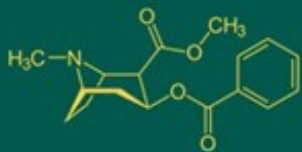


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Anthropogenic pollution in aquatic ecosystems: Implications for fisheries resources, aquatic biodiversity, antimicrobial resistance, and sustainable ecosystem management

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ABSTRACT

Anthropogenic pollution is a major and increasingly complex pressure on aquatic ecosystems, with consequences for water quality, aquatic biodiversity, fisheries productivity, aquatic animal health and ecosystem resilience. Rapid urbanization, industrialization, agricultural intensification and expanding aquaculture have increased the release of nutrients, potentially toxic elements, pesticides, petroleum hydrocarbons, pharmaceuticals, antimicrobial residues, plastics, microplastics and other emerging contaminants into aquatic environments. This review critically synthesizes current evidence on the sources, environmental fate, bioavailability and biological effects of these pollutants, with particular emphasis on their implications for fisheries resources, biodiversity and ecosystem functioning. Contaminants undergo complex transport, partitioning, transformation and accumulation processes, while environmental conditions regulate their persistence and biological availability. At the organismal level, exposure can induce oxidative stress, genotoxicity, endocrine disruption, immunotoxicity and tissue damage, ultimately affecting growth, reproduction, survival and disease susceptibility. At higher organizational levels, cumulative and mixture effects may alter species composition, trophic interactions, habitat suitability, recruitment and fisheries productivity. Particular attention is given to antimicrobial residues and antimicrobial resistance, highlighting aquatic environments as potential reservoirs and dissemination pathways with broader One Health implications. The review further emphasizes the limitations of conventional contaminant-specific assessment and the need to incorporate bioavailability, chronic exposure, contaminant mixtures, transformation products and multiple environmental stressors into ecological risk evaluation. Sustainable management approaches, including source reduction, advanced wastewater treatment, nature-based solutions, sediment remediation, ecological restoration, integrated monitoring and ecosystem-based management, are critically discussed. A source-to-impact framework is proposed to strengthen pollution assessment and support resilient aquatic ecosystems and sustainable fisheries management.

Keywords: Anthropogenic pollution, Aquatic ecosystems, Fisheries resources, Aquatic biodiversity, Emerging contaminants, Ecosystem-based management

1. Introduction

Aquatic ecosystems support biodiversity, fisheries, aquaculture, nutrient cycling and essential ecosystem services, but rapid urbanization, industrialization, agricultural intensification and waste generation have substantially increased anthropogenic pollution. Aquatic environments are exposed to conventional pollutants such as nutrients and potentially toxic elements (PTEs), as well as pesticides, petroleum hydrocarbons, pharmaceuticals, antimicrobial compounds, plastics, microplastics, PFAS and other emerging contaminants (Hader *et al.*, 2020; Luo *et al.*, 2014; Zhang *et al.*, 2023) [1, 2, 3]. Consequently, aquatic pollution has evolved from a localized water-quality problem into a complex ecological, fisheries and resource-management challenge. The ecological significance of pollutants depends not only on their environmental concentrations but also on their persistence, transport, transformation, bioavailability and biological accumulation. After entering aquatic systems, contaminants can partition among water, suspended particles, sediments and biota, while pH, temperature, salinity, redox conditions and organic matter regulate their environmental fate and availability (Schwarzenbach *et al.*, 2016; Luoma *et al.*, 2008) [5, 4]. Therefore, measured total concentrations may not adequately represent biologically relevant exposure or ecological risk, particularly for contaminants that persist in sediments or accumulate within aquatic organisms (Yu *et al.*, 2024) [6]. At the organismal level, anthropogenic contaminants can induce oxidative stress, genotoxicity, endocrine disruption, immuno

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toxicity and tissue damage, affecting growth, reproduction, development and survival (Bukola *et al.*, 2015; Walker, 2014) [7, 8]. These effects become more difficult to predict under realistic environmental conditions because organisms are commonly exposed to contaminant mixtures and concurrent stressors such as warming, hypoxia and habitat degradation. Such interactions may generate additive, synergistic or antagonistic responses, challenging conventional single-contaminant risk assessments (Jackson *et al.*, 2016; Orr *et al.*, 2024) [9, 10]. The consequences extend beyond individual organisms to populations, fisheries and ecosystem functioning. Pollution can reduce fish growth, reproductive success, recruitment and habitat suitability, while bioaccumulation of persistent contaminants may compromise seafood safety and fisheries value (Gobas *et al.*, 2000; Luoma *et al.*, 2008) [11, 4]. Selective effects on sensitive species can further modify community composition, trophic interactions, biodiversity and ecosystem processes (Hader *et al.*, 2020; Albert *et al.*, 2021) [1, 12]. Moreover, antibiotics and antimicrobial residues released from wastewater, agriculture and aquaculture can contribute to antimicrobial resistance (AMR), establishing an important link between aquatic pollution, aquatic animal health and One Health (Berendonk *et al.*, 2015; Larsson *et al.*, 2022) [13, 14]. Despite substantial advances in pollution research, significant uncertainties remain regarding chronic low-dose exposure, contaminant mixtures, transformation products, trophic transfer and interactions with other environmental stressors (Orr *et al.*, 2024; Yu *et al.*, 2024) [10, 6]. Therefore, this review critically examines anthropogenic pollution through a source-to-impact framework, integrating contaminant sources, environmental fate and bioavailability, ecotoxicological responses, fisheries and biodiversity consequences, AMR, and sustainable monitoring, remediation and ecosystem-based management.

2. Methodology

A structured literature search was conducted to critically synthesize evidence on anthropogenic pollution in aquatic ecosystems, focusing on contaminant sources, environmental fate and bioavailability, ecotoxicological effects, fisheries, biodiversity, AMR and sustainable management. Peer-reviewed literature was searched through Web of Science, Scopus, PubMed, ScienceDirect and Google Scholar using combinations of keywords including “anthropogenic pollution,” “aquatic ecosystems,” “emerging contaminants,” “microplastics,” “potentially toxic elements,” “fish health,” “aquatic biodiversity,” “antimicrobial resistance,” and “pollution management.” Recent studies were prioritized, while seminal studies were retained to establish fundamental concepts. Studies were included based on their relevance to contaminant occurrence, exposure, biological or ecological effects, fisheries and biodiversity impacts, AMR, risk assessment and management. Field studies, experimental investigations, systematic reviews and meta-analyses were emphasized, whereas irrelevant or insufficiently supported studies were excluded. Retrieved records were screened for relevance and duplicate records were removed before thematic synthesis. The evidence was critically organized into pollution sources, environmental fate and bioavailability, ecotoxicological responses, fisheries and biodiversity impacts, AMR, risk assessment and sustainable management. The synthesis followed a source-to-impact framework linking contaminant release → environmental exposure → biological responses → population and ecosystem effects → fisheries and biodiversity consequences → management implications. This approach enabled identification of consistent findings, contrasting evidence, methodological limitations and key research gaps relevant to risk-based and ecosystem-oriented management of aquatic pollution.

3. Classification and major sources of anthropogenic pollution

Anthropogenic pollution in aquatic ecosystems is best understood as a multisource pressure rather than a collection of isolated contaminants. Human activities alter the magnitude, composition, and timing of con-

taminant inputs through wastewater discharge, agricultural production, industrial processes, mining, fossil-fuel use, plastic consumption, and waste generation (Hader *et al.*, 2020; Carvalho *et al.*, 2022) [15, 1]. From a management perspective, pollution inputs are broadly classified into point sources and non-point sources based on their origin and transport pathways. The major anthropogenic pollution sources, dominant contaminants, environmental pathways, and their key impacts on aquatic ecosystems and fisheries resources are summarized in Table 1. Major contaminant classes include nutrients, pesticides, potentially toxic elements (PTEs), petroleum-derived hydrocarbons, plastics and microplastics, pharmaceuticals, antimicrobial compounds, and other emerging contaminants (Hader *et al.*, 2020; Luo *et al.*, 2014; Zhang *et al.*, 2023) [1, 2, 3]. Their ecological significance depends on the magnitude of release, persistence, chemical properties, and bioavailability, rather than source classification alone.

3.1. Domestic and municipal sources

Domestic wastewater is a complex anthropogenic input because it integrates contaminants generated by households, healthcare activities and urban consumption. Municipal sewage can contain nutrients, organic matter, suspended solids, detergents, pathogens, pharmaceuticals and personal-care chemicals (Hader *et al.*, 2020; Luo *et al.*, 2014) [1, 2]. Nutrient-rich discharges are particularly important where wastewater treatment is inadequate, because they increase external nutrient loading and may intensify eutrophication in susceptible receiving waters. The significance of municipal wastewater extends beyond conventional parameters such as biochemical oxygen demand and nutrient concentrations. Pharmaceuticals and other micropollutants can enter treatment systems continuously, while their removal varies substantially among compounds and treatment processes (Luo *et al.*, 2014) [2]. Thus, wastewater treatment may reduce overall contaminant loading without necessarily eliminating biologically active trace contaminants. Urban stormwater represents a complementary but more episodic pathway. Runoff from roads and impervious surfaces mobilizes sediments, hydrocarbons, metals, nutrients, tyre-derived particles and plastic debris. Unlike continuous wastewater discharge, stormwater loading is strongly event-dependent; consequently, high contaminant fluxes may occur over short periods and remain undetected by low-frequency monitoring (Hader *et al.*, 2020) [1]. This temporal variability is a major challenge for urban pollution assessment.

3.2. Agricultural sources

Agriculture is a predominantly diffuse source of aquatic contamination, with pollutant delivery controlled by land use, fertilizer and pesticide application, soil characteristics, rainfall, irrigation and drainage. Excess nitrogen and phosphorus can enter surface waters through runoff and leaching, while pesticides provide additional chemical inputs with potentially different persistence and transport characteristics (Hader *et al.*, 2020) [1]. The contaminant profile of agricultural landscapes is further complicated by livestock and intensive aquaculture. Manure and animal wastes contribute nutrients and organic matter, whereas veterinary pharmaceuticals and antimicrobial residues may enter adjacent water bodies through waste streams and runoff. Agricultural activities can also contribute PTEs through fertilizers, pesticides and contaminated soils (Carvalho *et al.*, 2022) [15]. Unlike regulated point discharges, agricultural contamination is difficult to control through source-specific regulation because pollutant generation occurs across large areas. Its seasonal and hydrologically driven nature further complicates estimation of annual contaminant loads. Therefore, agricultural pollution requires landscape- and watershed-scale assessment rather than isolated discharge monitoring.

3.3. Industrial and mining sources

Industrial pollution is characterized by considerable chemical heterogeneity because contaminant composition depends on the industrial sector, raw materials and production processes. Effluents may contain PTEs, hydrocarbons, solvents, dyes, phenolic compounds and other process-specific chemicals (Hader *et al.*, 2020) [1]. Mining and metal-processing activities are particularly important sources of PTEs, in

cluding Cd, Cr, Cu, Ni, Pb, Hg and Zn (Carvalho *et al.*, 2022) [15]. Their environmental significance differs from that of many degradable organic pollutants because elemental contaminants cannot be destroyed through biological degradation. Instead, their environmental presence is controlled largely by redistribution among water, particles, sediments and biota. This creates an important management challenge: reduction of contemporary industrial discharge does not necessarily equate to immediate removal of historical contamination. Contaminated sediments may retain pollutants and act as persistent reservoirs. Consequently, industrial pollution should be evaluated in terms of both current emissions and legacy contamination.

3.4. Petroleum-derived pollution

Petroleum-derived contamination is associated with extraction, refining, transportation, shipping, storage, urban activities and accidental releases. Crude oil consists of a complex mixture of hydrocarbons, including aliphatic compounds and aromatic hydrocarbons such as PAHs (Hader *et al.*, 2020) [1]. The principal analytical challenge is that petroleum contamination changes chemically after release. Volatilization, dissolution, weathering and degradation progressively modify the composition of the original mixture. Therefore, environmental risk cannot be inferred solely from the quantity of oil initially released; the composition and persistence of residual fractions are also relevant. While major spills can produce acute and highly visible contamination, chronic petroleum inputs from ports, shipping, urban runoff and industrial activities may be less conspicuous but environmentally persistent. This distinction is important because monitoring programs focused primarily on large spill events may overlook chronic background contamination.

3.5. Plastic pollution and microplastics

Plastic pollution differs from many conventional contaminants because the pollutant is not exclusively a chemical substance but a persistent material capable of undergoing physical fragmentation and environmental aging. Major pathways include mismanaged municipal waste, wastewater, urban runoff, fishing activities and industrial losses (Tursi *et al.*, 2022) [16]. Microplastics are generally categorized as primary particles, released directly at microscopic dimensions, and secondary particles, generated through fragmentation of larger plastics. Synthetic textile fibres, tyre and road wear, industrial pellets and degradation of plastic debris represent important sources (Tursi *et al.*, 2022; Pal *et al.*, 2025) [16, 17]. The analytical significance of microplastics lies in their highly variable physical characteristics. Particle size, shape, polymer type and degree of environmental weathering influence their occurrence and ecological relevance. Consequently, simply reporting particle abundance provides limited information unless particle characteristics and sampling methodology are also considered. A further limitation is the lack of complete methodological standardization among studies. Differences in sampling volumes, size detection limits, polymer identification and reporting units can produce substantially different estimates. Therefore, comparisons of microplastic contamination should be interpreted cautiously until harmonized analytical approaches are more widely adopted.

3.6. Emerging contaminants

Emerging contaminants represent a continually expanding category that includes pharmaceuticals, personal-care products, endocrine-disrupting chemicals, antibiotics, antimicrobial compounds, PFAS and other trace organic chemicals (Luo *et al.*, 2014; Zhang *et al.*, 2023) [2, 3]. Their classification as “emerging” does not necessarily imply recent chemical development; rather, it reflects increasing environmental detection, improved analytical capability or growing recognition of ecological concern. Domestic wastewater, healthcare facilities, pharmaceutical manufacturing, agriculture, industrial activities and consumer-product use represent important pathways. Many of these compounds occur at trace concentrations, but continuous release can produce persistent environmental exposure (Luo *et al.*, 2014) [2]. A major knowledge limitation is the monitoring gap between known and un-

known contaminants. Targeted analytical methods generally quantify preselected compounds and may therefore overlook transformation products and previously unidentified chemicals. Furthermore, treatment processes may transform some compounds into products with different environmental properties. This makes emerging-contaminant assessment increasingly dependent on non-target screening and improved chemical identification. Antimicrobial residues represent a particularly important subgroup because their significance extends beyond chemical toxicity. Repeated environmental exposure may create selective conditions favoring antimicrobial resistance, linking aquatic pollution with microbial ecology, aquatic animal health and One Health considerations.

3.7. Cumulative and mixed pollution

The classification of contaminants into separate categories can obscure the environmental reality that aquatic organisms are exposed to multiple pollutants simultaneously. Urban, agricultural and industrial sources may contribute nutrients, metals, pesticides, hydrocarbons, pharmaceuticals, plastics and microbial contaminants to the same water body (Hader *et al.*, 2020; Jackson *et al.*, 2016) [1, 9]. The resulting mixture may not behave as the simple sum of its individual components. Interactions can be additive, synergistic or antagonistic, while environmental conditions such as temperature, salinity, pH and oxygen availability may further modify biological responses (Jackson *et al.*, 2016) [9]. Therefore, compliance with individual contaminant thresholds does not necessarily guarantee absence of ecological risk. This issue represents a fundamental limitation of traditional source-specific assessment. Environmental exposure is mixture-based, whereas regulation is often substance-specific. Bridging this mismatch requires greater emphasis on cumulative contaminant loads, mixture toxicity and multiple-stressor assessment.

4. Environmental fate, transport and bioavailability of anthropogenic pollutants

Following their release into aquatic ecosystems, anthropogenic pollutants undergo dynamic processes of transport, phase partitioning, transformation, degradation and biological uptake, which collectively determine their persistence, distribution and ecological relevance. The environmental fate of a contaminant is governed by its physicochemical properties, including solubility, hydrophobicity, volatility, ionization and chemical stability, together with environmental conditions such as pH, temperature, salinity, dissolved oxygen, redox potential, suspended solids and organic matter (Hader *et al.*, 2020; Schwarzenbach *et al.*, 2016; Luoma *et al.*, 2008) [1, 5, 4]. Recent evidence indicates that emerging pollutants may be distributed among the aqueous phase, suspended particles, sediments and biota, making single-compartment monitoring inadequate for comprehensive exposure assessment (Yu *et al.*, 2024; Sultan *et al.*, 2024) [6, 18]. Importantly, environmental occurrence does not necessarily represent biological exposure. The fraction available for biological uptake may differ substantially from the total concentration measured in water or sediment because of differences in chemical speciation, partitioning and binding to environmental matrices (Luoma *et al.*, 2008; Adams *et al.*, 2020) [4, 19]. Thus, contaminant concentration, bioavailability and biological response should be considered as interconnected but distinct components of aquatic risk assessment.

4.1. Transport and environmental distribution

Aquatic contaminants are redistributed through river discharge, surface runoff, groundwater exchange, water currents, suspended-particle transport and sediment movement. Their distribution between dissolved and particulate phases is primarily controlled by physicochemical properties and environmental conditions (Schwarzenbach *et al.*, 2016) [5]. Hydrophobic and particle-reactive contaminants generally exhibit greater affinity for suspended matter and sediments, whereas more soluble compounds tend to remain relatively mobile in the aqueous phase. The transport of emerging contaminants is particularly complex because their spatial distribution reflects interactions among

source characteristics, hydrological connectivity, contaminant properties and environmental matrices. *Tran et al. (2018)* [20] emphasized the importance of source–pathway–receptor relationships in understanding the environmental distribution of emerging contaminants. Hydrological events such as flooding, high-flow conditions and sediment resuspension may further redistribute previously deposited contaminants and generate short-term exposure pulses. Therefore, observed contaminant concentrations represent the combined outcome of source input, transport, dilution, partitioning and environmental retention, rather than source strength alone.

4.2. Transformation, degradation and persistence

Following transport, contaminants may undergo biotic and abiotic transformation through microbial degradation, photolysis, hydrolysis, oxidation and reduction (*Schwarzenbach et al., 2016; Walker, 2014*) [5, 8]. The rates and pathways of transformation vary substantially among contaminant classes and environmental conditions. For organic contaminants, degradation may reduce parent-compound concentrations; however, transformation does not necessarily result in complete detoxification. Transformation products may exhibit different mobility, persistence or biological activity from their parent compounds. *Anagnostopoulou et al. (2022)* [21] emphasized that pesticide transformation products can remain environmentally relevant even after degradation of the parent compound. For potentially toxic elements, degradation is fundamentally different because elements cannot be destroyed through biological or chemical degradation. Instead, they undergo changes in speciation, oxidation state, complexation and phase partitioning, which can alter their mobility and biological availability (*Luoma et al., 2008; Adams et al., 2020*) [4, 19]. Thus, contaminant persistence should be interpreted in relation to both intrinsic chemical stability and environmental replenishment, rather than degradation rate alone.

4.3. Sediment–water interactions

Sediments are major environmental reservoirs for contaminants and play a central role in their long-term retention, redistribution and biological exposure. Organic matter, clay minerals, iron and manganese oxides, and sulfide phases can strongly regulate the partitioning and mobility of potentially toxic elements and organic contaminants (*Luoma et al., 2008; Zhang et al., 2014*) [4, 22]. *Zhang et al. (2014)* [22] demonstrated that sediment texture, organic matter, acid-volatile sulfides, Fe–Mn oxides, pH and redox conditions can substantially modify metal mobility and bioavailability. However, sediment deposition does not necessarily represent permanent contaminant removal. Changes in pH, redox potential, salinity, organic-matter decomposition and physical disturbance can alter contaminant–sediment interactions and promote desorption or remobilization. Consequently, contaminated sediments may function as both sinks during deposition and secondary sources during remobilization. This dynamic is particularly relevant to benthic organisms and fisheries because sediment-associated contaminants may maintain chronic exposure even when external contaminant inputs decline.

4.4. Bioavailability and biological uptake

Bioavailability refers to the fraction of a contaminant that is accessible for biological uptake and subsequent interaction with biological tissues. It is influenced by chemical speciation, solubility, partitioning, sediment characteristics, organic-matter interactions and environmental conditions (*Luoma et al., 2008; Schwarzenbach et al., 2016*) [4, 5]. For potentially toxic elements, water chemistry can produce substantial differences in bioavailability and toxicity even when total environmental concentrations are comparable (*Adams et al., 2020*) [19]. This demonstrates a fundamental limitation of relying exclusively on total contaminant concentrations for ecological risk assessment. Aquatic organisms may acquire contaminants through respiratory surfaces, integumentary contact and dietary pathways. In fish, gills provide an important interface for dissolved contaminants, whereas ingestion of contaminated prey and sediments contributes to dietary exposure. The relative contribution of these pathways depends on contaminant properties, species physiology, feeding behavior and habitat use.

4.5. Bioaccumulation and biomagnification

Bioaccumulation occurs when contaminant uptake exceeds elimination within an organism, resulting in an increasing internal contaminant burden. Biomagnification refers specifically to an increase in contaminant concentration across successive trophic levels (*Gobas et al., 2000*) [11]. Persistent and bioaccumulative contaminants may therefore reach relatively high concentrations in organisms occupying higher trophic positions. However, biomagnification is not a universal property of all contaminants because trophic transfer is influenced by uptake efficiency, metabolic transformation, elimination kinetics, lipid affinity and food-web structure (*Gobas et al., 2000; Walker, 2014*) [11, 8]. *Yu et al. (2024)* [6] reported that several groups of emerging pollutants, including PFAS, brominated flame retardants and microplastics, possess varying degrees of bioaccumulation and trophic-transfer potential, although the magnitude is highly contaminant- and organism-specific.

4.6. Environmental regulation of contaminant fate

Environmental conditions can substantially modify contaminant mobility, transformation and bioavailability. Changes in pH influence ionization, adsorption and metal speciation, whereas temperature affects chemical reaction rates and microbial activity (*Schwarzenbach et al., 2016*) [5]. Salinity can modify contaminant partitioning and complexation, particularly in estuarine environments. For potentially toxic elements, redox conditions are particularly important because changes between oxic and anoxic states can modify their chemical forms and mobility (*Luoma et al., 2008; Zhang et al., 2014*) [4, 22]. Organic matter may reduce bioavailability through strong binding, but dissolved and particulate organic matter can also facilitate contaminant transport. These interactions demonstrate that contaminant fate is context-dependent. Consequently, a contaminant concentration associated with a particular ecological response in one environment cannot necessarily be extrapolated directly to another environment with different physicochemical conditions.

Table 1. Major Anthropogenic Pollution Sources and Their Impacts on Aquatic Ecosystems

Source	Major pollutants	Major pathways	Key environmental/fisheries concerns
Domestic & municipal wastewater	Nutrients, pathogens, pharmaceuticals, detergents	Sewage, effluents, stormwater	Eutrophication, hypoxia, fish health impairment
Agriculture	N, P, pesticides, veterinary drugs, antimicrobials	Runoff, erosion, drainage	Eutrophication, toxicity, biodiversity loss
Aquaculture & livestock	Organic matter, nutrients, antibiotics, therapeutics	Effluents, waste discharge	Nutrient enrichment, disease and AMR risks
Industry	PTEs, hydrocarbons, solvents, dyes, phenolics	Industrial effluents, spills	Toxicity, bioaccumulation, sediment contamination

(continued on next page)

Source	Major pollutants	Major pathways	Key environmental/fisheries concerns
Mining & metal processing	Cd, Cr, Cu, Ni, Pb, Hg, Zn	Mine drainage, tailings, runoff	Chronic toxicity, bioaccumulation, fish mortality
Petroleum activities	Hydrocarbons, PAHs	Spills, leakage, runoff	Acute toxicity, tissue damage, habitat degradation
Plastic & microplastic sources	Macroplastics, microplastics, additives	Waste leakage, runoff, wastewater, fishing	Ingestion, entanglement, food-web transfer
Healthcare & consumer products	Pharmaceuticals, hormones, antimicrobials, PFAS	Wastewater, disposal, runoff	Chronic exposure, endocrine effects, AMR
Atmospheric deposition	PTEs, nitrogen compounds, POPs	Wet/dry deposition	Diffuse and long-range contamination
Multiple sources	Contaminant mixtures	Combined point/non-point pathways	Cumulative, additive and synergistic effects

4.7. Microplastics as modifiers of contaminant fate

Microplastics add complexity to contaminant transport because their surfaces can interact with metals and organic pollutants. Their environmental behavior is influenced by polymer composition, particle size, surface properties, ageing and biofilm development. Consequently, microplastics may provide additional surfaces for contaminant sorption and can alter the physical transport of associated chemicals. However, the role of microplastics as contaminant vectors should be interpreted cautiously. The magnitude of sorption, desorption and subsequent biological transfer depends on polymer characteristics, contaminant chemistry, environmental conditions and exposure pathways. Therefore, microplastics should be regarded as potential modifiers of contaminant transport and exposure rather than universally dominant vectors. This distinction is important because laboratory studies conducted under high contaminant-to-particle ratios may not always represent environmentally realistic conditions.

4.8. Emerging contaminants and transformation products

Emerging contaminants represent a particularly challenging component of aquatic pollution because their environmental occurrence, transformation and biological effects remain incompletely characterized. Yu *et al.* (2024) [6] reviewed pharmaceuticals and personal-care products, PFAS, disinfection by-products, brominated flame retardants and microplastics and highlighted substantial differences in their persistence, environmental transport, bioaccumulation and degradation behavior. Sultan *et al.* (2024) [18] further emphasized that estuarine ecosystems may receive diverse mixtures of emerging contaminants from multiple sources, while knowledge of their combined ecological effects and transformation pathways remains limited. A major analytical limitation is that conventional targeted monitoring generally focuses on a predefined set of known compounds. Consequently, unknown contaminants and transformation products may remain undetected. The increasing application of high-resolution mass spectrometry, suspect screening and non-target analysis therefore provides an important opportunity to characterize previously unidentified contaminants and transformation products.

5. Ecotoxicological effects of anthropogenic pollution on aquatic organisms

Anthropogenic pollutants affect aquatic organisms across multiple levels of biological organization, ranging from molecular and cellular disturbances to physiological dysfunction, impaired reproduction, altered behaviour and population-level effects. Potentially toxic elements, pesticides, petroleum hydrocarbons, pharmaceuticals, plastics and other emerging contaminants may act through oxidative stress, endocrine disruption, immunotoxicity, genotoxicity and metabolic disturbance. The magnitude of these effects depends on contaminant concentration, exposure duration, bioavailability, species sensitivity and environmental conditions (Hader *et al.*, 2020; Bukola *et al.*, 2015) [1, 7]. Importantly, aquatic organisms are typically exposed to complex contaminant mixtures, making field responses more difficult to predict from single-contaminant toxicity studies.

5.1. Molecular and cellular toxicity

Anthropogenic contaminants can disrupt cellular homeostasis through oxidative stress, mitochondrial dysfunction, membrane damage and altered gene expression. Potentially toxic elements, pesticides and organic pollutants may enhance reactive oxygen species (ROS) generation, leading to lipid peroxidation, protein oxidation and DNA damage when antioxidant defenses are exceeded (Walker, 2014; Bukola *et al.*, 2015) [8, 7]. Alterations in antioxidant enzymes, including superoxide dismutase, catalase and glutathione peroxidase, are therefore widely used as indicators of contaminant-induced stress. However, elevated antioxidant activity may initially represent an adaptive response rather than irreversible toxicity. Persistent exposure can progressively overwhelm these defenses, resulting in cellular dysfunction and tissue injury.

5.2. Histopathological and physiological impairment

Chronic contaminant exposure can cause structural and functional alterations in organs involved in respiration, detoxification, excretion and reproduction. In fish, the gills, liver, kidney and gonads are important target tissues. Bukola *et al.* (2015) [7] documented pollution-associated gill damage, epithelial lesions, hepatic injury, ulceration and other morphological abnormalities in fish. Such alterations can compromise respiration, osmoregulation, metabolism and detoxification, thereby reducing physiological performance. Histopathological endpoints are consequently valuable indicators of chronic exposure, although they should ideally be interpreted alongside biochemical and physiological biomarkers because tissue lesions alone may not establish contaminant-specific causality.

5.3. Genotoxicity and endocrine disruption

Several anthropogenic contaminants can interfere with genomic integrity and endocrine regulation. Oxidative DNA damage, DNA strand breaks and chromosomal abnormalities may occur following exposure to potentially toxic elements, pesticides and petroleum-derived contaminants (Walker, 2014) [8]. Endocrine-active chemicals, including selected pesticides, pharmaceuticals and plastic-associated compounds, can additionally interfere with hormone synthesis, receptor signalling and reproductive physiology. Such effects may reduce gametogenesis, spawning success and recruitment without producing immediate mortality. Therefore, genotoxic and endocrine responses may serve as early indicators of chronic ecological stress, although their translation into population-level effects requires further evidence.

5.4. Immunotoxicity and disease susceptibility

Anthropogenic pollution can impair immune competence and alter host-pathogen interactions in aquatic organisms. Chronic exposure may disrupt antioxidant defenses, immune-cell activity and physiological homeostasis, potentially increasing susceptibility to opportunistic infections (Bukola *et al.*, 2015) [7]. Pollution-associated lesions, including fin damage, gill pathology and ulceration, may reflect interactions among environmental stress, host condition and infectious agents rather than a direct effect of a single contaminant. This pollutant-host-pathogen interaction is particularly relevant to aqua

culture, where chronic environmental stress may increase disease susceptibility and compromise production.

5.5. Growth, reproduction and development

Sublethal contaminant exposure can modify energy allocation, metabolism, growth and reproductive performance. During chronic stress, metabolic resources may be redirected from growth and reproduction toward detoxification, antioxidant defense and tissue repair. Bukola *et al.* (2015) [7] identified reduced metabolism and chronic physiological impairment among important consequences of aquatic pollution in fish. Exposure during embryonic and larval development may be particularly consequential because these stages involve rapid cellular differentiation and high physiological sensitivity. From a fisheries perspective, persistent reductions in growth, fecundity or juvenile survival can ultimately reduce recruitment and stock productivity even in the absence of substantial acute mortality.

5.6. Neurotoxicity, behavioural alterations and ecological performance

Neuroactive contaminants, including selected pesticides, pharmaceuticals and petroleum-derived compounds, may interfere with neurotransmission and sensory processes, resulting in altered swimming, feeding, predator avoidance and habitat-use behaviour. Such responses can occur at concentrations below those causing acute mortality and therefore represent potentially sensitive indicators of sublethal stress. Their ecological significance depends on whether behavioural changes translate into reduced feeding efficiency, predator avoidance, reproduction or habitat occupancy. Consequently, behavioural endpoints should be evaluated under environmentally realistic exposure conditions before being extrapolated to population-level consequences.

5.7. Microplastics and co-contaminant interactions

Microplastics represent a distinctive anthropogenic stressor because they can cause particle-mediated effects while also interacting with other environmental contaminants. Their surfaces may adsorb potentially toxic elements, hydrophobic organic compounds, pharmaceuticals and other chemicals, while ingestion provides a potential route for biological exposure (Khan *et al.*, 2022) [23]. Vo *et al.* (2021) [24] reported associations between microplastic exposure and alterations in immune, reproductive, neurological and endocrine functions in aquatic organisms. However, the assumption that microplastics universally enhance contaminant toxicity requires caution. Their role as contaminant vectors depends on polymer composition, particle size, ageing, biofilm development, contaminant chemistry and environmental conditions (Khan *et al.*, 2022) [23]. Thus, microplastics should be regarded as potential modifiers of contaminant exposure rather than universally dominant vectors.

5.8. Mixture toxicity and population-level consequences

Aquatic organisms are commonly exposed to mixtures of metals, pesticides, hydrocarbons, pharmaceuticals, plastics and other stressors rather than individual contaminants. These combined exposures may produce additive, synergistic or antagonistic effects, while temperature, salinity, hypoxia and pH can further modify toxicity (Hader *et al.*, 2020; Khan *et al.*, 2022) [1, 23]. Consequently, single-contaminant laboratory studies may underestimate or overestimate responses under field conditions. Persistent exposure can impair growth, reproduction, immunity and survival, potentially reducing recruitment and population stability. However, biomarker responses alone do not necessarily indicate population-level impacts. Therefore, reliable ecotoxicological assessment should integrate contaminant exposure, bioavailability, biomarkers, physiological responses and population-level endpoints to distinguish biological stress from ecologically significant effects (Bukola *et al.*, 2015) [7].

6. Impacts of anthropogenic pollution on fisheries re-

sources, biodiversity and ecosystem functioning

Anthropogenic pollution can influence aquatic ecosystems beyond direct toxicity to individual organisms by altering population productivity, community structure, trophic interactions and ecosystem processes. Nutrients, potentially toxic elements, pesticides, petroleum hydrocarbons, pharmaceuticals, plastics and other emerging contaminants may act individually or interactively, producing consequences that range from impaired growth and reproduction to biodiversity loss and reduced fisheries productivity (Hader *et al.*, 2020; Bukola *et al.*, 2015) [1, 7]. The ecological significance of these effects depends on contaminant bioavailability, exposure duration, species sensitivity and the capacity of ecosystems to compensate for or recover from disturbance.

6.1. Effects on fish growth, reproduction and recruitment

Chronic exposure to anthropogenic contaminants can alter energy allocation, metabolism, growth and reproductive performance. Physiological resources may be redirected from somatic growth and reproduction towards detoxification, antioxidant defense and tissue repair. Contaminant-induced endocrine disruption may further affect gametogenesis, spawning, gamete quality and early-life-stage development (Walker, 2014; Bukola *et al.*, 2015) [8, 7]. Although these effects may not cause immediate mortality, persistent reductions in growth, fecundity or juvenile survival can ultimately decrease recruitment and population productivity. Thus, pollution may function as a chronic constraint on fisheries sustainability, particularly when combined with overfishing, habitat degradation and climate-related stress.

6.2. Fish health, mortality and disease susceptibility

Pollution can influence fish health through both direct toxicity and indirect modification of host-pathogen interactions. Acute exposure to high contaminant concentrations may produce mortality, whereas chronic exposure is more commonly associated with physiological stress, tissue damage and impaired immunity. Bukola *et al.* (2015) [7] reported pollution-associated gill lesions, ulceration, fin abnormalities and hepatic damage in fish. Reduced immune competence may increase susceptibility to opportunistic pathogens, particularly under intensive aquaculture conditions. Therefore, pollution and infectious disease should not always be considered independent stressors; their interaction may amplify disease risk and production losses.

6.3. Alteration of fish distribution, habitat use and capture fisheries

Pollution can reduce habitat suitability by modifying water quality, sediment characteristics, oxygen availability and prey resources. Sensitive species may avoid contaminated habitats, whereas tolerant species can become increasingly dominant, resulting in changes in fish distribution and community composition. Degradation of spawning, nursery and feeding habitats can consequently reduce the carrying capacity of fishing grounds. These changes may translate into lower catch rates, altered species composition and declining economic value of capture fisheries. Importantly, pollution-related fisheries decline may occur even without an increase in fishing pressure, indicating that environmental degradation can act as an independent or interacting driver of fisheries productivity.

6.4. Impacts on aquaculture productivity and biosecurity

Aquaculture systems are particularly vulnerable to poor environmental quality because cultured organisms are maintained at relatively high densities and depend directly on water and sediment conditions. Contaminants can impair growth, feed utilization, immunity and survival, while organic enrichment and chemical stress may increase disease susceptibility. Polluted source water can additionally introduce antimicrobial residues, resistant microorganisms and other contaminants into culture systems. Consequently, pollution control should be considered an integral component of aquaculture biosecurity, animal health management and production sustainability rather than solely an environmental protection measure.

6.5. Biodiversity loss, community structure and food-web alteration

Anthropogenic contaminants rarely affect all species equally. Differences in tolerance, exposure pathways, habitat use and physiological sensitivity can result in selective mortality or reduced performance of sensitive taxa, while pollution-tolerant organisms may proliferate. Such selective pressure can reduce species richness and alter community composition. Changes in phytoplankton, zooplankton and benthic communities can further modify prey availability and energy transfer to higher trophic levels. Persistent contaminants may also undergo bioaccumulation and trophic transfer, linking contaminant exposure across multiple trophic compartments (Gobas *et al.*, 2000; Luoma *et al.*, 2008) [11, 4].

6.6. Ecosystem functioning and ecological resilience

At the ecosystem level, anthropogenic pollution can modify primary productivity, nutrient cycling, decomposition, energy transfer and sediment processes. Excessive nutrient inputs may promote eutrophication and oxygen depletion, whereas toxic contaminants can disrupt microbial and benthic processes that contribute to ecosystem functioning (Hader *et al.*, 2020) [1]. The consequences may become more severe when pollution interacts with warming, hypoxia, altered hydrology or habitat modification. Ecological resilience—the capacity of an ecosystem to absorb disturbance and recover its structure and function—may consequently decline under persistent and cumulative contamination. This suggests that pollution management should focus not only on reducing individual contaminant concentrations but also on maintaining the functional integrity and recovery capacity of aquatic ecosystems.

6.7. Contamination of fishery products and food-safety implications

Persistent and bioaccumulative contaminants can accumulate in fish and shellfish through direct uptake and dietary exposure. Potentially toxic elements and persistent organic contaminants are of particular concern because of their persistence and slow elimination (Luoma *et al.*, 2008; Gobas *et al.*, 2000) [4, 11]. Bioaccumulation varies with species, age, trophic position, lipid content, feeding behaviour and contaminant-specific metabolism. Consequently, contamination of edible tissues may create food-safety concerns, particularly for species harvested from contaminated habitats. Beyond human-health risks, contaminated fishery products may reduce consumer confidence, market value and fisheries income.

6.8. Integrated implications for fisheries sustainability

Anthropogenic pollution can simultaneously affect fish growth, reproduction, immunity, habitat quality, biodiversity and ecosystem functioning, thereby reducing fisheries productivity and resilience. These effects may be intensified by overfishing, climate variability, habitat degradation and disease (Hader *et al.*, 2020; Bukola *et al.*, 2015) [1, 7]. Persistent contaminants may also remain biologically relevant through sediment storage and continued exposure after external inputs decline. Therefore, sustainable fisheries management requires integration of contaminant monitoring, bioavailability, biological responses, biodiversity, habitat condition, fishery productivity and seafood safety. Such an ecosystem-based approach is essential for maintaining resilient aquatic ecosystems and long-term fisheries sustainability.

7. Anthropogenic pollution, antimicrobial resistance and aquatic animal health

Anthropogenic pollution can influence aquatic animal health not only through direct toxicity but also by modifying microbial communities and promoting the selection and dissemination of antimicrobial resistance (AMR). Municipal wastewater, agricultural runoff, aquaculture effluents, hospital discharges and pharmaceutical residues can introduce antibiotics, resistant bacteria and antimicrobial resistance genes (ARGs) into aquatic environments. These inputs may interact with environmental stressors and create conditions that favour the persis-

tence and spread of resistance determinants (Berendonk *et al.*, 2015; Larsson *et al.*, 2022) [13, 14].

7.1. Antibiotic residues and selection of resistance

Continuous introduction of antibiotics into aquatic environments can exert selective pressure on microbial communities. Even concentrations below those causing acute toxicity may influence bacterial population structure and favour resistant phenotypes. Repeated exposure is therefore considered an important environmental driver of AMR, particularly in areas receiving wastewater and aquaculture discharges (Berendonk *et al.*, 2015; Larsson *et al.*, 2022) [13, 14].

7.2. Aquatic environments as reservoirs of resistance

Aquatic systems can act as reservoirs and dissemination pathways for antibiotic-resistant bacteria and ARGs. Wastewater, sediments and biofilms provide environments in which resistant microorganisms can persist and interact with diverse microbial populations. Horizontal gene transfer, including transformation, transduction and conjugation, can facilitate the movement of resistance determinants between bacteria, increasing their environmental dissemination (Berendonk *et al.*, 2015) [13].

7.3. Co-selection by metals and other contaminants

AMR selection is not restricted to antibiotic exposure. Potentially toxic elements and other antimicrobial compounds can contribute to co-selection, particularly when resistance determinants are genetically linked or when common cellular mechanisms provide resistance to multiple stressors. Heavy metals such as Cu, Zn, Cd, Hg and Pb have therefore been implicated in the environmental maintenance of antibiotic resistance (Baker-Austin *et al.*, 2006; Seiler *et al.*, 2012) [25, 26]. This interaction is particularly relevant in aquatic environments receiving mixed industrial, agricultural and aquaculture effluents.

7.4. Implications for aquatic animal health

Pollution-associated AMR can reduce the effectiveness of antimicrobial therapy and complicate the management of bacterial diseases in cultured and wild aquatic animals. Chronic exposure to contaminants may additionally compromise physiological and immune functions, potentially increasing susceptibility to infection. Thus, chemical pollution and AMR may act as interacting pressures rather than independent environmental problems.

7.5. Environmental dissemination and one health relevance

Resistant bacteria and ARGs can move between wastewater, sediments, aquatic organisms and surrounding environments, creating potential connections among environmental, animal and human microbial reservoirs. This makes aquatic ecosystems an important component of the broader One Health framework for AMR management (Larsson *et al.*, 2022) [14]. However, the detection of ARGs alone does not necessarily demonstrate an increased clinical risk; risk assessment should consider abundance, mobility, host association, phenotypic resistance and actual exposure pathways.

7.6. Implications for fisheries and aquaculture management

Effective management requires integration of antimicrobial stewardship, wastewater treatment, effluent control, AMR surveillance and responsible aquaculture practices. Monitoring should combine phenotypic antimicrobial susceptibility testing with molecular detection of ARGs and relevant environmental parameters. Such integrated surveillance can improve understanding of AMR transmission pathways and support evidence-based management of aquatic animal health.

8. Monitoring, risk assessment and management of anthropogenic pollution

Effective management of anthropogenic pollution requires an integrated assessment of contaminant occurrence, environmental fate, biological exposure and ecological effects. Recent studies emphasize that conventional chemical monitoring alone may not adequately capture chronic exposure, bioavailability or mixture effects, particularly

for emerging contaminants (Yu *et al.*, 2024; Zhang *et al.*, 2023) [6, 3]. Therefore, modern pollution assessment increasingly combines chemical analysis with biomonitoring, ecological indicators and risk-based approaches.

8.1. Environmental monitoring and contaminant surveillance

Monitoring should include water, sediment and aquatic biota to characterize contaminant distribution and temporal variability. Emerging pollutants such as pharmaceuticals, PFAS, microplastics and other trace contaminants require expanded analytical coverage because many remain poorly characterized in routine monitoring programs (Yu *et al.*, 2024) [6]. Standardized and long-term sampling is particularly important for identifying seasonal contamination and persistent pollution sources (Singh *et al.*, 2024) [27].

8.2. Biomonitoring and biological indicators

Biomarkers provide complementary information on the biological effects of pollution that cannot be obtained from chemical measurements alone. Biochemical, cellular, histopathological and molecular biomarkers can indicate contaminant exposure and early biological responses. Recent advances in biomarker research emphasize the integration of multi-level biomarkers, omics approaches and ecological indicators to improve environmental assessment. Sentinel fish can also provide valuable evidence of contaminant exposure; however, species-specific responses and environmental variability must be considered when interpreting biomonitoring results (Bancel *et al.*, 2024) [28].

8.3. Ecological risk assessment

Risk assessment should integrate exposure concentration, bioavailability, persistence, toxicity and species sensitivity rather than relying solely on total contaminant concentrations. For emerging pollutants, bioaccumulation, biomagnification and environmental persistence may substantially modify ecological risk (Yu *et al.*, 2024) [6].

8.4. Advanced analytical approaches

High-resolution mass spectrometry, suspect screening and non-target analysis are increasingly important for identifying previously unrecognized contaminants and transformation products. These approaches can improve understanding of contaminant sources, environmental fate and potential ecological risks beyond conventional targeted analysis (Mofijur *et al.*, 2024) [29].

8.5. Pollution prevention and source control

Pollution management should prioritize source reduction and preventive control rather than relying primarily on remediation after contamination has occurred. Improved wastewater treatment, agricultural runoff management, industrial effluent control and responsible chemical use are essential for reducing contaminant loading. Particular attention is required for emerging contaminants because wastewater-treatment systems may not completely eliminate many micropollutants (Yu *et al.*, 2024) [6].

8.6. Integrated ecosystem-based management

Long-term control of aquatic pollution requires coordination among environmental management, fisheries, aquaculture, agriculture and public-health sectors. Ecosystem-based management can address multiple stressors simultaneously and incorporate ecological, socioeconomic and stakeholder considerations (Haugen *et al.*, 2024) [30]. Importantly, AMR surveillance should also be incorporated into aquatic pollution monitoring, particularly in wastewater-impacted and aquaculture-associated systems. Recent evidence highlights the occurrence of antibiotics, resistant bacteria and resistance genes in aquatic environments and the need for standardized long-term monitoring (Singh *et al.*, 2024) [27]. Overall, effective pollution management should transition from chemical-specific monitoring toward integrated, risk-based and ecosystem-oriented assessment, combining contaminant surveillance, biological responses, advanced analytical tools, source control and adaptive management. This approach is es-

sential for protecting aquatic biodiversity, fisheries resources and ecosystem resilience.

9. Sustainable management and remediation strategies for anthropogenic pollution

Sustainable management of aquatic pollution requires a shift from pollution removal after contamination to prevention, source reduction and ecosystem-based control. Because contaminants originate from multiple sectors and can persist across water, sediment and biota, effective management should combine source control, wastewater treatment, ecological restoration, pollution monitoring and adaptive governance. Ecosystem-based management is increasingly recognized as a suitable framework for addressing interacting environmental pressures while maintaining ecosystem services and resource sustainability (Haugen *et al.*, 2024) [30].

9.1. Source reduction and pollution prevention

Reducing contaminant inputs at their source is generally more effective and sustainable than relying exclusively on downstream remediation. Priority measures include improved municipal and industrial wastewater treatment, control of agricultural runoff, responsible use of agrochemicals and antibiotics, proper management of plastic waste and regulation of aquaculture effluents. Such preventive measures can reduce contaminant loading before pollutants become widely distributed within aquatic ecosystems.

9.2. Advanced wastewater treatment and nature-based solutions

Conventional wastewater treatment may not completely remove several emerging contaminants, including pharmaceuticals and other micropollutants. Constructed wetlands and other nature-based solutions provide comparatively low-energy approaches based on adsorption, biodegradation, phytoremediation and microbial transformation. Their performance, however, depends on hydraulic loading, temperature, substrate, vegetation and contaminant characteristics (Wu *et al.*, 2023; Agaton, 2025) [32, 31].

9.3. Sediment management and ecological restoration

Contaminated sediments can function as long-term reservoirs of potentially toxic elements and persistent organic contaminants, maintaining exposure even after external pollutant inputs decline. Sediment management options include dredging, capping, stabilization, immobilization and biological remediation, with selection dependent on contaminant characteristics, sediment properties and ecological sensitivity. Yang *et al.* (2024) [33] highlighted the increasing importance of sustainable sediment-remediation and resource-valorization approaches for addressing both ecological contamination and long-term management challenges. Nevertheless, sediment removal is not inherently risk-free because dredging may resuspend contaminants and increase short-term exposure. Consequently, remediation decisions should consider contaminant bioavailability, ecological disturbance and potential secondary pollution, rather than total contaminant concentration alone.

9.4. Restoration of aquatic habitats

Restoration of wetlands, riparian zones, rivers, estuaries and coastal habitats can improve water quality while simultaneously enhancing biodiversity and ecosystem resilience. Wetlands can retain nutrients, suspended solids and contaminants, whereas restored riparian vegetation can reduce the transfer of sediments, nutrients and pollutants from terrestrial areas into receiving waters (Wu *et al.*, 2023; Albert *et al.*, 2021) [32, 12]. Riparian and wetland restoration can also improve habitat complexity, support aquatic communities and strengthen ecosystem functions, thereby contributing to fisheries-resource recovery (Palmer *et al.*, 2010; Haugen *et al.*, 2024) [34, 30]. However, restoration alone may have limited effectiveness where pollutant inputs remain high; therefore, habitat restoration should be integrated with source control, catchment-scale pollution reduction and long-term ecological monitoring (Haugen *et al.*, 2024) [30].

9.5. Nature-based solutions for AMR and emerging pollutants

Nature-based systems have additional potential for reducing antibiotics, antimicrobial-resistant bacteria and resistance genes entering aquatic ecosystems. Recent evidence indicates that treatment wetlands, river restoration and saltmarsh restoration can contribute to attenuation of antibiotics, AMR and pathogens, although performance varies among systems and environmental conditions (Pastor *et al.*, 2024) [35].

9.6. Integrated management for sustainable fisheries

Pollution control should be integrated with fisheries management, aquaculture practices, biodiversity conservation and food-safety surveillance. Management decisions should consider contaminant exposure together with habitat degradation, climate-related stress, overexploitation and disease pressure. Such ecosystem-based and adaptive management can improve the resilience of aquatic ecosystems while supporting sustainable fisheries production (Haugen *et al.*, 2024) [30]. Critical perspective: No single remediation technology can address the full spectrum of anthropogenic pollutants. Sustainable management therefore requires a site-specific combination of prevention, treatment, ecological restoration, monitoring and regulatory enforcement, with greater emphasis on reducing pollutant generation at the source rather than depending solely on end-of-pipe remediation.

10. Research gaps and future perspectives

Despite substantial advances, important uncertainties remain regarding the chronic, cumulative and ecosystem-level effects of anthropogenic pollution. Current evidence is still largely based on individual contaminants and controlled laboratory studies, whereas aquatic organisms experience complex mixtures and interacting stressors under field conditions (Orr *et al.*, 2024) [10]. Future research should prioritize chronic low-dose exposure, mixture toxicity, contaminant bioavailability, transformation products and trophic transfer, particularly for pharmaceuticals, PFAS and microplastics (Yu *et al.*, 2024; Zhou *et al.*, 2024) [6, 36]. Greater integration of high-resolution analytical techniques, biomonitoring, molecular approaches and predictive modelling is also required to improve contaminant detection and ecological-risk assessment. Critical knowledge gaps persist regarding pollution × climate change, eutrophication, habitat degradation and disease interactions, which may alter contaminant toxicity and ecosystem resilience. Research should therefore move beyond single-contaminant assessment toward field-realistic, multiple-stressor and ecosystem-based approaches, linking contaminant exposure with biodiversity, fisheries productivity, aquatic animal health and human health.

11. Conclusion

Anthropogenic pollution represents a multifaceted and persistent threat to aquatic ecosystems, fisheries resources and biodiversity. Its ecological consequences depend not only on contaminant concentrations but also on environmental transport, persistence, bioavailability, trophic transfer and interactions among multiple pollutants and environmental stressors. Nutrients, potentially toxic elements, pesticides, petroleum hydrocarbons, pharmaceuticals, antimicrobial residues, plastics and emerging contaminants can cause molecular and physiological disturbances, impair growth, reproduction, immunity and survival, and ultimately affect population stability and fisheries productivity. A critical synthesis indicates that conventional contaminant-specific assessments may underestimate ecological risk because aquatic organisms are exposed to complex mixtures under variable environmental conditions. Sediments and biota can also act as contaminant reservoirs, maintaining exposure after external inputs decline. Moreover, antimicrobial residues and resistant microorganisms connect aquatic pollution with antimicrobial resistance, aquatic animal health and One Health concerns. Pollution assessment should therefore integrate contaminant occurrence with bioavailability, biological responses and ecological consequences. Sustainable manage-

ment requires a shift from reactive remediation toward source prevention, integrated monitoring and ecosystem-based management. Improved wastewater treatment, agricultural and industrial pollution control, responsible antimicrobial use, plastic-waste reduction, sediment management, nature-based solutions and habitat restoration should be implemented according to site-specific ecological conditions. Future research should prioritize chronic low-dose exposure, mixture toxicity, transformation products, trophic transfer and interactions with climate change, disease and habitat degradation. Overall, integrating contaminant sources, ecological effects, fisheries productivity and human-health considerations provides a stronger basis for protecting aquatic ecosystem resilience and achieving sustainable fisheries management.

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