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Emerging Contaminants in Aquatic Environments: Sources, Detection, Toxicity, and Remediation

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Abstract

Aquatic ecosystems worldwide are increasingly threatened by the continuous release of emerging contaminants (ECs), a diverse group of chemical and biological substances that are not routinely monitored but pose significant risks to environmental and human health. These contaminants include pharmaceuticals, personal care products (PPCPs), endocrine-disrupting chemicals (EDCs), per- and polyfluoroalkyl substances (PFAS), microplastics, nanomaterials, pesticides, antibiotic resistance genes (ARGs), industrial chemicals, and artificial sweeteners. Conventional wastewater treatment plants are often unable to completely remove these contaminants, leading to their accumulation in surface water, groundwater, sediments, and aquatic organisms. Long-term exposure to ECs can induce endocrine disruption, reproductive abnormalities, neurotoxicity, oxidative stress, antimicrobial resistance, biodiversity loss, and ecosystem dysfunction. Recent advances in analytical chemistry, particularly chromatography coupled with mass spectrometry, biosensors, nanotechnology, and artificial intelligence-assisted monitoring, have significantly improved the detection and quantification of ECs at trace concentrations. Simultaneously, innovative remediation technologies, including adsorption, advanced oxidation processes, photocatalysis, membrane filtration, constructed wetlands, biochar-based materials, nanomaterials, and bioremediation, have demonstrated considerable potential for removing ECs from aquatic systems. This review discusses the major sources, classification, occurrence, detection techniques, environmental toxicity, remediation strategies, current challenges, and future perspectives of emerging contaminants in aquatic environments.

Keywords: *Emerging contaminants, Aquatic pollution, Pharmaceuticals, Microplastics, PFAS, Endocrine-disrupting chemicals.*

1. Introduction

Water is one of the most essential natural resources supporting life, ecosystem stability, agriculture, industry, and economic development. However, rapid industrialization, urbanization, population growth, pharmaceutical consumption, intensive agriculture, and expanding manufacturing activities have resulted in the continuous discharge of numerous chemical contaminants into aquatic environments. While traditional pollutants such as heavy metals and nutrients have long been monitored, increasing attention is now being directed toward emerging contaminants (ECs), which comprise a diverse group of synthetic and naturally occurring compounds that have only recently been recognized as significant environmental pollutants [1]. Emerging contaminants are generally characterized by their persistence, biological activity, resistance to conventional wastewater treatment processes, and potential adverse effects on aquatic organisms and human health.

Although many ECs occur at trace concentrations ranging from nanograms to micrograms per liter, their continuous release into aquatic ecosystems results in chronic exposure and long-term ecological consequences. Many of these compounds are biologically active even at extremely low concentrations, making them particularly concerning from an environmental perspective. The major classes of emerging contaminants include pharmaceuticals and personal care products (PPCPs), endocrine-disrupting chemicals (EDCs), antibiotics, hormones, pesticides, per- and polyfluoroalkyl substances (PFAS), microplastics, nanoplastics, industrial additives, flame retardants, surfactants, artificial sweeteners, cyanotoxins, and antibiotic resistance genes. These contaminants originate from municipal wastewater, hospitals, pharmaceutical industries, agricultural runoff, livestock production, aquaculture, landfill leachates, domestic sewage, and industrial effluents. Conventional wastewater treatment plants were primarily designed to remove suspended solids, nutrients, and biodegradable organic matter rather than trace organic contaminants. Consequently, substantial quantities of ECs pass through treatment systems and enter rivers, lakes, groundwater, estuaries, and marine environments [2]. Their persistence and bioaccumulation raise concerns regarding ecosystem degradation, food safety, drinking water quality, and biodiversity conservation. Recent advances in analytical instrumentation, environmental chemistry, molecular biology, and nanotechnology have improved our understanding of EC occurrence, transport, fate, toxicity, and remediation. This review provides a comprehensive overview of emerging contaminants in aquatic environments, highlighting their sources, classification, detection methods, environmental impacts, remediation technologies, challenges, and future research priorities.

2. Sources and Classification of Emerging Contaminants

Emerging contaminants originate from a wide range of anthropogenic activities and enter aquatic environments through both point and non-point sources. Municipal wastewater treatment plants represent one of the largest sources because domestic sewage contains pharmaceuticals, detergents, cosmetics, disinfectants, personal care products, hormones, and household chemicals that are only partially removed during treatment [3]. Hospital effluents contribute significant quantities of antibiotics, antiviral drugs, contrast agents, anesthetics, disinfectants, and cytotoxic pharmaceuticals that often persist in receiving water bodies. Agricultural activities are another major contributor to emerging contaminant pollution. Intensive livestock farming, aquaculture, and crop production rely heavily on antibiotics, veterinary pharmaceuticals, pesticides, herbicides, fungicides, growth promoters, and fertilizers. Rainfall-induced runoff transports these chemicals into rivers, lakes, reservoirs, and groundwater systems, where they may persist for extended periods.

Industrial sectors release numerous specialty chemicals including PFAS, plasticizers, flame retardants, dyes, surfactants, nanomaterials, solvents, and manufacturing additives. Textile industries, electronics manufacturing, pharmaceutical production, petrochemical processing, and plastic manufacturing are particularly important contributors to aquatic contamination [4]. Landfill leachates, urban stormwater runoff, septic systems, atmospheric deposition, and accidental chemical spills also contribute to the widespread distribution of emerging contaminants. Increasing use of synthetic polymers has resulted in growing concentrations of microplastics and nanoplastics in aquatic environments through degradation of larger plastic materials, wastewater discharges, and surface runoff [5]. Emerging contaminants are commonly classified according to their chemical composition and primary sources. Pharmaceuticals include analgesics, antibiotics, antidepressants, anti-inflammatory drugs, cardiovascular medicines, and hormones. Personal care products comprise fragrances, sunscreens, preservatives, cosmetics, and antimicrobial compounds. PFAS are highly fluorinated chemicals used in firefighting foams, non-stick cookware, waterproof textiles, and food packaging due to their exceptional chemical stability. Endocrine-disrupting chemicals include bisphenol A, phthalates, synthetic hormones, alkylphenols, and other compounds capable of interfering with hormonal regulation. Microplastics and nanoplastics represent particulate contaminants that accumulate in aquatic food webs, while antibiotic resistance genes constitute biological contaminants capable of spreading antimicrobial resistance among microbial populations.

Table 1: Major Emerging Contaminants in Aquatic Environments

Contaminant Class	Major Sources	Examples	Environmental Concern
Pharmaceuticals	Hospitals, households	Antibiotics, analgesics	Antimicrobial resistance
Personal Care Products	Domestic wastewater	Cosmetics, fragrances	Aquatic toxicity
Endocrine Disruptors	Plastics, industries	BPA, phthalates	Hormonal disruption
PFAS	Industrial activities	PFOA, PFOS	Persistence and bioaccumulation
Microplastics	Plastic waste	Polyethylene, polypropylene	Food web contamination
Pesticides	Agriculture	Atrazine, glyphosate	Ecotoxicity
Nanomaterials	Industrial products	Silver nanoparticles	Cellular toxicity

3. Detection and Analytical Techniques for Emerging Contaminants

The detection of emerging contaminants presents significant analytical challenges because these compounds typically occur at extremely low concentrations and often exist within complex environmental matrices. Sensitive, selective, and highly accurate analytical methods are therefore required for their identification, quantification, and environmental monitoring [6]. Chromatographic techniques coupled with advanced mass spectrometry remain the gold standard for EC analysis.

High-performance liquid chromatography coupled with tandem mass spectrometry (HPLC–MS/MS) is extensively employed for pharmaceuticals, hormones, PFAS, pesticides, and personal care products because of its excellent sensitivity and selectivity. Gas chromatography–mass spectrometry (GC–MS) is particularly suitable for volatile and semi-volatile contaminants, including certain pesticides, industrial chemicals, and flame retardants.

Ultra-high-performance liquid chromatography (UHPLC), high-resolution mass spectrometry (HRMS), and quadrupole time-of-flight mass spectrometry (QTOF-MS) enable both targeted and non-targeted screening of emerging contaminants, facilitating the discovery of previously unidentified compounds and transformation products. These techniques have significantly improved environmental monitoring by allowing simultaneous detection of hundreds of contaminants within a single analytical run [7]. Recent advances in biosensor technology have provided rapid, portable, and cost-effective alternatives for on-site monitoring. Electrochemical biosensors, optical sensors, fluorescence-based assays, immunosensors, and aptamer-based detection systems demonstrate high sensitivity while enabling real-time environmental surveillance. Nanomaterial-enhanced sensors incorporating graphene, carbon nanotubes, metal nanoparticles, and quantum dots further improve detection performance through enhanced signal amplification [8]. Artificial intelligence and machine learning are increasingly integrated into environmental monitoring systems to process large analytical datasets, identify contamination patterns, predict pollutant transport, and optimize monitoring strategies. These digital technologies support early warning systems and facilitate more efficient environmental risk assessment.

Table 2: Analytical Techniques for Detecting Emerging Contaminants

Analytical Method	Target Contaminants	Major Advantages
HPLC–MS/MS	Pharmaceuticals, PFAS, hormones	High sensitivity and accuracy
GC–MS	Volatile organic contaminants	Excellent compound identification
UHPLC–HRMS	Unknown contaminants	Comprehensive screening
ICP–MS	Metallic nanoparticles	Trace elemental analysis
Electrochemical biosensors	Pharmaceuticals, pesticides	Rapid field detection
Fluorescence sensors	Organic contaminants	High selectivity
Immunosensors	Hormones, antibiotics	Specific biomolecular recognition

4. Toxicity and Ecological Impacts of Emerging Contaminants

Emerging contaminants pose substantial risks to aquatic ecosystems because of their persistence, bioavailability, and continuous introduction into water bodies. Although many of these contaminants occur at concentrations ranging from nanograms to micrograms per liter, prolonged exposure can produce significant ecological and biological effects. Unlike conventional pollutants, emerging contaminants often exhibit chronic toxicity, endocrine-disrupting activity, bioaccumulation potential, and synergistic interactions with other environmental pollutants [9]. Aquatic organisms are particularly vulnerable due to their continuous exposure through water, sediments, and food sources. Pharmaceuticals, especially antibiotics, antidepressants, anti-inflammatory drugs, and hormones, alter physiological processes in fish, amphibians, mollusks, crustaceans, and aquatic plants. Exposure to endocrine-disrupting chemicals such as bisphenol A (BPA), phthalates, and synthetic estrogens interferes with hormone regulation, resulting in reproductive abnormalities, altered sex ratios, developmental defects, and reduced fertility in aquatic organisms.

Microplastics and nanoplastics have become major environmental concerns because they are readily ingested by zooplankton, shellfish, fish, and marine mammals. Their accumulation causes digestive blockage, oxidative stress, inflammation, reduced feeding efficiency, impaired growth, and decreased reproductive success. Furthermore, plastic particles serve as carriers for heavy metals, pathogenic microorganisms, and hydrophobic organic contaminants, facilitating the transport of multiple pollutants throughout aquatic food webs [20]. Per- and polyfluoroalkyl substances (PFAS) are among the most persistent environmental contaminants due to the exceptional stability of carbon–fluorine bonds. Their resistance to degradation enables long-term accumulation in aquatic ecosystems and living organisms. PFAS exposure has been associated with liver toxicity, immune dysfunction, endocrine disruption, developmental abnormalities, and increased cancer risk in experimental studies.

Antibiotic residues in aquatic environments contribute significantly to the emergence and dissemination of antimicrobial resistance. Continuous low-level exposure promotes the selection of resistant bacterial populations and facilitates horizontal gene transfer of antibiotic resistance genes among environmental microorganisms. This phenomenon represents a serious global public health concern because resistant pathogens may eventually spread through drinking water, food chains, and recreational water sources [11]. The combined presence of multiple emerging contaminants often produces additive or synergistic toxic effects that are considerably greater than those caused by individual compounds. Such mixture toxicity complicates environmental risk assessment and emphasizes the need for integrated monitoring strategies that consider complex contaminant interactions rather than individual pollutants alone.

Table 3: Ecological and Human Health Impacts of Emerging Contaminants

Contaminant	Primary Toxic Effects	Affected Organisms
Pharmaceuticals	Antibiotic resistance, behavioral changes	Fish, bacteria, aquatic invertebrates
Endocrine-disrupting chemicals	Hormonal imbalance, reproductive disorders	Fish, amphibians, mammals
PFAS	Bioaccumulation, liver toxicity, immune suppression	Aquatic organisms and humans
Microplastics	Oxidative stress, intestinal damage	Fish, shellfish, plankton
Pesticides	Neurotoxicity, reduced biodiversity	Aquatic insects, fish, amphibians
Nanomaterials	Cellular toxicity, oxidative damage	Microorganisms and aquatic fauna

5. Remediation Technologies for Emerging Contaminants

The efficient removal of emerging contaminants requires advanced treatment technologies because conventional wastewater treatment plants are generally ineffective in eliminating many persistent organic pollutants. Recent research has therefore focused on developing innovative physical, chemical, biological, and hybrid remediation techniques capable of degrading or removing a broad spectrum of contaminants [12]. Adsorption remains one of the most effective and economical approaches for removing emerging contaminants from water. Activated carbon, biochar, graphene oxide, carbon nanotubes, zeolites, and metal-organic frameworks (MOFs) exhibit excellent adsorption capacities for pharmaceuticals, pesticides, dyes, PFAS, and endocrine-disrupting chemicals. Modified biochar materials have attracted considerable attention because of their low cost, environmental sustainability, and high adsorption efficiency [13]. Advanced oxidation processes (AOPs) utilize highly reactive species, particularly hydroxyl radicals and sulfate radicals, to mineralize complex organic contaminants into less harmful products. Technologies such as ozonation, Fenton oxidation, photocatalysis, electrochemical oxidation, ultraviolet irradiation combined with hydrogen peroxide, and persulfate activation have demonstrated high removal efficiencies for pharmaceuticals, pesticides, antibiotics, and industrial chemicals [14]. Membrane filtration technologies, including reverse osmosis, nanofiltration, ultrafiltration, and membrane bioreactors, provide highly efficient physical separation of emerging contaminants from wastewater. Although membrane systems achieve excellent removal efficiencies, membrane fouling, high operational costs, and concentrate disposal remain important limitations.

Bioremediation employs microorganisms, algae, fungi, and aquatic plants to degrade or transform contaminants into less toxic compounds. Constructed wetlands integrate physical filtration, microbial degradation, and plant uptake, providing environmentally sustainable treatment systems suitable for municipal and industrial wastewater. Certain bacterial and fungal species possess specialized enzymes capable of degrading pharmaceuticals, pesticides, and endocrine-disrupting chemicals under both aerobic and anaerobic conditions [15]. Nanotechnology has significantly expanded remediation capabilities through the development of nanoadsorbents, magnetic nanoparticles, photocatalytic nanomaterials, and multifunctional nanocomposites. Titanium dioxide, zinc oxide, iron oxide nanoparticles, graphene-based materials, and metal-organic frameworks exhibit enhanced catalytic activity and adsorption performance, enabling rapid degradation of persistent contaminants under environmentally relevant conditions.

Table 4: Remediation Technologies for Emerging Contaminants

Technology	Target Contaminants	Major Advantages
Activated carbon adsorption	Pharmaceuticals, dyes, PFAS	High adsorption efficiency
Biochar adsorption	Heavy metals, pesticides, antibiotics	Sustainable and economical
Advanced oxidation processes	Organic pollutants	Complete degradation potential
Membrane filtration	Dissolved contaminants	High separation efficiency
Photocatalysis	Pharmaceuticals, pesticides	Environmentally friendly degradation
Constructed wetlands	Mixed wastewater contaminants	Low operating cost
Bioremediation	Organic contaminants	Eco-friendly treatment
Nanomaterials	Multiple contaminant classes	High catalytic performance

6. Challenges and Future Perspectives

Despite substantial progress in understanding and managing emerging contaminants, several scientific and technological challenges remain. One major limitation is the enormous diversity of contaminants entering aquatic environments each year. Thousands of new chemicals are introduced into commercial use annually, while only a small fraction undergo comprehensive environmental monitoring and risk assessment. Another challenge involves the detection of contaminants at ultra-trace concentrations and the identification of unknown transformation products formed during wastewater treatment or environmental degradation. These transformation products may exhibit toxicity equal to or greater than that of their parent compounds, highlighting the need for advanced analytical techniques capable of comprehensive contaminant screening. Current wastewater treatment infrastructure was not originally designed to remove emerging contaminants. Upgrading treatment plants with advanced oxidation processes, membrane technologies, adsorption systems, and biological treatment units requires substantial financial investment and technical expertise. Developing cost-effective, energy-efficient, and environmentally sustainable treatment technologies therefore remains a major research priority [16]. Future research should emphasize integrated remediation systems combining adsorption, photocatalysis, membrane filtration, nanotechnology, and biological treatment to maximize contaminant removal while minimizing operational costs. Artificial intelligence, machine learning, remote sensing, and smart environmental monitoring networks are expected to improve contaminant prediction, environmental surveillance, and treatment optimization [17]. Greater international collaboration, standardized monitoring protocols, stronger environmental regulations, and comprehensive ecotoxicological studies are essential for protecting aquatic ecosystems from the growing threat of emerging contaminants. The adoption of circular economy principles, green chemistry, sustainable manufacturing practices, and environmentally benign chemical design will further contribute to reducing contaminant release into aquatic environments.

7. Conclusion

Emerging contaminants have become one of the most significant environmental challenges affecting freshwater and marine ecosystems worldwide. Pharmaceuticals, personal care products, endocrine-disrupting chemicals, PFAS, pesticides, microplastics, nanomaterials, antibiotic resistance genes, and other newly recognized pollutants are continuously introduced into aquatic environments through municipal wastewater, industrial discharges, agricultural runoff, healthcare facilities, and urban activities. Their persistence, bioaccumulation potential, and biological activity at trace concentrations pose substantial risks to aquatic biodiversity, ecosystem functioning, drinking water quality, and human health. Recent advances in analytical chemistry, including chromatography coupled with high-resolution mass spectrometry, biosensors, nanotechnology-based sensors, and artificial intelligence-assisted monitoring, have greatly improved the detection and characterization of emerging contaminants. These technologies support more effective environmental monitoring, early risk assessment, and informed decision-making for pollution management. Innovative remediation technologies such as adsorption using activated carbon and biochar, advanced oxidation processes, photocatalysis, membrane filtration, constructed wetlands, bioremediation, and nanotechnology-based treatment systems have demonstrated considerable promise for removing emerging contaminants from contaminated waters. Hybrid treatment approaches integrating multiple remediation technologies are expected to provide enhanced removal efficiency while improving economic and environmental sustainability. Nevertheless, important challenges remain regarding contaminant diversity, mixture toxicity, transformation products, treatment costs, and regulatory standardization.

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