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Emerging Contaminants in Aquatic Ecosystems: Sources, Effects, and Mitigation Approaches

Xueli Zhang, Xiaohong Liu, Chunyang Zhan
Hainan Institute of Biotechnology, Haikou, 570206, Hainan, China
Corresponding author: chunyang.zhan@hitar.org
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Abstract This study explores emerging pollutants in aquatic ecosystems, their sources, impacts, and mitigation methods. With the progress of industrialization and population growth, more and more emerging pollutants (such as drug residues, pesticides, heavy metals, etc.) enter water bodies through various pathways, which have a profound impact on aquatic species and ecosystem services. The problem with the study is that the accumulation and continuous exposure of these pollutants not only pose a toxicological threat to aquatic organisms, but may also affect human health through the food chain and water sources. Therefore, it is important to identify the sources and pathways of emerging pollutants and their impacts on ecology and health, develop effective monitoring and treatment technologies, and promote adaptive policies on a global scale, providing a basis for further governance and protection work.
Keywords Emerging contaminants; Aquatic ecosystems; Bioaccumulation; Toxicological impact; Mitigation approaches

1 Introduction

Aquatic ecosystems, encompassing both marine and freshwater environments, cover over two-thirds of the Earth's surface and are vital for maintaining global climate stability and supporting biodiversity. These ecosystems provide essential services, including water purification, habitat for numerous species, and resources for human consumption and recreation (Álvarez-Ruiz and Picó, 2020; Häder et al., 2020). Freshwater systems, although covering only a small fraction of the Earth's surface, host a significant proportion of the planet's biodiversity, including many species that are not found anywhere else (Reid et al., 2018).

The increasing presence of emerging pollutants (EPs) in aquatic ecosystems poses a significant threat to both environmental and human health. These pollutants, which include pharmaceuticals, personal care products, heavy metals, pesticides, and microplastics, can be bioaccumulated and biomagnified, leading to adverse effects on aquatic biota and potential risks to humans through the consumption of contaminated water and organisms (Impellitteri et al., 2023). The impact of these contaminants is exacerbated by their ability to alter the physicochemical properties of water, disrupt food webs, and contribute to the decline of biodiversity (Gallardo et al., 2016; Reid et al., 2018). Understanding the sources, effects, and mitigation strategies for EPs is crucial for developing effective environmental policies and conservation efforts (Mierzejewska and Urbaniak, 2020).

This study provides a comprehensive overview of the current knowledge status of newly emerging pollutants in aquatic ecosystems. It will explore the various sources of these pollutants, their ecological and physiological impacts on aquatic organisms, and potential mitigation methods that can be used to reduce their effects; Emphasize the urgent need for stricter environmental regulations and innovative solutions to protect aquatic ecosystems and ensure their sustainability for future generations.

2 Identification of Emerging Contaminants

2.1 Definition and classification

Emerging contaminants (ECs), also known as contaminants of emerging concern (CECs), are a diverse group of chemicals that have recently been detected in the environment, primarily due to advancements in analytical techniques that allow for the identification of these substances even at trace levels (Stefanakis and Becker, 2020). These contaminants include a wide range of substances such as pharmaceuticals, personal care products, pesticides, hormones, nanomaterials, and microplastics (Naidu et al., 2016; Srikanth, 2019). ECs can be of synthetic origin or naturally occurring, and their environmental and public health risks are not yet fully understood due to limited data on their interactions and toxicological impacts (Hossein, 2019). The classification of ECs is broad and encompasses various categories, including but not limited to antibiotics, endocrine disruptors, industrial chemicals, and biological contaminants like bacteria and viruses (Gavrilescu et al., 2015; Nilsen et al., 2018). The continuous detection of new chemicals over time raises significant concerns regarding their fate, transport, transformations, and impacts on aquatic environments and human health.

2.2 Sources and pathways

The sources and pathways of emerging contaminants into aquatic ecosystems are diverse and complex. ECs can enter the environment through various anthropogenic activities, including agricultural runoff, wastewater effluents, industrial discharges, and urban runoff (Srikanth, 2019; Rathi et al., 2020). Wastewater treatment plants are significant point sources, as they often release pharmaceuticals, personal care products, and other chemicals directly into water bodies (Carere et al., 2021). Additionally, non-point sources such as agricultural fields contribute pesticides and fertilizers, which can leach into groundwater or be carried by surface runoff into rivers and lakes. The presence of ECs in the environment is further exacerbated by the continuous release of new chemicals, which are not routinely monitored and thus remain undetected until advanced analytical methods are applied. Once in the aquatic environment, these contaminants can persist and be transported across different environmental matrices, including water, soil, and sediments, potentially affecting a wide range of ecological receptors (Deere et al., 2021). The pathways of ECs are influenced by various factors, including their chemical properties, environmental conditions, and the presence of other contaminants, which can complicate their fate and behavior in the ecosystem. Understanding these sources and pathways is crucial for developing effective management and mitigation strategies to protect aquatic ecosystems and human health from the adverse effects of emerging contaminants.

3 Effects on Aquatic Life and Ecosystems

3.1 Toxicological impact on aquatic species

3.1.1 Endocrine disruption

Emerging contaminants (ECs), particularly endocrine-disrupting compounds (EDCs), have been shown to cause significant endocrine disruption in aquatic species. These compounds, which include pharmaceuticals and personal care products (PPCPs), can interfere with the hormonal systems of aquatic organisms, leading to reproductive and developmental abnormalities (Yuan, 2024). For instance, exposure to EDCs such as estrone (E1), estriol (E3), and 17α-ethynylestradiol (EE2) has been linked to feminization of male fish, reduced fertility, and altered sex ratios in fish populations (Su et al., 2020). The effects of these disruptions are often permanent and can impair the development of the endocrine system and the organs that respond to endocrine signals, leading to long-term consequences for affected species (Talib and Randhir, 2016).

3.1.2 Bioaccumulation

Bioaccumulation of ECs in aquatic organisms is another critical concern. Pharmaceuticals, personal care products, and other ECs can accumulate in the tissues of aquatic species, leading to toxic effects over time. Studies have shown that compounds such as azithromycin, DEET, diphenhydramine, and fluoxetine are frequently detected in aquatic environments and can bioaccumulate in fish and other organisms (Deere et al., 2021). This bioaccumulation can lead to sublethal effects, including behavioral changes, growth inhibition, and increased susceptibility to diseases (Saidulu et al., 2021). The persistence of these contaminants in the environment and their ability to bioaccumulate pose significant risks to aquatic life and can disrupt entire food webs.

3.2 Impacts on ecosystem services

The presence of ECs in aquatic ecosystems can have profound impacts on ecosystem services. These contaminants can alter the structure and function of aquatic communities, affecting biodiversity, water quality, and the overall health of the ecosystem. For example, ECs such as pharmaceuticals and personal care products can affect the growth and reproduction of key species, leading to changes in community composition and reductions in biodiversity (Prichard and Granek, 2016). Additionally, the presence of ECs can impair the ability of aquatic ecosystems to provide essential services such as water purification, nutrient cycling, and habitat provision (Bilal et al., 2019). The disruption of these services can have cascading effects on both aquatic and terrestrial ecosystems, highlighting the need for effective management and mitigation strategies to protect these vital resources (Gogoi et al., 2018).

4 Human Health Implications

4.1 Exposure pathways

Emerging contaminants in aquatic ecosystems can reach humans through various exposure pathways. One of the primary routes is through the consumption of contaminated seafood, which can lead to bioaccumulation and biomagnification of harmful substances such as mercury. Mercury, particularly in its methylmercury form, is a significant concern due to its potential for causing acute and chronic health issues in humans (Rodrigues et al., 2019). Additionally, the increase in water temperature due to global warming can exacerbate the toxicity of environmental contaminants, further affecting the food chain and ultimately human health (Manciocco et al., 2014). Contaminants can also be transferred from aquatic to terrestrial ecosystems through both biotic and abiotic pathways, such as emerging adult aquatic insects or flood events, which can then affect terrestrial food webs and human health (Schulz and Bundschuh, 2020). Moreover, the presence of microplastics in aquatic environments poses a risk as they can be ingested by aquatic organisms, which are then consumed by humans, leading to potential health risks (Foley et al., 2018).

4.2 Potential health risks

The potential health risks associated with emerging contaminants in aquatic ecosystems are diverse and significant. Mercury contamination, for instance, can lead to neurological and developmental issues, particularly in vulnerable populations such as pregnant women and young children (Rodrigues et al., 2019). The ingestion of contaminated fish and shellfish can result in the accumulation of various harmful substances, including heavy metals and persistent organic pollutants, which can cause a range of health problems from acute poisoning to long-term chronic diseases (Häder et al., 2020). The presence of microplastics in the food chain can also lead to physical and chemical hazards, as these particles can carry toxic chemicals and pathogens, potentially leading to gastrointestinal and other systemic health issues (Foley et al., 2018). Furthermore, the continuous release of pharmaceuticals, personal care products, and other emerging contaminants into aquatic environments can disrupt endocrine systems and lead to reproductive and developmental problems in humans (Impellitteri et al., 2023). The complexity of these contaminants and their interactions within the food web make it challenging to fully assess and mitigate their health risks, highlighting the need for advanced analytical methods and stricter environmental regulations (Lapworth et al., 2012; Hernández et al., 2019).

5 Detection and Monitoring

5.1 Analytical techniques for detection

5.1.1 Advanced spectroscopy

Advanced spectroscopy techniques have become indispensable in the detection of emerging contaminants in aquatic ecosystems. High-resolution mass spectrometry (HRMS) is particularly effective for the suspect and non-target screening of halogenated contaminants and their transformation products, which often exist in trace amounts (Badea et al., 2020). Additionally, techniques such as surface-enhanced Raman spectroscopy (SERS) and fluorescence spectroscopy offer significant advantages over traditional methods. These include high sensitivity, selectivity, and the ability to monitor contaminants in real-time, making them suitable for rapid and low-cost detection (Manivannan et al., 2020). Low-Resolution Raman Spectroscopy (LRRS) has also shown promise in detecting low concentrations of harmful cyanobacterial species within dense algal cultures, demonstrating its potential for real-time monitoring in bioreactors and other aquatic environments (Olubunmi et al., 2021).

5.1.2 Biomonitorin
Biomonitoring involves the use of living organisms to assess the presence and impact of contaminants in the environment. This approach is crucial for detecting a wide array of undetected contaminants that may be mobile and persistent across various environmental matrices, including water, soil, and sediments (Gavrilescu et al., 2015). The development of biosensors capable of real-time environmental monitoring is an emerging field that holds promise for the detection of multiple species of contaminants. These biosensors can exploit specialized microbes or enzymes to degrade endocrine disruptors and other micropollutants, thereby providing a more comprehensive understanding of the ecological and health risks posed by these contaminants (Lohmann et al., 2017).

5.2 Monitoring strategies
Effective monitoring strategies are essential for managing the risks associated with emerging contaminants in aquatic ecosystems. The Aquatic Global Passive Sampling (AQUA-GAPS) network exemplifies a strategic approach to global monitoring. This decentralized network uses passive sampling techniques to detect persistent organic pollutants (POPs) and other contaminants of concern in freshwater and coastal marine sites (Figure 1), thereby providing consistent and comparable data on a global scale (Lohmann et al., 2017). Another innovative approach involves the use of Effect-Based Methods (EBMs), which combine chemical analysis with eco-genotoxicological assays to assess the genotoxic activity of chemicals in urban river stretches. This method has proven effective in identifying the presence of pharmaceuticals, pesticides, and personal care products, even at low concentrations, and can inform future monitoring and remediation efforts (Carere et al., 2021).

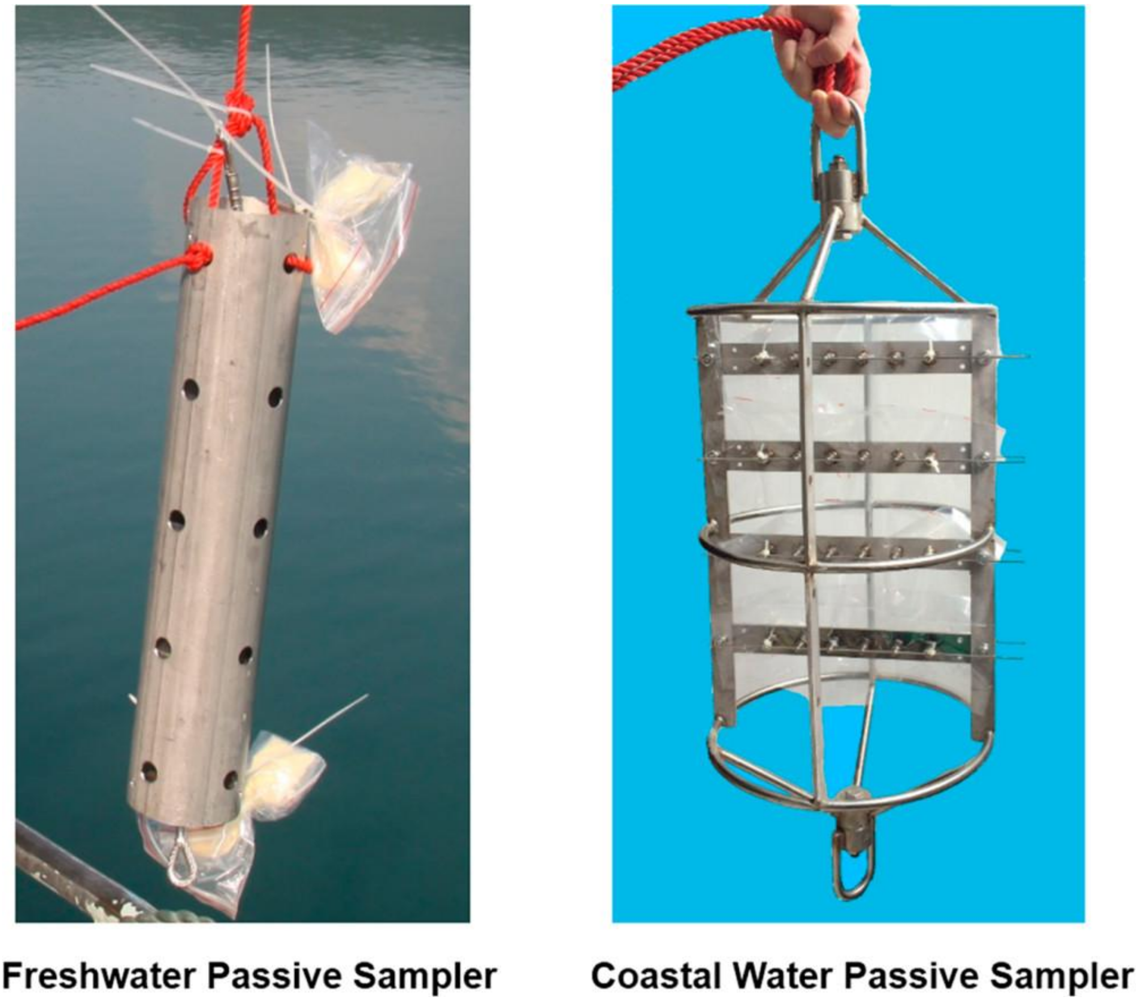

Figure 1 Passive samplers will be deployed, equipped with both polyethylene and silicone rubber samplers (Adopted from Lohmann et al., 2017)

6 Mitigation and Treatment Approaches

6.1 Conventional treatment technologies

Conventional treatment technologies have been the cornerstone of water treatment for decades. These methods typically include primary, secondary, and tertiary treatment processes. Primary treatment involves the physical removal of large particles through sedimentation, while secondary treatment employs biological processes to degrade organic matter. However, these conventional methods are often insufficient for the complete removal of emerging contaminants (ECs) such as pharmaceuticals, personal care products, and endocrine-disrupting chemicals. Studies have shown that these contaminants persist through traditional treatment processes, leading to their accumulation in aquatic ecosystems and posing significant risks to human and wildlife health (Rodríguez-Narváez et al., 2017; Gogoi et al., 2018; Rasheed et al., 2019). The inefficacy of conventional methods necessitates the exploration of more advanced and integrated treatment approaches to address the challenges posed by ECs.

6.2 Emerging technologies

Emerging technologies offer promising solutions for the effective removal of ECs from water bodies. Advanced oxidation processes (AOPs), membrane filtration, and adsorption techniques have shown significant potential in recent studies. AOPs, which include methods such as ozonation and photocatalysis, are effective in breaking down complex organic contaminants into less harmful substances (Bilal et al., 2019). Membrane filtration technologies, such as nanofiltration and reverse osmosis, provide high removal efficiencies for a wide range of ECs, although they can be cost-prohibitive (Talib and Randhir, 2016). Adsorption using low-cost adsorbents, such as biochar and agricultural waste, has also been identified as a viable and sustainable option for EC removal (Varsha et al., 2021; Rathi and Kumar, 2021). Additionally, biological treatment methods, including the use of microalgae and enzyme-assisted biodegradation, have shown promise in degrading and removing ECs from wastewater (Singh et al., 2021). These emerging technologies, while still under development and optimization, represent a critical advancement in the field of water treatment.

6.3 Policy and regulation

Effective management of ECs in aquatic ecosystems requires robust policy and regulatory frameworks. Current regulations often fall short in addressing the complexities associated with ECs, primarily due to the lack of comprehensive health standards and guidelines for these contaminants (Gogoi et al., 2018). Policymakers need to develop and implement stringent regulations that encompass the entire lifecycle of ECs, from their production and use to their disposal and treatment. This includes setting permissible limits for EC concentrations in water bodies, promoting the use of best management practices, and encouraging the adoption of advanced treatment technologies. Additionally, public awareness and education campaigns are essential to modify human behavior and reduce the release of ECs into the environment (Talib and Randhir, 2016; Deere et al., 2021). Collaborative efforts between governments, industries, and the scientific community are crucial to establish effective policies and regulations that safeguard both environmental and public health.

7 Case Studies

7.1 Successful remediation cases

Successful remediation of aquatic ecosystems contaminated by emerging pollutants has been achieved through various innovative approaches. One notable method involves the use of bioturbators, which are organisms that disturb sediment layers (Wu and Chen, 2024), thereby enhancing microbial processes that facilitate contaminant removal. A systematic review and meta-analysis have shown that bioturbators, such as polychaetes, can significantly increase the release of metals and nutrients from sediments, thus aiding in the bioremediation process. The effectiveness of this method varies depending on environmental factors such as temperature, pH, and sediment grain size, highlighting the need for context-specific applications (Pal et al., 2010). Additionally, the application of Effect-Based Methods (EBMs) in urban river stretches has proven effective in identifying and mitigating the presence of genotoxic and teratogenic pollutants. For instance, in the Tiber River, EBMs have been used to detect and address the diffuse chemical pollution caused by pharmaceuticals, pesticides, and personal care products, leading to improved water quality and ecosystem health (Carere et al., 2021).

7.2 The aral sea recovery project

The Aral Sea, once one of the largest lakes in the world, has faced severe ecological degradation due to extensive water diversion for agricultural purposes. Efforts to recover the Aral Sea have focused on reducing the inflow of pollutants and restoring natural water levels. One of the key strategies has been the implementation of advanced water treatment technologies to remove emerging contaminants from inflowing rivers. These technologies include adsorption processes, membrane filtration, and advanced oxidation processes, which have been shown to effectively remove a wide range of micropollutants, including pharmaceuticals and endocrine disruptors (Mohanavelu et al., 2021). The success of these technologies in the Aral Sea Recovery Project underscores the importance of adopting state-of-the-art treatment methods to address complex contamination issues in large aquatic ecosystems.

7.3 Cleanup of the ganges river

The Ganges River, one of the most polluted rivers in the world, has been the focus of numerous cleanup initiatives aimed at reducing the levels of emerging contaminants. The river is heavily contaminated with pharmaceuticals, personal care products, and industrial chemicals, which pose significant risks to both human health and aquatic life. Recent efforts have included the deployment of integrated water quality assessment methods that combine chemical analyses with eco-genotoxicological assays. These methods have been instrumental in identifying the sources and impacts of pollution, thereby guiding targeted remediation efforts (Carere et al., 2021). Additionally, the use of biological treatment methods, such as the application of bioturbators, has shown promise in enhancing the natural attenuation of contaminants in the river sediments (Gonzalez et al., 2019). These combined approaches have led to measurable improvements in water quality and have set a precedent for future remediation projects in similarly polluted rivers around the world.

8 Concluding Remarks

Emerging contaminants (ECs), including pharmaceuticals, personal care products (PPCPs), endocrine-disrupting compounds (EDCs), and other chemicals, have been detected in various aquatic environments worldwide. These contaminants pose significant risks to both human health and aquatic ecosystems due to their persistence and bioaccumulation potential. Studies have shown that current wastewater treatment plants are not adequately designed to remove these contaminants, leading to their widespread presence in surface water, groundwater, and even drinking water. The adverse effects of ECs on aquatic life, such as reproductive and developmental abnormalities, have been well-documented, highlighting the urgent need for effective mitigation strategies. Additionally, the presence of ECs in sediments and their association with microplastics further complicates their environmental impact.

Future research should focus on several key areas to address the challenges posed by emerging contaminants. First, there is a need for comprehensive toxicity data to better understand the sublethal effects of ECs on aquatic organisms and ecosystems. Second, the development of advanced treatment technologies that can efficiently remove a wide range of ECs from wastewater is crucial. This includes exploring cost-effective and sustainable methods such as adsorption, nanofiltration, and advanced oxidation processes. Third, more research is needed to understand the fate and transformation of ECs in different environmental compartments, including their interactions with microplastics and other pollutants. Finally, long-term monitoring programs should be established to track the occurrence and effects of ECs in various aquatic environments, providing valuable data for risk assessment and management.

To mitigate the risks associated with emerging contaminants, several policy recommendations are proposed. Regulatory agencies should establish and enforce stringent guidelines for the discharge of ECs into the environment, including setting maximum allowable concentrations for various contaminants. There is also a need for international collaboration to develop standardized methods for monitoring and assessing the environmental impact of ECs. Public awareness campaigns and educational programs can play a vital role in reducing the release of ECs by promoting responsible disposal of pharmaceuticals and personal care products. Additionally, incentives for industries to adopt green chemistry practices and develop environmentally friendly alternatives to harmful chemicals should be encouraged. Implementing these policy measures will require a coordinated effort from governments, industries, and the scientific community to protect aquatic ecosystems and public health from the adverse effects of emerging contaminants.

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Conflict of Interest Disclosure
The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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