Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 3 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Emerging Contaminants in Marine Ecosystems: Ecological Threats and Management Strategies

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ABSTRACT

Emerging contaminants in marine ecosystems have become a significant environmental issue globally due to their widespread presence, persistence, and potential ecological and toxicological risks. This research critically synthesizes the current knowledge on the primary categories of emerging contaminants, including micro plastics, pharmaceuticals and personal care products (PPCPs), per- and polyfluoroalkyl substances (PFAS), endocrine-disrupting chemicals, and other industrial pollutants. Toxins are introduced into marine ecosystems by many anthropogenic sources, such as wastewater discharge, agricultural runoff, industrial effluents, and maritime activities. Upon discharge, they exhibit complex environmental behaviours like as long-distance migration, sediment buildup, bioaccumulation, and trophic transfer throughout marine food webs. The reviewed literature indicates that emerging contaminants can inflict significant detrimental effects on marine organisms, including oxidative stress, endocrine disruption, reproductive impairment, developmental toxicity, and behavioral abnormalities. Moreover, concurrent exposure to many pollutants may provide synergistic or additive harmful effects, so amplifying ecological issues beyond those posed by individual contaminants. Notwithstanding the increasing interest in research, substantial deficiencies persist in information pertaining to long-term monitoring, mixture toxicity studies, deep-sea pollution, and standardized analytical methodologies. Moreover, the current remediation techniques and regulatory structures remain insufficient to address the increasing intricacy of marine pollution.

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The evaluation emphasizes the immediate necessity for cohesive monitoring systems, advanced treatment technologies, and enhanced environmental regulations to mitigate the hazards posed by emerging contaminants. A multidisciplinary approach encompassing environmental research, toxicology, and policy formulation is essential to safeguard marine ecosystem health and ensure long-term sustainability.

Keywords: Emerging contaminants, Marine pollution, Micro plastics, PFAS, Ecological risk assessment, Management Approaches

1. Introduction

1.1 Marine Environment and Global Ecological Importance

Marine ecosystems represent one of the largest and most diverse ecological systems on Earth, covering around 71% of the planet's surface and supporting a myriad of biological, chemical, and physical processes essential for life. The oceans provide vital ecological services including climate management, nutrient cycling, carbon sequestration, food production, transportation, and biodiversity conservation. Marine environments provide millions of livelihoods through fishing, aquaculture, and tourism businesses. Nonetheless, increasing human-induced pressures have significantly altered the structure and function of marine ecosystems, prompting concerns over environmental quality and ecological sustainability (Halpern et al., 2019). Accelerated industrialization, urban expansion, intensive agriculture, and population growth have heightened the influx of pollutants into coastal ecosystems. Long-term monitoring has focused on traditional pollutants such as heavy metals and persistent organic pollutants; nevertheless, there is increasing apprehension over newly identified chemicals that pose considerable ecological and toxicological risks and remain largely uncontrolled (Zhou et al., 2024).

1.2 Concept and Classification of Emerging Contaminants

Emerging contaminants (ECs) are chemical compounds that have recently been detected in environmental matrices or recognised for their implications on environmental and human health. These pollutants are not novel chemicals; nonetheless, enhanced analytical capabilities have augmented their detection and heightened awareness of their environmental significance.

Emerging contaminants encompass a wide array of chemicals, including pharmaceuticals and personal care products (PPCPs), endocrine-disrupting compounds (EDCs), microplastics, antibiotics, per- and polyfluoroalkyl substances (PFAS), plasticisers, pesticides, nanomaterials, flame retardants, and disinfection by-products (DBPs). A multitude of these contaminants exhibit environmental persistence, possess bioaccumulation potential, are hazardous, and defy degradation processes, hence raising significant concerns for marine ecosystems (Zhou et al., 2024; Science of the Total Environment, 2024).

1.3 Sources and Pathways of Emerging Contaminants in Marine Systems

Numerous pathways exist via which developing contaminants penetrate marine ecosystems. Primary sources encompass effluents from wastewater treatment facilities, industrial discharges, agricultural runoff, pharmaceutical residues, domestic sewage, maritime activities, aquaculture operations, and atmospheric deposition. Urban wastewater systems are regarded as a primary conduit for pollution transfer, as these substances are not consistently eradicated by conventional treatment methods. Micro plastics and pharmaceutical contaminants have been progressively recorded in coastal streams, estuaries, sediments, and

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marine organisms globally. Due to the strong carbon-fluorine bonds, PFAS compounds, referred regarded as "forever chemicals," have significant persistence and mobility, enabling them to traverse extensive distances in aquatic environments (Qiqi et al., 2024).

1.4 Ecological Risks Associated with Emerging Contaminants

The presence of emerging contaminants in marine ecosystems has raised considerable ecological concerns because of their potential effects on aquatic organisms and food web dynamics. These contaminants may induce acute and chronic toxicity, endocrine disruption, reproductive abnormalities, oxidative stress, developmental impairments, and behavioral changes in marine organisms.

Microplastics may function as carriers of other pollutants by adsorbing contaminants onto their surfaces and facilitating transport through aquatic food chains. Their interactions with PFAS and other toxic substances may increase ecological risks through synergistic effects. Recent studies have suggested that combinations of contaminants may exhibit greater toxicity than individual contaminants alone, highlighting the complexity of marine pollution scenarios (Journal of Contaminant Hydrology, 2024).

Furthermore, contaminant bioaccumulation and biomagnification may affect higher trophic levels and potentially influence human health through seafood consumption. Long-term exposure to these contaminants may disrupt ecosystem stability and biodiversity conservation efforts (Science of the Total Environment, 2024).

1.5 Need for Effective Monitoring and Management Strategies

Despite increasing concern regarding emerging contaminants, effective environmental monitoring and regulatory frameworks remain limited in many regions. Existing water treatment technologies often demonstrate insufficient removal efficiencies for persistent contaminants such as PFAS and microplastics. Consequently, advanced treatment methods including membrane filtration, adsorption technologies, advanced oxidation processes, nanotechnology-based approaches, and biological remediation strategies have gained increasing research attention (Zhou et al., 2024).

Additionally, integrated environmental policies emphasizing pollution prevention, sustainable waste management, risk assessment, and international collaboration are required to minimize contaminant release and protect marine ecosystems. Strengthening monitoring systems and implementing effective management strategies will be essential for maintaining marine ecological integrity and achieving long-term environmental sustainability.

1.6 Scope and Objectives of the Review

This review aims to provide a comprehensive overview of emerging contaminants in marine environments by discussing their major types, occurrence, sources, transport pathways, ecological risks, and management approaches. The review further highlights current research advances and identifies knowledge gaps requiring future investigation for effective marine environmental protection.

2. Literature Review

2.1 Overview of Emerging Contaminants in Marine Environments

Emerging contaminants (ECs) have become a major focus of environmental research because of their increasing occurrence and persistence in aquatic systems. Unlike

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conventional pollutants, these compounds have only recently gained attention due to improvements in analytical techniques and growing evidence of their ecological impacts. Emerging contaminants comprise diverse chemical groups including pharmaceuticals and personal care products (PPCPs), endocrine-disrupting compounds (EDCs), micro plastics, antibiotics, nanomaterials, flame retardants, and per- and polyfluoroalkyl substances (PFAS). These compounds are continuously introduced into marine environments through anthropogenic activities and may persist for extended periods because of resistance to natural degradation processes (Zhou Q et al., 2024).

Recent investigations have demonstrated that marine contamination is not restricted to coastal areas alone; contaminants have also been detected in open oceans, sediments, and deep-sea ecosystems, suggesting their extensive global distribution (Yu et al., 2024).

2.2 Pharmaceuticals and Personal Care Products (PPCPs) in Marine Ecosystems

Pharmaceuticals and personal care products are among the most frequently detected emerging contaminants in marine environments. These compounds include antibiotics, analgesics, hormones, cosmetics, and disinfectants. Their primary sources include wastewater treatment plant discharges, domestic sewage, hospital effluents, and aquaculture activities (Punginelli D et al., 2023).

Because many pharmaceutical compounds possess biological activity and incomplete removal during wastewater treatment, they may remain environmentally persistent. Marine organisms exposed to pharmaceutical residues can experience endocrine disruption, reproductive abnormalities, altered behavior, and physiological stress responses. Studies have particularly identified antibiotics and hormonal compounds as significant ecological concerns because of their potential role in antimicrobial resistance and hormonal disturbances in marine species.

2.3 Microplastics as Emerging Marine Pollutants

Microplastics, generally defined as plastic particles smaller than 5 mm, have emerged as a serious environmental concern worldwide. Sources of microplastics include degradation of larger plastic materials, industrial waste, personal care products, synthetic fibers, and fishing activities.

Numerous studies have documented the occurrence of microplastics in seawater, marine sediments, shellfish, fish species, and marine mammals. Their small size enables ingestion by organisms across multiple trophic levels, increasing the possibility of food-web transfer and bioaccumulation. Additionally, microplastics can function as carriers for other contaminants by adsorbing toxic chemicals onto their surfaces (Biswas et al., 2024).

Growing evidence also indicates that microplastics may influence physiological functions including feeding behavior, metabolism, growth performance, and reproductive capacity in aquatic organisms (agboola & Benson, 2021).

2.4 Per- and Polyfluoroalkyl Substances (PFAS) in Marine Systems

Per- and polyfluoroalkyl substances (PFAS), often termed "forever chemicals," represent a class of synthetic chemicals characterized by exceptional chemical stability and resistance to environmental degradation. These compounds have been extensively used in industrial manufacturing, firefighting foams, packaging materials, textiles, and consumer products.

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PFAS contamination has become a growing environmental issue because of their persistence and mobility within aquatic systems. Studies have demonstrated that PFAS can accumulate in fish tissues and marine organisms even in locations distant from known pollution sources. Such persistence raises concerns regarding ecological and human health consequences through seafood consumption pathways (Saetchnikov et al., 2023).

Their resistance to conventional wastewater treatment methods further complicates environmental management efforts (Wang et al., 2024).

2.5 Bioaccumulation and Trophic Transfer of Emerging Contaminants

Bioaccumulation refers to the progressive accumulation of contaminants within biological tissues over time, while bio magnification describes increasing contaminant concentrations at higher trophic levels. Several studies have reported that emerging contaminants may accumulate in marine organisms including fish, mollusks, crustaceans, and marine mammals.

Persistent contaminants such as PFAS and micro plastics exhibit strong potential for trophic transfer through marine food chains. Long-term accumulation may influence biodiversity, ecosystem stability, and human health due to seafood consumption. Recent studies suggest that contaminant transfer across trophic levels represents one of the most critical environmental pathways affecting marine ecosystems (Giroux et al., 2024).

2.6 Combined Toxicity and Synergistic Effects of Emerging Contaminants

Traditionally, contaminants have been evaluated individually; however, marine organisms are frequently exposed to mixtures of pollutants simultaneously. Recent evidence indicates that interactions among contaminants may increase toxicity beyond expected levels.

Studies investigating interactions between PFAS and micro plastics demonstrated enhanced adverse effects including reduced reproductive performance, developmental abnormalities, and physiological stress responses in aquatic organisms. Such findings indicate that combined contaminant exposure may represent a greater ecological risk than isolated pollutant exposure (Isukuru *et al.*, 2026).

This emerging area of research highlights the importance of mixture-based risk assessment approaches in marine environmental studies.

2.7 Current Challenges in Monitoring Emerging Contaminants

Monitoring emerging contaminants remains challenging because of their chemical diversity, low environmental concentrations, and limited regulatory frameworks. Conventional detection techniques often require highly sensitive analytical instruments and standardized methodologies.

Recent developments in sensor technologies, high-resolution mass spectrometry, and advanced molecular approaches have improved contaminant detection and monitoring capabilities. Nevertheless, substantial knowledge gaps remain regarding long-term environmental behavior and ecological consequences (Lian et al., 2025).

3. Methodology

3.1 Research Design

This study conducted a comprehensive narrative review of emerging contaminants in marine environments, encompassing their origins, prevalence, ecological

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implications, and management strategies. The review methodology was employed to consolidate the available scientific literature and to provide a comprehensive understanding of current knowledge, research deficiencies, and future perspectives on marine pollution studies. This review did not incorporate field sampling and laboratory experiments typical of experimental research; instead, it utilised published papers, reports, and peer-reviewed authoritative sources to compile and critically evaluate the available evidence.

3.2 Literature Search Strategy

A thorough literature review was conducted to find pertinent studies on emerging contaminants in marine ecosystems, employing significant scientific databases including Science Direct, Springer Link, Wiley Online Library, PubMed, Scopus, and Google Scholar. The search strategy employed meticulously chosen combinations of keywords, including "emerging contaminants in marine environments," "micro plastics ocean pollution," "PFAS marine contamination," "pharmaceuticals in seawater," "marine ecosystem toxicity pollutants," and "marine pollution management strategies." Boolean operators (AND, OR) were employed to refine the search process, enhance accuracy, and ensure that only highly relevant and topic-specific content was incorporated into the review.

3.3 Inclusion and Exclusion Criteria

To ensure quality and relevance of selected literature, the following criteria were applied:

Inclusion Criteria:

This review encompassed peer-reviewed journal articles and publications from 2015 to 2026, with a particular emphasis on research conducted between 2020 and 2026, as well as those pertinent to marine or aquatic environments. Additionally, literature about new contaminants, toxicity, and remediation strategies were incorporated. To achieve a comprehensive synthesis of the current scientific literature, review articles, original research papers, and meta-analyses were considered.

Exclusion Criteria:

articles and blogs without peer review, studies unrelated to marine ecosystems, duplicate publications, and articles not accessible in full text were eliminated from this evaluation. Research focusing solely on land pollution was dismissed unless a direct and substantiated connection to maritime shipping or marine environmental contamination pathways was shown.

3.4 Data Extraction and Organization

Data were systematically extracted from the selected literature based on key aspects, including types of emerging contaminants (e.g., microplastics, PFAS, pharmaceuticals, and personal care products), sources and pathways into marine systems, distribution and occurrence in marine environments, toxicological and ecological effects, and documented remediation and management strategies. The collected data was subsequently grouped into topics, facilitating a coherent and logical discourse throughout the review and enabling the synthesis and comparison of findings across studies.

3.5 Quality Assessment of Literature

Each chosen study underwent a rigorous evaluation based on several quality criteria, including the journal's impact and credibility, sample size, methodological rigour (particularly for experimental studies), relevance to marine ecosystems, clarity of

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presentation, reproducibility of results, and citation frequency as a measure of scientific recognition. This study selected studies published in high-impact, peer-reviewed journals and the latest publications to ensure the reliability, validity, and scientific relevance of the synthesized information.

3.6 Data Analysis Approach

This review utilized a qualitative synthesis method for analysis. A thorough evaluation of the pertinent literature was conducted, evaluated, and synthesized into key topic categories, including sources and routes of pollutants, environmental dispersion patterns, ecological and toxicological effects, and mitigation and management approaches. This thematic approach facilitated a comprehensive understanding of emerging contaminants in the marine environment by identifying analogous patterns and distinctions across research studies. The variability of the existing studies, the inconsistencies in methodologies, and the alterations in reporting formats throughout the reviewed literature precluded the execution of a statistical meta-analysis.

3.7 Limitations of the Methodology

Although this review provides a comprehensive synthesis, certain limitations exist:

- Dependence on previously published data
- Potential publication bias toward positive results
- Limited availability of long-term ecological studies for some contaminants
- Variability in analytical methods across studies

4. Results and Discussion

4.1 Overview of Emerging Contaminants in Marine Environments

The literature review indicates escalating effects on marine ecosystems due to various emerging contaminants, including microplastics, pharmaceuticals and personal care products (PPCPs), per- and polyfluoroalkyl substances (PFAS), endocrine-disrupting chemicals (EDCs), pesticides, and industrial additives. The persistence and worldwide spread of these pollutants are evidenced by their prevalence in seawater, sediments, and marine animals across coastal, estuarine, and deep-sea ecosystems. Recent studies have shown that they are not confined to heavily industrialised regions but also occur in distant coastal environments, indicating their capacity for long-distance transmission and global environmental significance (Zhou et al., 2024).

4.2 Sources and Distribution Patterns

Research indicates that the primary pathway for the introduction of newest contaminants into marine systems is via effluents from wastewater treatment plants. Agricultural runoff, industrial discharges, maritime operations, aquaculture practices, and atmospheric deposition are significant contributors to marine pollution loads. The dispersion of these contaminants throughout the marine environment is complex and influenced by hydrodynamics, salinity, temperature, and sediment interactions. Micro plastics predominantly inhabit coastal areas and surface water; however they have also been shown to build in deep-sea sediments. Likewise, PFAS compounds have high mobility and may be transported across extensive distances owing to their chemical stability. Pharmaceuticals and antibiotics are increasingly detected in estuary and nearshore waters due to continuous discharge from metropolitan populations.

4.3 Bioaccumulation and Trophic Transfer

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The reviewed studies consistently demonstrate that emerging contaminants have the ability to bio accumulate in marine organisms and transfer across trophic levels. Micro plastics have been detected in a wide range of organisms, including plankton, bivalves, fish, and marine mammals. Their ingestion can lead to physical and chemical stress, including gut blockage, reduced feeding efficiency, and metabolic disruption.

PFAS and certain pharmaceuticals have been shown to accumulate in fish tissues, raising concerns about human exposure through seafood consumption. Bio magnification processes suggest that higher trophic level organisms, such as predatory fish and marine mammals, may experience greater contaminant burdens compared to lower trophic levels.

4.4 Ecological and Toxicological Effects

The ecological impacts of emerging contaminants are diverse and depend on the type, concentration, and exposure duration. Microplastics can induce oxidative stress, inflammation, and reproductive toxicity in marine organisms. Additionally, they act as carriers for other toxic substances, increasing their bioavailability and combined toxicity.

Pharmaceuticals, particularly antibiotics and hormones, have been linked to endocrine disruption, behavioral changes, and antimicrobial resistance in aquatic ecosystems. PFAS compounds are associated with immune system impairment, developmental toxicity, and long-term persistence in biological tissues.

Overall, the literature suggests that mixture toxicity is a major concern, as marine organisms are exposed to multiple contaminants simultaneously, leading to synergistic or additive effects that are often more severe than individual exposures.

4.5 Combined Pollution Effects and Synergistic Interactions

Recent studies highlight that emerging contaminants rarely exist in isolation in marine environments. Instead, complex mixtures of microplastics, heavy metals, pharmaceuticals, and industrial chemicals interact in ways that may amplify ecological risks. For example, microplastics can adsorb PFAS, pesticides, and organic pollutants, facilitating their transport and ingestion by marine organisms.

Such synergistic interactions increase toxicity levels and complicate risk assessment models, as traditional single-substance evaluation approaches may underestimate actual environmental risks. This highlights the need for integrated assessment frameworks that consider combined contaminant effects.

4.6 Current Management and Remediation Approaches

The literature identifies several management strategies aimed at reducing emerging contaminant pollution in marine environments. Advanced wastewater treatment technologies such as membrane filtration, activated carbon adsorption, ozonation, and advanced oxidation processes have shown promising results in removing contaminants from effluents before discharge.

Bioremediation approaches using microorganisms and phytoremediation using marine plants are emerging as sustainable alternatives. Additionally, policy-based interventions focusing on plastic waste reduction, pharmaceutical regulation, and industrial discharge control are essential for long-term mitigation.

Despite these advances, current treatment systems are often insufficient to completely eliminate persistent compounds such as PFAS and microplastics, indicating a need for technological innovation and stronger regulatory frameworks.

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4.7 Research Gaps Identified

The review identifies several key research gaps, including limited long-term monitoring data, insufficient understanding of deep-sea contamination, lack of standardized detection methods, and inadequate assessment of mixture toxicity. Furthermore, the ecological impacts of many newly identified contaminants remain poorly understood, particularly in tropical and developing regions.

There is also a need for improved global monitoring networks and harmonized methodologies to better assess the environmental fate and ecological risks of emerging contaminants.

6. Future Research Perspectives and Knowledge Gaps

6.1 Need for Long-Term Monitoring and Global Surveillance

Despite significant progress in identifying emerging contaminants in marine environments, long-term monitoring data remain limited across most regions of the world, particularly in developing and tropical countries. Most existing studies are short-term and localized, making it difficult to assess temporal trends, seasonal variability, and long-term ecological impacts. Future research should prioritize the establishment of continuous global monitoring networks that integrate coastal, offshore, and deep-sea sampling stations. Such systems would allow for standardized data collection and facilitate global comparisons of contamination levels and trends over time.

In addition, the development of real-time monitoring technologies, including biosensors and remote sensing tools, could significantly enhance early detection and tracking of emerging contaminants in marine ecosystems.

6.2 Standardization of Analytical Methods

One of the major challenges identified in the literature is the lack of standardized methodologies for detecting and quantifying emerging contaminants. Variability in sampling techniques, extraction procedures, and analytical instruments often leads to inconsistencies in reported data, making cross-study comparisons difficult.

Future research should focus on the development of globally standardized protocols for sampling, detection, and reporting of contaminants such as microplastics, PFAS, and pharmaceuticals. Harmonized analytical frameworks would improve data reliability, reproducibility, and comparability across different geographical regions and research groups.

6.3 Understanding Mixture Toxicity and Synergistic Effects

Most existing toxicological studies have focused on single-contaminant exposure; however, marine organisms are typically exposed to complex mixtures of pollutants in natural environments. The interactions between microplastics, heavy metals, pharmaceuticals, and persistent organic pollutants may result in additive, synergistic, or antagonistic effects that are not yet fully understood.

Future research should prioritize mixture toxicity studies under environmentally realistic conditions. Advanced experimental approaches, including multi-stressor exposure experiments and computational toxicology models, are needed to better predict combined effects on marine organisms and ecosystems.

6.4 Fate, Transport, and Transformation Processes

Although the occurrence of emerging contaminants in marine environments is well documented, their long-term fate, transport mechanisms, and transformation pathways remain poorly understood. Processes such as photodegradation,

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biodegradation, sedimentation, adsorption, and desorption significantly influence contaminant behavior in marine systems.

Future studies should investigate the transformation products of emerging contaminants, as these by-products may sometimes be more toxic than parent compounds. Improved modeling approaches integrating oceanographic, chemical, and biological processes are also required to predict contaminant movement and persistence in marine ecosystems.

6.5 Impacts on Deep-Sea and Polar Ecosystems

Most research on marine contamination has focused on coastal and estuarine environments, while deep-sea and polar regions remain largely underexplored. However, recent evidence suggests that even remote environments are not free from contamination, as microplastics and persistent chemicals have been detected in deep ocean sediments and Arctic waters.

Future research should expand geographic coverage to include deep-sea ecosystems, polar regions, and hydrothermal vent systems. Understanding contamination in these extreme environments is essential for assessing the global scale of marine pollution and its ecological consequences.

6.6 Development of Advanced Remediation Technologies

Current wastewater treatment systems are often insufficient for complete removal of persistent emerging contaminants such as PFAS, microplastics, and certain pharmaceuticals. There is a critical need for the development of more efficient, cost-effective, and environmentally sustainable remediation technologies.

Future research should explore advanced oxidation processes, nanotechnology-based filtration systems, bioengineered microbial consortia, and hybrid treatment systems. Additionally, the potential of marine organisms for bioremediation, including algae and bacteria capable of degrading contaminants, should be further investigated.

6.7 Ecological and Human Health Risk Assessment

While many studies have focused on environmental occurrence, fewer have addressed the long-term ecological and human health risks associated with chronic exposure to emerging contaminants. Bioaccumulation in seafood raises significant concerns regarding human dietary exposure, particularly in coastal communities dependent on marine resources.

Future research should integrate ecological risk assessment with human health risk evaluation using interdisciplinary approaches. This includes linking environmental contamination data with toxicological, epidemiological, and food safety studies to better understand exposure pathways and health outcomes.

6.8 Policy Development and Regulatory Frameworks

A significant gap exists between scientific findings and environmental policy implementation. Many emerging contaminants remain unregulated or poorly regulated at national and international levels. This regulatory gap limits effective management and mitigation efforts.

Future research should support the development of evidence-based policies and regulatory frameworks for emerging contaminants. Strengthening international collaboration and harmonizing environmental standards will be essential for effective global management of marine pollution.

6.9 Integration of Artificial Intelligence and Modeling Tools

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Recent advancements in artificial intelligence (AI), machine learning, and environmental modeling offer promising tools for predicting contaminant distribution, toxicity, and environmental behavior. However, these approaches are still underutilized in marine contamination research.

Future studies should integrate AI-based predictive models with environmental datasets to improve forecasting of contamination hotspots, ecological risks, and remediation outcomes. Such approaches can significantly enhance decision-making processes in environmental management.

7. Conclusion

Emerging contaminants in marine ecosystems represent a rapidly escalating and complex environmental issue with significant ecological, toxicological, and socio-economic implications. The current analysis indicates that micro plastics, medicines, personal care items, per- and polyfluoroalkyl substances (PFAS), endocrine-disrupting chemicals, and various industrial compounds are increasingly pervasive in marine ecosystems worldwide. Their extensive distribution, resilience, and potential for long-range mobility illustrate the global extent of marine pollution. This study indicates that novel contaminants originate from several anthropogenic sources, namely wastewater effluents, agricultural runoff, industrial discharges, and maritime activities. In maritime environments, these contaminants exhibit complex environmental destiny behaviours, including adsorption to sediments, bioaccumulation in marine organisms, and trophic transfer throughout food webs. Such processes raise concerns over long-term biodiversity decline and ecological instability, hence augmenting the likelihood of ecosystem-level disturbance.

Eco toxicological research indicates that exposure to emerging contaminants may lead to a range of harmful biological effects, including oxidative stress, endocrine disruption, reproductive impairment, developmental abnormalities, and behavioral changes in marine animals. The combination and synergistic toxicity of pollutant mixtures is particularly concerning, since it may elevate ecological risks above those assessed from single component exposure estimates.

Researchers are progressively investigating the issue of marine pollution; yet, several challenges remain in effectively addressing it. This encompasses insufficient long-term monitoring data, weak understanding of deep-sea and polar pollution, absence of standardized testing methodologies, and deficient regulatory frameworks for several emerging contaminants. Moreover, current wastewater treatment and remediation techniques typically fail to completely eliminate highly persistent pollutants like PFAS and micro plastics. In conclusion, emerging contaminants pose a significant threat to the health and sustainability of marine ecosystems. A multi-disciplinary approach is required to address this issue, incorporating advanced monitoring technologies, innovative remediation strategies, robust ecological risk assessment frameworks, and strengthened environmental laws. Future research must concentrate on global monitoring systems, standardized methodologies, evaluation of combinatorial toxicity, and the creation of sustainable, cost-effective therapeutic alternatives. International collaboration will be essential to mitigate the impacts of emerging contaminants and to guarantee the enduring preservation of marine biodiversity and ecosystem services.

References

Agboola, O. D., & Benson, N. U. (2021). Physisorption and chemisorption

Annual Methodological Archive Research Review
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Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

mechanisms influencing micro (nano) plastics-organic chemical contaminants interactions: a review. *Frontiers in Environmental Science*, *9*, 678574.

Biswas, B., Joseph, A., Ranjan, V. P., & Goel, S. (2024). Adsorption of emerging contaminants on microplastics in the environment: a systematic review. *ACS ES&T Water*, *4*(12), 5207-5224.

Giroux, M. S., Siddiqui, S., & Brander, S. M. (2024). Classic contaminants in aquatic ecosystems: POPs, PFAS, heavy metals, and microplastics. In *Aquatic ecotoxicology: Understanding pollutants, aquatic organisms, and their environments* (pp. 43-58). Cham: Springer International Publishing.

Halpern BS, Frazier M, Potapenko J, et al. (2019). Recent pace of change in human impact on the world's ocean. *Scientific Reports*, 9:11609.

Isukuru, E. J., Isaiah, O. W., Okpanachi, V., Okunade, M. T., Abejoye, A., Felix, A. O., ... & Kikanme, K. N. (2026). Combined Toxicity of PFAS and Microplastics in Aquatic Ecosystems: Synergistic, Additive, and Antagonistic Interactions. *Water, Air, & Soil Pollution*, *237*(12), 698.

Lian, R., Yang, Y. D., Moreno Jr, J. L., Eggimann, B. L., Chen, J., Gibson-Elias, L. J., ... & Hooley, R. J. (2025). Self-aggregative recognition and extraction of perfluorooctanesulfonate with flexible cationic water-soluble deep cavitands. *Journal of the American Chemical Society*, *147*(26), 22768-22777.

Occurrence, bioaccumulation, fate, and risk assessment of emerging pollutants in aquatic environments: A review. (2024). *Science of the Total Environment*, 923:171388.

Pharmaceuticals and Microplastics in Aquatic Environments: A Comprehensive Review of Pathways and Distribution, Toxicological and Ecological Effects. (2025). *International Journal of Environmental Research and Public Health*, *22*(5):799.

Saetchnikov, A. V., Tcherniavskaia, E. A., Saetchnikov, V. A., & Ostendorf, A. (2023). Detection of per-and polyfluoroalkyl water contaminants with a multiplexed 4D microcavities sensor. *Photonics Research*, *11*(11), A88-A96.

Tricks and tracks of prevalence, occurrences, treatment technologies, and challenges of mixtures of emerging contaminants in the environment: With special emphasis on microplastic. (2024). *Journal of Contaminant Hydrology*, 265:104389.

Wang, H., Gao, X., & Zuo, Y. (2024). Research and application of water treatment technologies for emerging contaminants (ECs): A pathway to solving water environment challenges. *Water*, *16*(13), 1837.

Yu, Y., Wang, Z., Yao, B., & Zhou, Y. (2024). Occurrence, bioaccumulation, fate, and risk assessment of emerging pollutants in aquatic environments: A review. *Science of the Total Environment*, *923*, 171388.

Zhou Q, Chen H, Liu G, Wang X. (2024). Occurrence, sustainable treatment technologies, potential sources, and future prospects of emerging pollutants in aquatic environments: a review. *Frontiers in Environmental Science*, 12:1455377.