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Emerging Contaminants in Drinking Water: Implications for Public Health and Water Treatment

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Abstract

Emerging contaminants (ECs) in drinking water have become an important issue of concern in the world because of their prevalence, persistence, and the possible dangers they pose to human health. Pharmaceuticals and personal care products (PPCPs), endocrine-disrupting chemicals (EDCs), per- and polyfluoroalkyl substances (PFAS), microplastics, and antibiotic resistance genes (ARGs) are those pollutants. Their long-term release and biological activity are of concern due to long-term exposure and the impact of accumulation despite the fact that they are typically found in low concentrations. The study is a narrative review, which examines the vital sources, phenomena, and routes of ECs in the drinking water systems. The greatest contributors are the wastewater treatment plants effluents, agricultural runoffs, industry runoffs, and urban activities that carry them into surface water and groundwater used as drinking water sources. The other consequence of EC exposure on the health of the population observed in the review is the interference with endocrine systems, chronic toxicity and spread of antimicrobial resistance. The efficacy of the traditional and modern water treatment technologies is critically compared. Even though the traditional processes have low removal efficiency, emerging methods such as membrane filtration, adsorption, and advanced oxidation processes have high efficiency but are most likely associated with high costs and operational complexities. In general, gaps in terms of monitoring, toxicological evidence, and regulatory systems are still critical. In a bid to overcome these challenges, there is need to come up with combined approaches that entail improved detection, sustainable treatment technologies and risk-based management strategies.

Keywords: Emerging contaminants; Drinking water; PFAS; Endocrine disruption; Water treatment; Public health

1. Introduction

Safe drinking water is a basic requirement of human health, environmental sustainability, and socio-economic development. In the last few decades, there have been major advancements in water treatment technology and regulatory systems that have been effective in curbing the occurrence of water-borne diseases caused by microbial contamination. Nevertheless, increasing focus is currently being given to a wide range of pollutants, referred to as emerging contaminants (ECs), that pose novel and challenging issues to the water quality management (Lapworth et al., 2012).

Emerging contaminants have a broad definition; they refer to substances (synthetic or naturally occurring) that are not regularly monitored but have the possibility of leading to negative ecological and human health outcomes. They are pharmaceuticals and personal care products (PPCPs), endocrine-disrupting chemicals (EDCs), per- and polyfluoroalkyl substances (PFAS) and microplastics, and antibiotic resistance genes (ARGs) (Richardson & Ternes, 2018; aus der Beek et al., 2016). Even though they usually occur in minimal concentrations (ng/L -µg/L), ECs are of growing concern owing to their persistence, biological activity, and constant introduction into water bodies.

The developments in the field of analytical methods, specifically liquid chromatography with mass spectrometry (LC-MS/MS), have made it possible to detect ECs on the level of ultra-trace in surface water, groundwater, and even treated drinking water (Schwarzenbach et al., 2006; Richardson & Kimura, 2020). Many ECs, unlike traditional pollutants, display pseudo-persistence, i.e. they persist in the environment not necessarily due to their degradation resistance, but due to constant emission of anthropogenic sources like wastewater effluents, industrial waste, and agricultural overflows (Kummerer, 2009).

Wastewater treatment plants (WWTPs) are very important in the regulation of water pollution, but they are not particularly aimed at eliminating most of the ECs. Consequently, incomplete elimination causes their release into the receiving water bodies, which in most cases are used in the provision of drinking water (Michael et al., 2013). Likewise, agricultural activities that use pesticides, fertilizers, veterinary pharmaceuticals among others are sources of EC pollution especially in rural and peri-urban areas.

Besides chemical pollutants, there has been a great concern with biological pollutants like antibiotic resistance genes. Antimicrobial resistance is a health threat considered to be immense and a global health emergency by the World Health Organization because of the presence of antibiotics in aquatic environments (Berendonk et al., 2015). Water systems that are used by people may serve as the possible channels through which the spread of resistant bacteria and resistance genes may occur.

The health effects of exposures to EC are complicated and remain to be comprehended. Hormonal systems of many ECs, especially EDCs, can be disrupted at extremely low levels resulting in possible outcomes of reproductive problems, developmental disorders, and metabolic illnesses (Gore et al., 2015). In addition, the interaction of several contaminants, known as mixture toxicity, is also problematic to risk assessment because many conventional methods assume one compound at a time.

Regulatory frameworks of ECs are not extensive even though the scientific evidence is on the rise. Although some substances like PFAS have been recently regulated more tightly, most ECs are not monitored and regulated as there is not enough information to understand their toxicology and analysis constraints (Post et al., 2017). This gap creates the need of more efficient surveillance policies and risk-based regulatory practices.

In terms of treatment, the conventional coagulation, sedimentation, and filtration procedures tend to be ineffective in dissolving ECs. Such emerging treatment processes like advanced oxidation processes, membrane filtration and adsorption have been an upside that has been usually associated with high expenses and challenges (Shannon et al., 2008; Snyder et al., 2007).

This review aims to provide a comprehensive synthesis of the emerging contaminants of drinking water, their classification, sources, occurrence, impact on human health as well as treatment methods. It also brings out the existing issues and prospects with proper management and regulation.

2. Methodology

2.1 Literature Search Strategy

This narrative review was conducted using the major scientific databases, Scopus, Web of Science, PubMed, and ScienceDirect. Terms such as *emerging contaminants, drinking water, PfAS,* *pharmaceuticals, endocrine-disrupting chemicals, microplastics, and water treatment* were used to search. Boolean operators (AND, OR) were used.

2.2 Selection Criteria

Inclusion Criteria

The inclusion criteria included studies that:

1. were concentrated on new water system contaminants,
2. covered occurrence, health effects, or treatment technologies, and
3. were published in peer-reviewed journals.

Exclusion Criteria

Studies were excluded that:

1. were not peer-reviewed,
2. not about drinking water, and
3. not scientifically rigorous

2.3 Time Period and Information Sources

This review covers the articles published since 2000 till 2025, but specifically recent landmark studies. Reported materials such as; *World Health Organization (WHO)* were used as a source of supplements.

2.4 Data Analysis and Synthesis

The research papers were critically reviewed and categorized according to the following: classification, sources, occurrence, health effects and treatment methods. This narrative synthesis will give a general idea of the state-of-the-art, gaps in knowledge and opportunities. Figure 1 shows the conceptual framework of this review, which links the sources, transport, occurrence, treatment and human health impacts

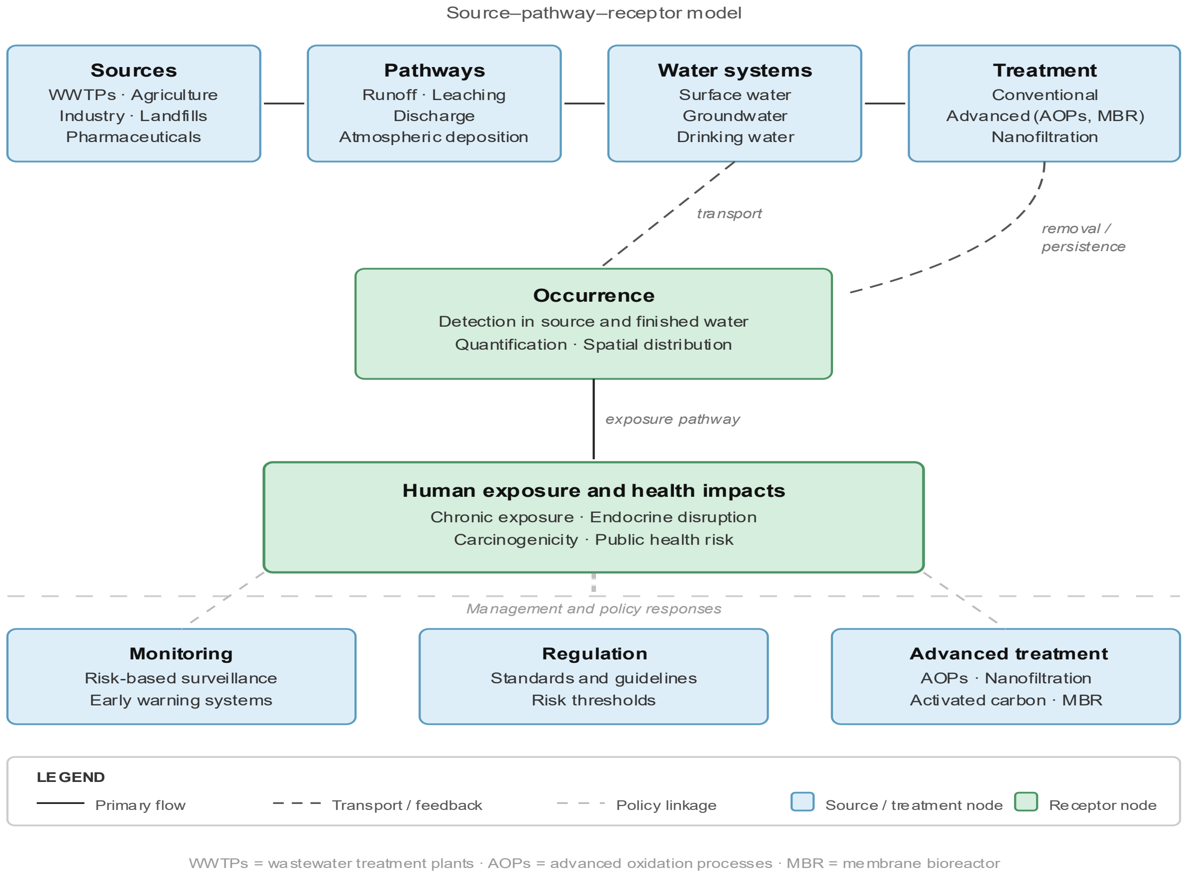

Figure 1. Conceptual framework of emerging contaminants in drinking water systems

Conceptual model of emerging contaminants to drinking water systems, which shows the chain of events that starts with anthropogenic sources, transport routes, presence in the water matrices, treatment mechanisms, and the outcome of human exposures.

3. Results: Occurrence, Sources, and Classification of Emerging Contaminants

The section covers the classification of emerging contaminants (ECs), sources, the occurrence in drinking water systems, their patterns of distribution, and the behaviors in the environment.

3.1 Types and Characteristics of Emerging Contaminants

Emerging contaminants (ECs) are a heterogeneous group of chemical and biological compounds that have dissimilar physicochemical characteristics, environmental persistence, and toxicological impacts. They are majorly pharmaceuticals and personal care products (PPCPs), endocrine-disrupting chemicals (EDCs), per- and polyfluoroalkyl substances (PFAS), microplastics, and antibiotic resistance genes (ARGs).

One of the most common ECs entering water systems is PPCPs as they are widely used and constantly released into the water. Indicators are usually carbamazepine and diclofenac due to their persistence and other biodegradation-resistant properties (aus der Beek et al., 2016). Among them, synthetic hormones and bisphenol A (EDCs) are of particular concern since they are capable of disrupting hormonal systems even at very low doses (Diamanti-Kandarakis et al., 2009; Vandenberg et al., 2012).

PFAS are a very recalcitrant group of pollutants that have strong affinities between carbon and fluorine, therefore, they do not degrade readily and can accumulate in the water system and body tissues (Buck et al., 2011; Sunderland et al., 2019). Microplastics and nanoplastics are the product of the breakdown of the larger plastic products, or industrial use, which are becoming more common in drinking water and can serve as carriers of other pollutants (Koelmans et al., 2019; Wright & Kelly, 2017). ARGs are not similar to the chemical contaminants because they are biological organisms that can propagate the antimicrobial resistance among microbes (Pruden et al., 2006; Berendonk et al., 2015)

The complexity of the environmental behavior of ECs is pointed out by the diversity of these compounds. Polarities, solubility and persistence differences affect their transport, bioavailability and removal. This variability makes monitoring and treatment more difficult and necessitates compound-specific and group-based treatment.

3.2 Sources and Environmental Pathways

Anthropogenic sources are the greatest contributors of emerging contaminants, which flow into water bodies via point and non-point sources. Wastewater treatment plants (WWTPs) are assumed to be primary point sources since they receive a combination of domestic, industrial, and hospital effluents that include pharmaceuticals, personal care products, and chemical residues. The traditional treatment processes are not directly aimed at eliminating these micropollutants and hence end up with incomplete elimination and continued release to the water bodies (Michael et al., 2013).

In Figure 2, the key environmental pathways through which emerging contaminants pass on their way out of anthropogenic sources to the point of drinking water abstraction are presented.

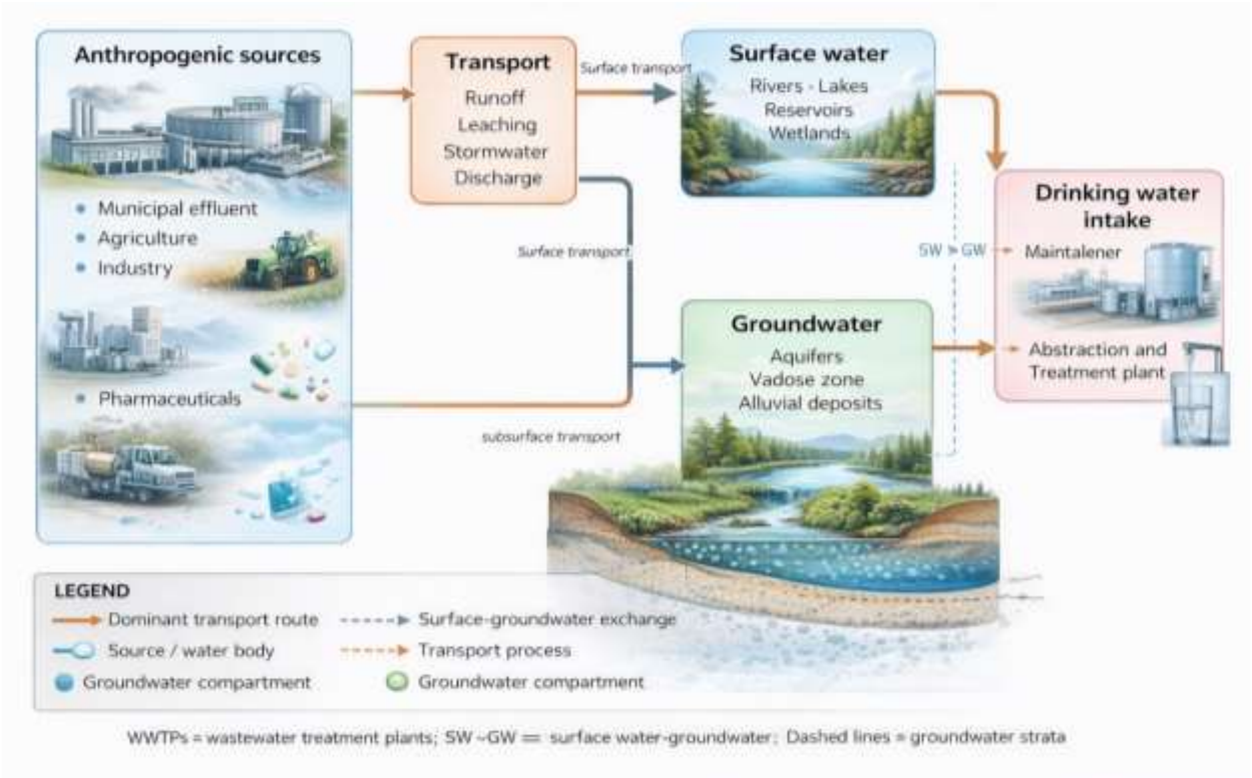

Figure 2. Environmental pathways of emerging contaminants to drinking water systems

Anthropogenic sources of emerging contaminants and their environmental pathways to the drinking water intake systems by means of transport processes and environmental compartments, such as the surface water and groundwater

The agricultural practices are the biggest contributors to EC contamination, especially as non-point sources. The use of pesticides, fertilizers, and veterinary drugs contributes to the fact that the contaminant is introduced into the soil and water system, and it is carried by the surface run-off and leaching processes (Kummerer, 2009). The PFAS, solvents, and microplastics are also added to the contaminants by industrial and urban sources when discharged directly and through stormwater runoff (Sunderland et al., 2019).

Another source of ECs that is not noticed frequently is landfills. The wastes that are decomposed form leachates that consist of complex organic and inorganic contaminants that can percolate into the groundwater unless handled (Eggen et al., 2010).

When released, ECs are transported through interconnected environmental pathways, including surface water flow, groundwater infiltration, and hydrological cycling. Physicochemical characteristics like solubility and persistence and environmental conditions affect their movement. Importantly, this process of interaction between several sources leads to the constant inflow of contaminants, which adds to the pseudo-persistence of ECs in aquatic systems. This continuous loading makes mitigation processes challenging since even the degradable compounds might still be detected because of continued release (Rice & Westerhoff, 2017)

3.3 Occurrence and Distribution in Water Systems

The use of emerging contaminants in drinking water has been broadly observed in all parts of the world, and this is due to their wide usage, longevity and continuity of their introduction in the environment. They are widespread both in surface water, groundwater, and treated drinking water, and are generally reported in the range of ng/L to µg/L.

Surface water bodies (rivers and lakes) are also highly susceptible to EC contamination as a result of direct contributions of wastewater effluents, agricultural run-offs, and urban discharges. The presence of such pharmaceuticals as carbamazepine and sulfamethoxazole, PFAS compounds are constantly reported in drinking water supply surface water (aus der Beek et al., 2016; Sunderland et al., 2019).

Groundwater systems, which were traditionally believed to be less prone to contamination, are getting more and more influenced by ECs via leaching and infiltration. PFAS and some pharmaceuticals are persistent and mobile compounds that have been found in aquifers, which is a source of concern over their long-term contamination and low natural attenuation (Lapworth et al., 2012).

Despite the fact that drinking water treatment procedures decrease the levels of contaminants, most ECs are not eliminated. Consequently, low traces can be found in the drinking water that has been completed. The carbamazepine and PFAS compounds, in particular, are quite recalcitrant to the traditional treatment systems, which should emphasize the shortage of the currently available treatment facilities (Richardson & Ternes, 2018).

The population density, the industrial activity, the physicochemical characteristics, and the treatment efficiency are some of the factors that affect the distribution of ECs. Also influenced by seasonal changes and hydrological conditions are concentrations of contaminants, whereby in low-flow situations, higher concentrations are usually found.

Furthermore, the inconsistency in the reported concentrations indicates the disparity in the analytical capabilities, monitoring approaches, and regional practices. This implies that the existing data might not reflect the actual picture of the EC contamination, especially those areas with inadequate monitoring facilities. Regional variation is also significant in the occurrence of emerging contaminants, which is dependent on the variation in industrialization, population density, and wastewater management practices. Research in the developed world (Europe and North America) indicates that ECs are relatively lower in concentration because of the well-developed treatment facilities and the presence of stronger regulatory measures. Conversely, developing areas tend to have a greater number of higher contaminants, owing to poor wastewater treatment and urbanization that lead to high environmental loading.

Besides, the monitoring plans and analytical aptitudes are also different and this is one of the causes of variation in the reported concentrations. Under-reporting EC occurrence, particularly of new and emerging contaminants such as nanoplastics and transformation products is possible due to lack of standardized monitoring protocols and detection capacity in most cases.

Seasonal and hydrological processes also affect the contaminants. One such example is that during dry seasons where the dilution is low, one may find that the higher concentrations exist and due to rainfall, there is a possibility of more contaminants being carried by the runoff. These dynamic changes have seen the need to have continuous surveillance and adaptive management controls to ensure that the exposure risks are well established.

Table 1. Standard contaminant concentration levels of the selected emerging pollutants of drinking water systems

Category	**Example Compounds**	**Concentration Range**
Pharmaceuticals	Carbamazepine, Ibuprofen	10–1000 ng/L
EDCs	BPA, Estradiol	1–100 ng/L
PFAS	PFOS, PFOA	1–500 ng/L
Microplastics	Various polymers	10–10,000 particles/L

4. Discussion: Public Health Implications and Treatment Technologies

This section explains the consequences of emerging contaminants in regard to the health of the people and assesses the performance of the existing treatment technologies.

4.1 Public Health Implications

Emerging contaminants (ECs) in drinking water are of high concern to the general population due to their persistence, bioactivity and low-dose exposure. Unlike the traditional pollutants, the ECs are not typically believed to cause acute toxicity, but instead, are connected to chronic and cumulative effects on the health that are more difficult to detect and manage.

The other major problem is that the endocrine-disrupting chemicals (EDCs) can have biological impacts at extremely low levels. The more traditional toxicological models are linear dose-response models, whereas the EDCs are often non-monotonic dose-response models, that is, exposure at low doses may cause disproportionately large effects (Vandenberg et al., 2012). This strains the current levels of regulation and suggests that the current level of safety limits might be below the actual risks.

PFAS on the same note are not characteristic contaminants since they are bio accumulative and persistent. Despite the epidemiological studies that have determined immune suppression, thyroid dysfunction and developmental consequences that are related to PFAS exposure, there is a lot of confusion on how safe levels of exposure are. Various regulatory bodies have proposed the values of different guidelines that constitute scientific uncertainty and a changing risk evaluation approach (Sunderland et al., 2019). This discrepancy puts the importance of standardized international standards.

The other vital problem is the contribution of ECs to antimicrobial resistance (AMR) promotion. Antibiotics with even low concentrations in water can have a selective pressure on microbial communities, promoting the increase in antibiotic resistance genes (ARGs) (Berendonk et al., 2015). Nevertheless, the proportion of drinking water to general AMR transmission is controversial, which shows that there is a discrepancy between the evidence of environmental detection and direct health impacts.

There is an added complexity with microplastics. Although they are common in drinking water, the direct health impact of the substances is yet to be properly identified. The emerging issues revolve around the possibility of them serving as vectors of toxic substances and pathogens and their capacity to access biological barriers on the nanoscale (Wright & Kelly, 2017). However, there is a lack of quantitative risk analysis of microplastics, which highlights a significant research gap.

Notably, exposure to ECs is in the form of complex mixtures and not in the form of single compounds. The result of mixture toxicity may be additive, synergistic, or antagonistic, which cannot be effectively described using the traditional risk assessment of single-compound (Kortenkamp et al., 2009). This constraint suggests that the current regulatory controls may be underestimating the overall health effects of the EC exposure.

Overall, despite the fact that the existence of EC has been well-established, there are numerous uncertainties related to long-term health outcomes, safe exposure limit, and mixture toxicity. In order to address these uncertainties, there is a necessity to shift towards integrated, precautionary, and mixture-based risk assessment approaches.

4.2 Water Treatment Technologies

A major technical challenge is the effective removal of the emerging contaminations in the drinking water due to their chemical diversity, low levels and their resistance to the conventional treatment processes. Despite the realized efficiencies that have been achieved through advanced technologies, as a matter of fact, application of these technologies is normally restricted by economical and operational factors.

Conventional treatment methods, such as coagulation, sedimentation, as well as filtration, are not very effective in the removal of EC since these contaminants are usually in a dissolved state. Although such processes are able to reduce part of the hydrophobic compounds, they are not predictable in their performance and may not guarantee complete elimination of EC (Snyder et al., 2003). In order to overcome this drawback, there is a need to integrate modern treatment technologies.

Economic, operational, and environmental factors are also a critical factor when it comes to the choice and application of suitable technologies besides the technical performance of the treatment processes. Although more sophisticated treatment methods like the reverse osmosis (RO) and advanced oxidation processes (AOPs) have shown an excellent removal efficiency of a variety of emerging contaminants, they have not been extensively utilized because of their high costs of capital, energy consumption, and maintenance. This is more so in the developing regions, where the water treatment infrastructure is usually limited due to financial and technical factors.

The critical comparison of treatment technologies shows that there is no universal treatment method that could be applied to all types of ECs. As an illustration, AOPs are very effective in degradation of organic micropollutants including pharmaceuticals and endocrine disruptor but their effectiveness may be diminished in complex water matrices because of radical scavenging effects. In addition, when the AOP treatment is not completely mineralized, it can result in the creation of transformation products, some of which can be more toxic than the parent compounds, and create secondary risks not necessarily considered during treatment assessment**.**

RO and nanofiltration (NF) are membrane filtration technologies that have a near-complete removal of most contaminants that include PFAS. Nevertheless, these systems produce concentrated waste streams (brine), which must be disposed of correctly so as to avoid recontamination of the environment. Moreover, membrane fouling also is a reliable problem of operation that reduces performance and increases the costs of maintenance. These restrictions point to trade-offs between the efficiency and sustainability of treatment.

One of the cost-effective methods that is highly applicable in the treatment of drinking water is the adsorption processes particularly with the application of activated carbon. However, their operation highly depends on the nature of contaminants, such as their size and hydrophobicity. In addition, the adsorbent saturation requires periodical regeneration or replacement, which can decrease the cost-effectiveness in the long run. Recent adsorbents such as biochar and nanostructured adsorbents have been shown to have potential in the laboratory research but their scalability and environmental friendliness are yet to be investigated.

The next significant trend is the creation of hybrid systems of treatment that are designed to combine a number of processes to improve the efficiency of removal and overcome the shortcomings of single technologies. Ozonation and activated carbon adsorption, as an example, have been shown to be complementary to one another in order to increase the degradation of contaminants and minimize the formation of by-products. Hybrid systems add complexity to system design, operation and monitoring although they are effective.

Another key challenge is the unavailability of standardized treatment performance evaluation measures. The efficiencies of the reported removals are normally observed to be highly different among the studies due to the variation in the experimental conditions of the studies, the concentration of contaminants and the methods applied in the analysis. This variety makes comparing the technologies difficult and the best solutions to the real-life context difficult to identify.

In general, despite the great achievements of creating sophisticated technologies in the field of treatment, the adoption of these technologies needs to be considered in the context of sustainability, cost, and feasibility of operations. Future studies are needed to focus on how to come up with more energy-efficient, low-cost and scalable treatment options, especially in areas with low resources.

In Figure 3, a conceptual overview of the key treatment pathways of emerging contaminants, from conventional treatment to advanced treatment procedures, is presented.

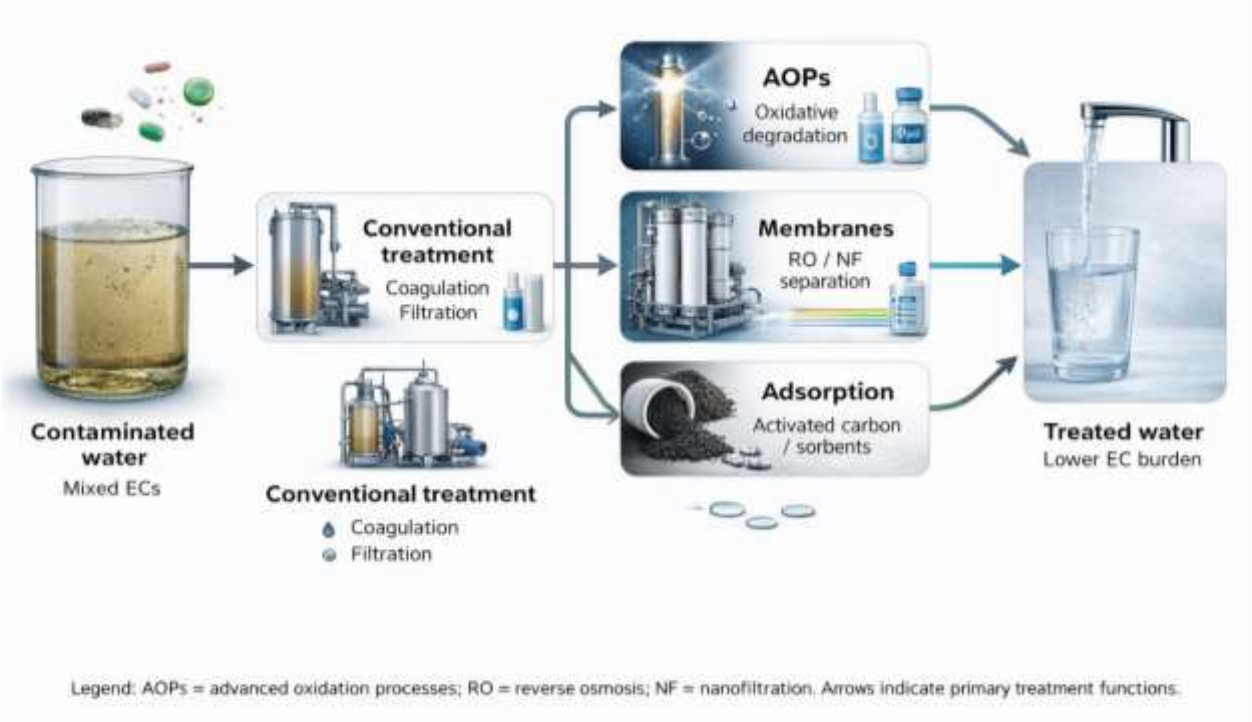

Figure 3. Comparative framework of treatment technologies for emerging contaminant removal

Comparison of treatment technologies on emerging contaminants removal, which demonstrates the evolution of the traditional treatment methods to the advanced oxidation, membrane filtration, and adsorption techniques before the delivery of treated water

A comparative analysis of treatment technologies, their benefits, shortcomings, and applicability are shown in Table 2. Advanced technologies have been shown to be high in removal efficiencies, but their application is still limited by cost and complexity.

Table 2. Comparative evaluation of treatment technologies for emerging contaminant removal

Technology	Target Contaminants	Removal Efficiency	Key Advantages	Limitations	Practical Applicability
Conventional Treatment	Limited (hydrophobic ECs)	Low	Low cost, widely used	Ineffective for most ECs	High (existing systems)
AOPs	PPCPs, EDCs	High	Effective degradation	By-products, high energy	Moderate
RO/NF	PFAS, pharmaceuticals	Very high (>95%)	Broad-spectrum removal	Energy intensive, waste brine	Low–Moderate

Adsorption (AC)	Organic ECs	Moderate–High	Cost-effective, flexible	Saturation, regeneration needed	High
Biological	Biodegradable ECs	Variable	Eco-friendly	Limited scope	Moderate
Hybrid Systems	Multiple ECs	Very high	Enhanced removal efficiency	High complexity, cost	Low

5. Challenges and Research Gaps

Regulatory frameworks for emerging contaminants remain limited and inconsistent across regions. Although some compounds, including PFAS, have guideline values, most contaminants do not have standardized limits because of a lack of enough toxicological evidence. Table 3 provides a comparison of some of the regulatory guidelines in which regional differences and the gaps are shown.

Table 3. Selected regulatory guidelines for emerging contaminants in drinking water

Contaminant	**Region/Agency**	**Guideline Value**	**Notes**
PFOS + PFOA	US EPA (2024 advisory)	4 ng/L (each)	Interim health advisory level
PFAS (sum of several compounds)	European Union (2020)	100 ng/L	Drinking Water Directive
PFAS (total)	European Union (2020)	500 ng/L	Includes broader PFAS group
PFOA	WHO (2022)	100 ng/L	Provisional guideline
PFOS	WHO (2022)	100 ng/L	Provisional guideline
Bisphenol A (BPA)	European Union	2.5 µg/L	Parametric value
Carbamazepine	No formal standard	—	Monitored but unregulated
Microplastics	WHO (2019)	No guideline	Insufficient evidence
Antibiotics/ARGs	Global	No standard	Emerging concern

The difference in regulatory limits by region indicates a high level of scientific uncertainty and disparity in risk assessment methods especially in PFAS where guideline values range between single-digit ng/L and hundreds of ng/L. This discrepancy points to the lack of harmonized international standards and the necessity of precautionary and evidence-based regulation taking into consideration long-term exposure and mix effects.

5.1 Monitoring, Toxicity, and Risk Assessment Limitations

Although there is increasing focus on the emerging contaminants (ECs), a number of challenges prevent effective monitoring and risk assessment. The absence of standardized monitoring structures is one of the problems. Even with thousands of ECs, only a small proportion of them is regularly analyzed because the cost and technical demand of the sophisticated measures like LC-MS/MS are very high (Richardson & Ternes, 2018). This is especially a drawback in the developing countries where technical capacity is a bottleneck.

The other important gap is the absence of comprehensive toxicological information. The majority of research is done on single contaminants but in reality, there is mixed exposure. Such combinations could cause additive or synergistic impact that cannot be properly quantified by the prevailing risk assessment methods, resulting in the challenge of predicting health hazards (Kortenkamp et al., 2009).

5.2 Treatment and Regulatory Challenges

Besides the limitation on monitoring, the current technology of treatment is not equally effective with all ECs. The persistent compounds like PFAS are not easy to get rid of and certain treatment procedures can produce transformation products whose toxicity is not known. This makes it difficult to design treatments as well as safety appraisal.

There are also weak regulatory frameworks of ECs. Although some of these contaminants like PFAS, are being controlled, the majority of ECs do not have clear standards since the data is limited and the occurrence varies (Post et al., 2017). What is more, the data provided in the developing areas is not complete, and there is no complete global picture on the distribution and risks of EC.

In general, these issues can be solved by means of enhanced surveillance, superior toxicological knowledge, more useful technologies of treatment and enhanced and coherent regulatory systems. The limitation of the existing monitoring systems is one of the most important issues related to the management of emerging contaminants. The detection of ECs at low doses of traces, such as liquid chromatography-mass spectrometry (LC-MS/MS) will necessitate advanced analytical methods but they are expensive and demand specialized skills. Consequently, surveillance is usually limited to few compounds and thus a large percentage of the contaminants in water systems may be neglected. This is especially much in developing nations where there is a shortage of monitoring systems and technology.

The other significant gap is the lack of full knowledge of the long-term health outcomes particularly in cases of chronic low dose exposure. The majority of the toxicological research is devoted to the study of single contaminants, but, in the real-life situation, exposure is to complex mixtures of chemicals, and biological agents. The interactions among these contaminants can become additive or synergistic, which makes it difficult to assess the risks but can cause the issue of underestimation of health risks.

Mixture toxicity is one of the most important problems that are still not solved. The existing regulatory systems are mainly founded on assessments of individual compounds and fail to consider integrated exposure situations. This is especially worrying considering the presence of several ECs in the drinking water systems at the same time.

Moreover, the methods of regulations differ significantly among regions, as it is mentioned in Table 3. Lack of harmonized international standards is indicative of scientific uncertainty, as well as a lack of policy priorities. Although there are certain limits set in some areas regarding some pollutants like PFAS, there are still numerous ECs that have not been regulated, which hinders the success of the risk management measures.

The solutions to these challenges include the development of integrated monitoring systems, better toxicological research on mixture effects and the introduction of consistent science-based regulatory frameworks.

6. Future Perspectives

6.1 Advancements in Monitoring and Treatment Technologies

The development of advanced and cost-effective monitoring and treatment systems should be the focus of future endeavors to control emerging contaminants (ECs). The existing analytical techniques including

LC-MS/MS are very sensitive and yet costly and in technical terms are difficult. New methods, such as real-time sensors, biosensors, and non-target screening with a high-resolution mass spectrometry, have a high promise of finding a wider spectrum of contaminants, including unknown compounds and transformation products (Richardson & Kimura, 2020).

Simultaneously, sustainable water treatment technologies have to be enhanced. Although processes like reverse osmosis and advanced oxidation are effective, they consume high energy and require high cost of operation, thus they cannot be applied on a large scale. Future studies need to be done on low-cost and energy-efficient alternatives, including biochar-based adsorption, solar-driven oxidation processes, and hybrid systems that integrate biological and physicochemical processes. Also, it is important that the development of toxic transformation products during treatment is minimized, which is also a top research agenda.

6.2 Integrated Management, Policy, and Risk Assessment

In addition to treatment technologies, there will be a need to switch towards source management and integrated water management. The environmental loads can be minimized significantly, by minimizing the release of the contaminants on the source by enhancing the pharmaceutical disposal practices, green chemistry and increased industrial control. Circular economy principles can also be used to assist in sustainable water management.

The risk assessment techniques will also need to be modified to be able to deal with the complexity of EC exposure. The traditional single compound tests cannot be applied, one has to incorporate the mixture toxicity, cumulative exposure and the vulnerable groups in the frameworks of the future. Artificial intelligence and computational toxicology can be used in decision-making and enhancing health hazard prediction.

It is also essential to reinforce regulatory systems and cooperation on the international level. Numerous ECs have no regulation and the standards differ between regions. The world will be safer when it comes to water because of integrated and evidence-based laws and improved information exchange. The involvement of the stakeholders and sensitization of the people also play a role in reducing the contributions of the contaminants and promoting sustainable practices.

To conclude, technological innovation, preventive measures, and good policy frameworks should be incorporated in future strategies to help in response to emerging contaminants in drinking water.

7. Conclusion

Emerging contaminants (ECs) are becoming an increasing threat to the safety of drinking water as they are widespread, persistent, and may have health effects. These contaminants are commonly being found in both source and treated drinking water and they have their origin in wastewater, agriculture, industry, and urban runoff.

The conventional treatment procedures are mostly ineffective in eliminating most ECs and the advanced treatment technologies like membrane filtration, adsorption, and advanced oxidation have better elimination but have high costs and restrictions in their operation. In terms of public health, ECs such as endocrine-disrupting chemicals, PFAS and pharmaceuticals as well as antibiotic resistance genes, are of concern as far as chronic exposure, mixture effects, and antimicrobial resistance are concerned.

There are still significant gaps, such as poor monitoring, a lack of toxicological information, and poor regulatory frameworks. To fill these gaps, there should be more analytical techniques, risk assessment techniques, and more support of policies.

Overall, the control of ECs in drinking water requires a complex strategy of combining highly effective treatment, source control, and regulatory development that will guarantee the safety of human health in the long run.

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