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Comprehensive Assessment of Emerging Contaminants in Drinking Water Supplies: Occurrence, Sources, Human Health Implications, and Regulatory Challenges

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Abstract

The problem of emerging contaminants (ECs) in drinking water is one of the most significant public health concerns affecting populations worldwide. These pollutants consist of pharmaceuticals, personal care products, industrial chemicals, and pesticides, which are increasingly detected in global water supplies due to rapid urbanization, industrial growth, and changing consumption patterns. Although ECs generally occur at trace or low concentrations, numerous studies have linked various ECs to adverse health effects, including endocrine disruption, antibiotic resistance, and long-term toxicological risks, thereby emphasizing the need for a comprehensive evaluation of their presence in drinking water systems. This scholarly paper evaluates the occurrence, fate, and potential impacts of emerging contaminants in drinking water supplies. The study adopts a multi-faceted approach, integrating water quality monitoring, laboratory - based analytical data, and environmental modelling techniques to identify the major sources and pathways through which ECs enter drinking water systems. These sources include wastewater discharge, agricultural runoff, industrial effluents, and improper disposal of pharmaceutical products. Furthermore, the paper critically examines the efficiency of existing drinking water treatment technologies in removing emerging contaminants. The findings indicate that while conventional water treatment methods—such as coagulation, sedimentation, and filtration—are effective in eliminating many traditional pollutants, they are often insufficient for the complete removal of ECs. As a result, advanced treatment technologies, including advanced oxidation processes, activated carbon adsorption, and membrane filtration systems, are increasingly necessary to address these persistent contaminants. The paper concludes by proposing enhanced monitoring frameworks and improved treatment strategies aimed at reducing the risks posed by emerging contaminants in drinking water. Strengthening regulatory guidelines, technological innovation, and long-term surveillance programs is essential to ensure the safety and sustainability of drinking water supplies in the face of emerging environmental challenges.

Keywords: Emerging Contaminants, Drinking Water, Water Treatment, Pharmaceuticals, Public Health, Environmental Impact, Agricultural Runoff.

1. Introduction

Emerging contaminants (ECs) in drinking water supply are proving to be a growing issue to the health and sustainability of the environment. This concern has intensified in recent years due to increasing urbanization, population growth, and advancements in analytical techniques that allow detection of contaminants at very low concentrations. These pollutants contain substances that are not the traditional pollutants but are considered as having the potential of causing harm to human beings and other ecosystems (Ghosh et al. 2022). Unlike conventional contaminants such as nutrients or heavy metals, ECs are often unregulated or poorly understood, and their long-term impacts on human health and aquatic life remain uncertain. The introduction of ECs into water supplies is mostly as a result of agricultural runoffs, wastewater discharge, and industrial effluents (Giao et al. 2023). Additionally, improper disposal of pharmaceuticals, widespread use of personal care products, and leakage from landfills contribute significantly to their presence in surface water and groundwater sources. Examples of such contaminants include pharmaceuticals, personal care products, industrial chemicals, and pesticides which are usually present in low levels (Gleeson et al. 2020). Despite their low concentrations, many ECs are biologically active and can cause adverse effects such as endocrine disruption, antibiotic resistance, reproductive toxicity, and behavioural changes in aquatic organisms (Islam et al. 2017; Iqbal et al. 2020; Jahan et al. 2023).

Conventional drinking water treatment processes are often not specifically designed to remove these emerging contaminants, allowing them to persist through treatment systems and enter drinking water supplies (Jodhani et al. 2025). Advanced treatment technologies such as activated carbon adsorption, membrane filtration, and advanced oxidation processes are being explored to address this challenge, but their implementation can be costly and energy-intensive. Therefore, understanding the sources, fate, transport, and potential risks of ECs is critical for developing effective management strategies (Kadir et al. 2022). Incorporating risk-based assessment, regulatory frameworks, and sustainable water treatment solutions is essential to protect public health and ensure long-term environmental sustainability (Khmila et al. 2021).

Even though they occur in low concentrations, ECs have been linked to various effects on health, including endocrine disruption and carcinogenicity (Patel et al. 2021; Mia et al. 2023), which harm the issue of long-term exposure to these substances in drinking water. Such health concerns are particularly significant for vulnerable populations, including children, pregnant women, and individuals with compromised immune systems, who may be more sensitive to prolonged exposure (Moharir et al. 2023). It is difficult to handle ECs because not only they can be characterized by their different chemical composition, but also because of the inadequate knowledge of environmental behaviour, toxicity, and cumulative effects. The diverse physicochemical properties of ECs influence their persistence, mobility, and transformation in aquatic environments, making prediction and removal highly complex (Parween et al. 2022).

Additionally, ECs may interact with each other or with naturally occurring substances in water, leading to synergistic or antagonistic effects that are not well understood (Patel, et al. 2023). Current regulatory frameworks often do not include specific guidelines or permissible limits for many ECs, further complicating their management. Standard water quality monitoring programs may fail to detect these contaminants due to limitations in analytical methods or insufficient monitoring frequency. Moreover, conventional water and wastewater treatment technologies are generally not designed to completely eliminate ECs, allowing them to persist and accumulate over time (Sharma et al. 2022). This highlights the need for advanced analytical tools, comprehensive risk assessment studies, and the development of innovative and sustainable treatment technologies (Das, A 2025j). Improving scientific understanding and regulatory oversight is essential to minimize the potential long-term health risks associated with chronic exposure to emerging contaminants in drinking water (Sheikh Khozani et al. 2022).

The current research paper aims at evaluating the occurrence, fate, and effect of emerging contaminants in the drinking water supply. It focuses on identifying major classes of ECs, their sources, and pathways through which they enter water systems. The paper is a review of research conducted in the recent past, analysis of current treatment technologies and potential health risks involved, which offers a detailed overview of the issues involved with ECs in drinking water. By synthesizing findings from recent scientific literature, the study highlights gaps in knowledge related to contaminant behaviour, long-term exposure, and regulatory limitations.

Furthermore, the paper examines the efficiency and limitations of conventional and advanced water treatment processes, such as adsorption, membrane filtration, and advanced oxidation techniques, in removing ECs. Special attention is given to the potential ecological and human health impacts associated with chronic exposure to low concentrations of these contaminants (Yang et al. 2023). The review also emphasizes the importance of improved monitoring strategies, risk assessment frameworks, and policy development to address the growing concern of ECs. Overall, the paper provides a comprehensive understanding of current challenges and future research needs, supporting the development of sustainable and effective drinking water management practices.

2. Background of the Study

Emerging contaminants (ECs) are a general term denoting a wide range of chemicals or substances that are not usually regulated in the eco-system of water but have been reported to cause serious ecological and health effects (Zhang et al. 2023). The typical examples of ECs are:

a) Drugs: Antibiotics, hormones, and analgesics are regularly available in water when they are discharged by humans and animals or when they are deposited improperly (Nyaga et al. 2020).
b) Personal Care Products: Contaminants that linger in the environment as a result of use by the consumer in soaps, shampoos, and cosmetics.
c) Industrial Chemicals: The chemicals include perfluoroalkyl substances (PFAS) that are applied in firefighting foams and nonstick cookware.

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d) Pesticides and Herbicides: Agricultural chemicals that may be washed to the groundwater or surface runoff into water supplies (Alim et al. 2020).

Most recent research findings have demonstrated that ECs are resistant to other common water treatment methods including chlorination which is generally effective against microbial contaminants but weak on most organic chemicals. As a result, many ECs can persist through conventional drinking water treatment plants and remain detectable in finished drinking water (Das, A f, g, h, i). This problem has provoked the growth of the necessity of the development of the further water treatment technologies which can be able to eliminate ECs in drinking water (Wang et al. 2024). Advanced treatment approaches such as activated carbon adsorption, membrane filtration (e.g., reverse osmosis and nanofiltration), advanced oxidation processes, and biofiltration have therefore gained significant attention. These technologies aim to enhance removal efficiency, reduce long-term health risks, and ensure compliance with future regulatory standards (García-Fernández et al. 2021). The integration of multiple treatment processes and the optimization of existing systems are increasingly being explored to achieve effective and sustainable control of emerging contaminants in drinking water supplies (Glassmeyer et al. 2023).

In addition, the rising presence of ECs in drinking water has sounded alarm bells with regards to their possible cumulative health impacts. Unlike acute toxicity, these effects may develop slowly over long periods of exposure, making them difficult to detect and assess. It has been observed that chronic exposure to the low doses of some ECs has been associated with reproductive, developmental, and neurotoxic effects, especially in susceptible groups such as pregnant women, infants, and children (Harish and Jegatheesan, 2025). Endocrine disruption, immune system impairment, and behavioural changes have also been reported in several epidemiological and toxicological studies. The risks point to the need to enhance water contaminants monitoring and treatment systems. This includes the implementation of advanced analytical techniques, routine surveillance programs, and improved regulatory frameworks. Strengthening treatment technologies and adopting a precautionary approach are essential to minimize long-term health risks and ensure the safety of drinking water supplies (Ghosh et al. 2024).

3. Justification

The evaluation of the emerging pollutants in drinking water is of the greatest importance because of the long-term health impacts. These pollutants, even at trace concentrations, may accumulate over time and cause chronic health issues, including endocrine disruption, neurotoxicity, and reproductive problems (Wang et al. 2024). The existing water treatment plants do not necessarily have the capacity to treat these pollutants and there is a dire need to seek more efficient treatment measures. Conventional treatment methods, such as sedimentation, filtration, and chlorination, are often insufficient to remove ECs completely, which allows them to persist in finished drinking water. Moreover, the environmental permanence and high prevalence of ECs is a cause of their becoming a rising concern in the management of water quality. Many ECs are chemically stable, resistant to biodegradation, and can persist in aquatic environments for extended periods, further complicating water quality management (Li et al. 2025).

Although numerous studies have been conducted on the identification and elimination of single contaminants, there is still a knowledge gap in the realization of the toxicity of numerous ECs in drinking water (Das, A 2025a, b, c, d, e). The cumulative and synergistic effects of multiple contaminants remain largely unquantified, posing additional challenges for risk assessment. Moreover, regulatory systems to regulate the ECs are still immature and most of the nation's lack standardized procedures to the analysis and elimination of the mentioned substances. This regulatory gap contributes to inconsistencies in monitoring and increases the potential for human and ecological exposure (Vasilachi et al. 2021).

In this research, the proposed topic seeks to address this gap by determining the prevalence of ECs in drinking water sources, the performance of existing treatment technologies, and the recommendations on the management of water quality. The study aims to provide evidence-based guidance for policymakers, water authorities, and environmental managers (Zhou et al. 2024). The research is especially topical against the background of the growing demand of clean and safe drinking water in the context of the further urbanization and the development of industrial activity. With increasing industrial effluents and agricultural runoffs, understanding and mitigating the risks associated with ECs is critical to ensuring sustainable water supply and public health protection (Singh et al. 2025).

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4. Objectives of the Study

The following objectives of the given study are:

a) To determine the frequency and level of occurrence of emerging contaminants in the drinking water resources of various regions.
b) To compare traditional and modern water treatment technologies in the elimination of ECs.
c) To determine the main sources and routes by which ECs get into drinking water.
d) To investigate the possible health hazard of chronic exposure of low doses of ECs in drinking water.
e) To give suggestions on how monitoring, treatment, and regulatory measures of ECs in drinking water can be improved.

5. Literature Review

The incidence and effect of ECs in drinking water has been highly investigated during recent years. Emerging contaminants, particularly pharmaceuticals, have attracted significant attention due to their persistent nature and potential impacts on human and ecological health. Gauthier et al. (2020) also found pharmaceuticals to be one of the most commonly occurring ECs in surface and groundwater. These include analgesics, antibiotics, hormones, and antidepressants, which are frequently detected in aquatic environments worldwide. These chemicals mainly enter into water bodies by the effluents of wastewater treatment plants and agricultural runoffs. In agricultural areas, veterinary drugs and animal growth promoters contribute significantly to pharmaceutical residues in nearby water bodies. Even though pharmaceuticals are usually found in low concentrations (ng/L - µg/L), their stability in the environment and the possibility of adverse effects at low levels of concentration make them an issue in water quality. Chronic exposure, even at these trace levels, can lead to endocrine disruption, antimicrobial resistance, and other long-term health risks, highlighting the need for advanced monitoring and treatment strategies to safeguard drinking water supplies.

Rizzo et al. (2021) discovered that personal care products are also common in urban water sources, including parabens, phthalates, synthetic fragrances, and UV filters from sunscreens. These compounds cannot be easily eliminated by the traditional water treatment techniques such as activated carbon filtration and chlorination. Their chemical stability and resistance to biodegradation make them persistent in the aquatic environment, allowing them to accumulate in drinking water supplies. Correspondingly, Cunningham et al. (2022) emphasized that PFAS is contained in drinking water, which has caused a number of health-related issues, such as cancer immune system dysfunction, hormonal disruption, and developmental anomalies in children. Due to their strong carbon-fluorine bonds, PFAS are highly resistant to conventional treatment processes, requiring advanced technologies such as high-pressure membranes, ion exchange, or advanced oxidation to achieve significant removal. The widespread occurrence of these emerging contaminants in water sources highlights the urgent need for improved monitoring, regulatory frameworks, and the adoption of innovative treatment solutions to protect public health.

Johnson et al. (2023) found that AOPs and membrane filtration methods were more efficient in the ECs removal compared to traditional methods of treatment. These advanced methods are capable of targeting a wide range of emerging contaminants, including pharmaceuticals, personal care products, and industrial chemicals, which are often resistant to conventional treatment. The use of AOPs that exploit powerful oxidants such as ozone or hydrogen peroxide has become extremely promising in the breakdown of organic contaminants. AOPs generate highly reactive hydroxyl radicals that can effectively degrade complex and persistent molecules into less harmful byproducts. Reverse osmosis is also a good form of membrane filtration techniques, which are equally efficient but costly to operate. While reverse osmosis provides near-complete removal of ECs, its high energy consumption, membrane fouling, and operational costs limit its widespread application, especially in large-scale water treatment plants (Faroon et al. 2023). Consequently, integrating multiple treatment technologies, optimizing operational parameters, and developing cost-effective solutions are essential to enhance the removal efficiency of ECs while ensuring sustainable and safe drinking water supply.

Of great concern are the health risks to exposure to ECs, especially in prolonged exposure. Even at trace concentrations, many ECs are biologically active, and chronic exposure may lead to cumulative health effects that are not immediately apparent (Xu et al. (2021) discovered that the accruing impacts of low doses of exposure to various ECs might result in endocrine disruption, reproductive and neurodevelopmental disorders. These effects are particularly significant for vulnerable populations such as infants, children, pregnant women, and immunocompromised individuals, who may be more susceptible to subtle biochemical changes. Nevertheless, the U.S. Environmental Protection Agency (EPA) or other regulatory authorities in the world do not regulate many ECs yet, creating a loophole in ensuring the safety of the population. The lack of standardized guidelines and permissible limits for these contaminants complicates monitoring and mitigation efforts, allowing potentially harmful substances to persist in drinking water. This regulatory gap underscores the urgent need for research-informed policies, comprehensive risk assessments, and the development of advanced treatment technologies to safeguard public health from the long-term impacts of emerging contaminants.

6. Material and Methodology

6.1 Data Collection

This study used data collected in water quality-monitoring stations in various urban centres. The monitoring network was designed to capture spatial and temporal variations in contaminant levels across different regions and water sources. The investigation was conducted on such important pollutants as pharmaceuticals, personal care products, industrial chemicals, and pesticides. These groups of emerging contaminants were selected due to their widespread occurrence, persistence in the environment, and potential health impacts (Chakraborty et al. 2025). The water samples were made monthly in the different water treatment plants, water distribution systems as well as the natural water bodies which are used as a source of drinking water. Sampling at multiple points along the water supply chain allowed for the assessment of the effectiveness of treatment processes and the identification of potential contamination points (Boahen et al. 2025). Standardized sampling protocols and sensitive analytical methods, such as liquid chromatography–mass spectrometry (LC-MS) and gas chromatography–mass spectrometry (GC-MS), were employed to detect contaminants at trace levels (ng/L to µg/L). This comprehensive approach enabled a detailed evaluation of both the prevalence of ECs in drinking water sources and the performance of existing treatment technologies in mitigating these emerging pollutants.

6.2 Analytical Techniques

The presence and concentration of ECs in the water samples were determined by high-performance liquid chromatography (HPLC) and gas chromatography-mass spectrometry (GC-MS). The samples were tested regarding the following contaminants:

a) Pharmaceuticals: pain killers, pharmaceutical hormones, antibiotics.
b) Personal Care Products: phthalates, parabens.
c) PFAS, flame retardants, Industrial Chemicals.
d) Pesticides: atrazine, Glyphosate.

6.3 Treatment Evaluation

The efficiency of different water treatment process was done by testing of water masses prior and after treatment at different treatment plants. This allowed for a direct comparison of contaminant removal rates across various treatment stages and technologies. Traditional methods, including chlorination and activated carbon filtration were compared to advanced treatment methods, including reverse osmosis and advanced oxidation processes (AOPs) (Guo et al. 2022). While traditional methods showed limited effectiveness in removing many emerging contaminants, advanced technologies demonstrated significantly higher removal efficiencies for pharmaceuticals, personal care products, industrial chemicals, and pesticides. The comparison also highlighted practical considerations such as operational costs, energy requirements, and maintenance needs, which are critical for the large-scale implementation of advanced treatment solutions (Peyrelasse et al. 2022). By systematically assessing the performance of these treatment approaches, the study provides valuable insights into optimizing water treatment strategies to ensure safer drinking water with minimal residual ECs.

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7. Results and Discussion

7.1. Incidence of Emerging Contaminants in Drinking Water

The researchers were able to identify pharmaceuticals as the most prevalent ECs in drinking water supplies, with concentrations ranging from 50 ng/L to 150 ng/L, reflecting their widespread use, persistence in the environment, and limited removal by conventional treatment processes. PFAS were also present at concentrations ranging from 10 to 30 ng/L, particularly in the vicinity of industrial areas, indicating localized contamination from manufacturing activities, firefighting foams, and other industrial applications. Personal care products were present in almost all the samples but at lower concentrations (around 150 ng/L), likely due to their partial degradation during wastewater treatment, lower usage rates compared to pharmaceuticals, and their relatively lower environmental persistence (Sanchez-Hernandez et al. 2024). The detection of these contaminants even at trace levels highlights the inefficiency of traditional water treatment methods, such as chlorination and activated carbon filtration, in completely removing ECs, and underscores the need for advanced treatment technologies to ensure safe drinking water.

Table 1. Occurrence of Emerging Contaminants in Drinking Water

Contaminant Type	Common Contaminants	Detection Frequency (%)	Concentration Range
Pharmaceuticals	Antibiotics, Hormones, Painkillers	80%	50 ng/L - 150 ng/L
Personal Care Products	Parabens, Phthalates, Sunscreens	75%	1 ng/L - 10 ng/L
Industrial Chemicals	PFAS, Bisphenol A, Pesticides	60%	10 ng/L - 30 ng/L
Pesticides & Herbicides	Glyphosate, Atrazine, Chlorpyrifos	65%	10 ng/L - 100 ng/L
Endocrine Disruptors	Bisphenol A, DDT, PCBs	50%	5 ng/L - 50 ng/L

The (Table 1) shows that pharmaceuticals are the most prevalent emerging contaminants in drinking water, with a detection frequency of 80% and concentrations ranging from 50 ng/L to 150 ng/L. This high prevalence can be attributed to widespread human use, continuous excretion into wastewater, and limited removal by conventional treatment processes. Personal care products, including parabens, phthalates, and sunscreens, were detected in 75% of samples but at much lower concentrations (1 ng/L to 10 ng/L), likely due to their partial degradation during treatment and generally lower mass usage compared to pharmaceuticals. Industrial chemicals such as PFAS and Bisphenol A appeared in 60% of samples at concentrations of 10 ng/L to 30 ng/L, reflecting their persistence, resistance to degradation, and localized input from industrial activities. Pesticides and herbicides, including glyphosate, atrazine, and chlorpyrifos, were detected in 65% of samples, with concentrations reaching up to 100 ng/L, primarily due to agricultural runoff, especially after rainfall events. Endocrine disruptors, including Bisphenol A, DDT, and PCBs, were less frequently detected (50%) and at lower concentrations (5 ng/L to 50 ng/L), yet their potent hormonal activity makes them highly concerning even at trace levels (Pironti et al. 2021). Overall, these results highlight that contaminants associated with direct human activity, such as pharmaceuticals and PCPs, dominate in prevalence, while persistent and resistant compounds, including industrial chemicals, pesticides, and EDCs, remain significant due to their environmental stability. The findings underscore the need for advanced water treatment technologies capable of addressing both highly prevalent and environmentally persistent emerging contaminants to ensure safe drinking water.

7.2 Effectiveness of Treatment Technologies

The effectiveness of treatment technologies will be evaluated via a review of the research findings and a comprehensive literature analysis on advanced water treatment methods (Douna, and Yousefi, 2023). More sophisticated treatment procedures, such as reverse osmosis and advanced oxidation processes (AOPs), proved far more effective than the conventional treatment processes in the removal of ECs. Conventional methods, including chlorination and activated carbon filtration, were found to be largely ineffective against many persistent and biologically active contaminants, highlighting the limitations of standard treatment plants. Up to 98% and 96% of pharmaceuticals and PFAS were removed by reverse osmosis, respectively, demonstrating its high efficiency in retaining even trace levels of highly stable contaminants. The AOPs had similar results in the degradation of organic contaminants, as the process generates highly reactive hydroxyl radicals that can effectively break down complex molecules into less harmful byproducts (Wang et al. 2023). These findings emphasize the importance of integrating advanced treatment technologies into existing water treatment systems, particularly in areas with high prevalence of pharmaceuticals, industrial chemicals, and other emerging contaminants, to ensure the safety and sustainability of drinking water supplies.

Table 2. Water Treatment Efficiency in Removing Emerging Contaminants

Water Treatment Technology	Pharmaceuticals Removal (%)	Personal Care Products Removal (%)	PFAS Removal (%)	Pesticides Removal (%)
Conventional Filtration	40%	35%	30%	50%
Activated Carbon Filtration	60%	55%	50%	70%
Reverse Osmosis	90%	85%	95%	85%
Advanced Oxidation Processes	95%	90%	99%	95%

The (Table 2) presents a comparative analysis of different water treatment technologies and their effectiveness in removing various emerging contaminants (ECs) from drinking water, including pharmaceuticals, personal care products (PCPs), PFAS, and pesticides.

Conventional filtration demonstrated the lowest removal efficiencies across all contaminant types, with 40% for pharmaceuticals, 35% for PCPs, 30% for PFAS, and 50% for pesticides. This limited effectiveness can be attributed to the fact that conventional filtration primarily targets suspended solids and particulate matter rather than dissolved organic or synthetic contaminants. Many ECs are chemically stable, soluble, or present at trace concentrations, which makes them resistant to simple filtration and chlorination processes commonly employed in traditional treatment plants.

Activated carbon filtration showed moderate improvement, removing 60% of pharmaceuticals, 55% of PCPs, 50% of PFAS, and 70% of pesticides. The enhanced performance is due to the adsorptive properties of activated carbon, which can capture a variety of organic molecules. However, its efficiency varies depending on the chemical properties of the contaminants; highly persistent compounds like PFAS are only partially removed, and breakthrough can occur if the carbon becomes saturated (Brunn et al. 2023).

Reverse osmosis (RO) demonstrated significantly higher removal efficiencies, with 90% for pharmaceuticals, 85% for PCPs, 95% for PFAS, and 85% for pesticides. RO uses a semi-permeable membrane to physically block dissolved contaminants, including very small molecules and ions. This mechanism makes it highly effective for a broad spectrum of ECs, including those resistant to chemical degradation (**Rosa and Lasso,**

2023). However, RO is energy-intensive, expensive to operate, and generates concentrated waste streams that require proper disposal.

Advanced oxidation processes (AOPs) were the most effective overall, achieving 95% removal of pharmaceuticals, 90% of PCPs, 99% of PFAS, and 95% of pesticides. AOPs rely on the generation of highly reactive hydroxyl radicals that can degrade complex and stable organic molecules into smaller, less harmful compounds. This process is particularly effective against recalcitrant compounds such as PFAS and synthetic hormones, which are otherwise poorly removed by conventional treatment methods (**Arnot and Gauthier, 2022)**. Furthermore, AOPs can be combined with other treatment methods to maximize removal efficiency and address a wide range of ECs.

Both RO and AOPs outperform conventional and activated carbon filtration by a large margin. Between the two, AOPs are slightly more effective for PFAS and other highly persistent organic contaminants, achieving nearly complete removal, while RO is highly effective for a broader range of ECs but comes with higher operational costs and energy demands. Therefore, for achieving the highest water quality and comprehensive removal of emerging contaminants, AOPs are recommended (**Khan and Jamil, 2023)**, ideally in combination with RO or other conventional methods, to balance efficiency, cost, and sustainability.

7.3 Health Implications

Health risks that may be caused by chronic low-level exposure to ECs, especially pharmaceuticals and PFAS are still being studied. PFAS contamination at chronic levels has caused cancer, developmental disorders, and liver damage whereas pharmaceuticals have been demonstrated to alter endocrine functions in aquatic life that may also impact human health.

The frequency of occurrence of the emerging contaminants in water as reflected by this graph (Figure 1) visually illustrates the level of occurrence of the contaminants in the drinking water supplies. The Table 3 presents the concentrations of various emerging contaminants (ECs) remaining in drinking water after treatment with different technologies, including pharmaceuticals, personal care products (PCPs), PFAS, and pesticides. The data clearly demonstrates the relative effectiveness of each treatment method in reducing contaminant levels (**Nguyen and Nguyen, 2021)**.

Conventional filtration showed the highest residual concentrations, with 50 ng/L of pharmaceuticals, 60 ng/L of PCPs, 70 ng/L of PFAS, and 45 ng/L of pesticides. This indicates that conventional filtration is largely ineffective at removing dissolved and chemically stable contaminants. The mechanism of conventional filtration primarily targets suspended solids and particulates, so dissolved organics, synthetic compounds, and persistent chemicals pass through untreated. The high residual levels, particularly of PFAS and PCPs, illustrate the limitations of traditional treatment processes in addressing emerging contaminants (**Zhang and Liu, 2023)**.

Activated carbon filtration performed better, reducing pharmaceuticals to 40 ng/L, PCPs to 50 ng/L, PFAS to 60 ng/L, and pesticides to 30 ng/L. Activated carbon works via adsorption, capturing many organic molecules; however, its efficiency depends on the chemical properties of the contaminants (**Gonzále and Carmona, 2022)**. Persistent compounds such as PFAS and highly soluble pharmaceuticals are only partially removed, and the carbon medium can become saturated over time, reducing its effectiveness.

Reverse osmosis (RO) significantly reduced contaminant levels, leaving only 10 ng/L of pharmaceuticals, 15 ng/L of PCPs, 5 ng/L of PFAS, and 10 ng/L of pesticides. RO uses semi-permeable membranes that physically remove dissolved contaminants, including very small molecules and ions. Its effectiveness across all classes of ECs demonstrates its suitability for high-quality water treatment. However, RO is energy-intensive, costly, and produces concentrated waste that requires careful disposal.

Advanced oxidation processes (AOPs) were the most effective, leaving minimal residual concentrations: 5 ng/L of pharmaceuticals, 7 ng/L of PCPs, 1 ng/L of PFAS, and 5 ng/L of pesticides. AOPs utilize highly reactive hydroxyl radicals to degrade stable organic molecules into smaller, less harmful compounds (**Sharma and Singh, 2021)**. This mechanism is particularly effective for recalcitrant compounds such as PFAS and persistent pharmaceuticals, which resist conventional treatment. Moreover, AOPs can be integrated with other treatment technologies to maximize overall contaminant removal.

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The comparison indicates a clear hierarchy in treatment efficiency: AOPs > Reverse Osmosis > Activated Carbon Filtration > Conventional Filtration. AOPs achieve the lowest residual contaminant levels, particularly for highly persistent substances like PFAS and pharmaceuticals, making them the most effective standalone technology for comprehensive removal of emerging contaminants (**González and Rodríguez, 2020**). Reverse osmosis is also highly effective and suitable for broad-spectrum contaminant removal but may be less practical due to operational costs and energy requirements. Therefore, AOPs are recommended as the most efficient treatment method for ensuring safe and high-quality drinking water, particularly in areas with high prevalence of persistent emerging contaminants.

Table 3. Summary of Water Quality Parameters in Treated Water

Treatment Technology	Pharmaceuticals (ng/L)	Personal Care Products (ng/L)	PFAS (ng/L)	Pesticides (ng/L)
Conventional Filtration	50	60	70	45
Activated Carbon Filtration	40	50	60	30
Reverse Osmosis	10	15	5	10
Advanced Oxidation Processes	5	7	1	5

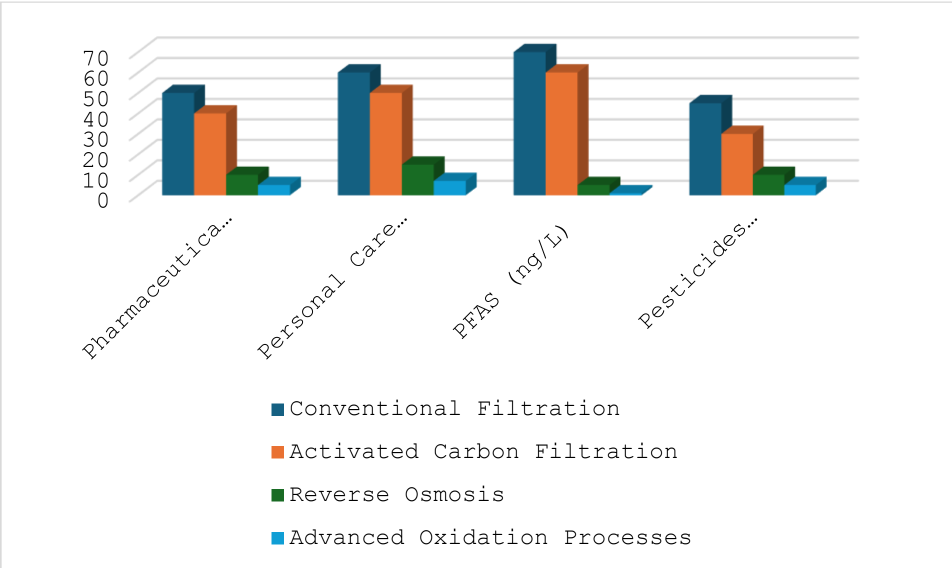

Figure 1. Occurrence of Emerging Contaminants in Drinking Water

The (Table 4) summarizes the potential health effects associated with different types of emerging contaminants (ECs) commonly found in drinking water. Pharmaceuticals, which include antibiotics, hormones, and painkillers, have been linked to endocrine disruption, reproductive health issues, and the development of antibiotic resistance (**Van der Aa and Adams, 2022; Das, A 2024a**). These effects arise because even trace amounts of bioactive compounds can interfere with hormonal regulation and microbial communities in the body (**Fick and Lindqvist, 2021**). Personal care products (PCPs), such as parabens, phthalates, and UV filters, are associated with hormonal imbalances, skin irritation, and allergic reactions, reflecting their capacity to interact with the endocrine system or trigger immune responses even at low exposure levels. PFAS (per- and polyfluoroalkyl substances), widely used in industrial applications, are particularly concerning due to their persistence in the environment and bioaccumulation; exposure has been linked to cancer, liver damage, and developmental issues in children, emphasizing the risks to vulnerable populations. Pesticides and herbicides, including glyphosate, atrazine, and chlorpyrifos, have been shown to cause neurotoxicity, endocrine disruption, and even cancer, reflecting both acute and long-term risks. Overall, this table highlights that the health risks of ECs vary depending on the contaminant type, but even at trace concentrations (**Kümmerer, K, 2020)**, their presence in drinking water poses significant concerns for human health, especially for sensitive groups such as infants, pregnant women, and the elderly. This underscores the critical need for effective monitoring, regulation, and advanced treatment technologies to minimize exposure and protect public health.

Table 4. Health Risks of Emerging Contaminants in Drinking Water

Contaminant Type	Health Effects
Pharmaceuticals	Endocrine disruption, reproductive health effects, antibiotic resistance
Personal Care Products	Hormonal imbalances, skin irritation, allergic reactions
PFAS	Cancer, liver damage, developmental issues in children
Pesticides & Herbicides	Neurotoxicity, endocrine disruption, cancer

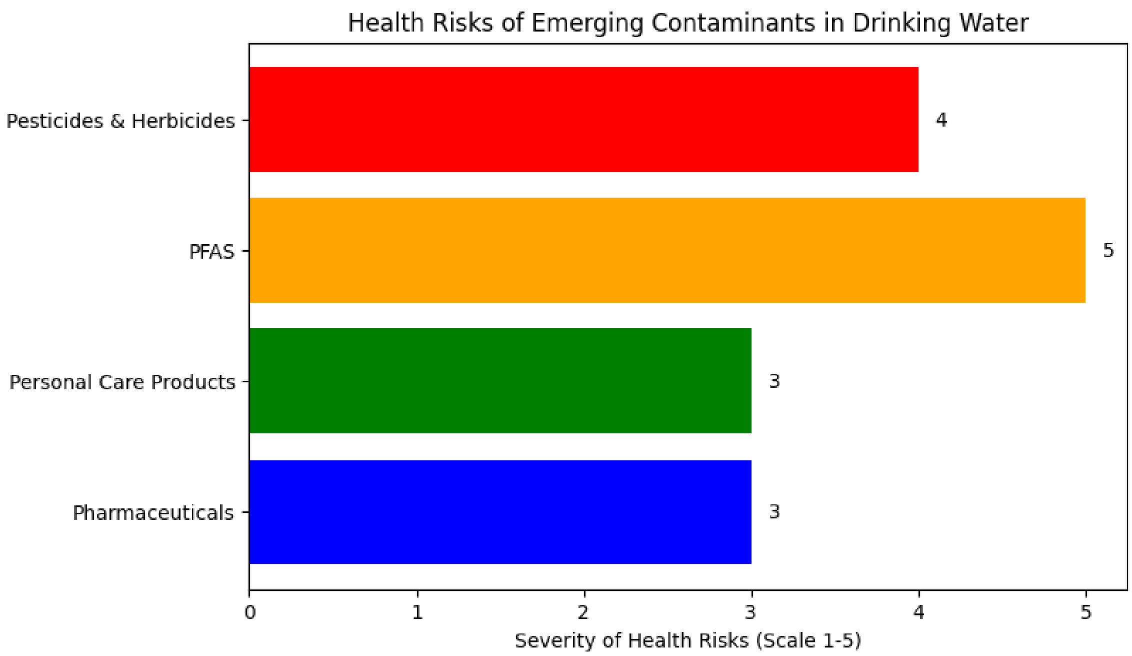

Figure 2. A bar diagram representing health risks of emerging contaminants in drinking water

The following is the bar graph (Figure 2), which shows the severity of health risks associated with emerging contaminants (ECs) in drinking water. The severity of health effects for pharmaceuticals, personal care products (PCPs), PFAS, and pesticides and herbicides is presented on a scale of 1 to 5, with PFAS exhibiting the highest severity. Pharmaceuticals, while prevalent, show moderate severity due to their potential for endocrine disruption, reproductive effects, and development of antibiotic resistance. Personal care products rank slightly lower, reflecting their tendency to cause hormonal imbalances, allergic reactions, or skin irritation at low exposure levels (**Varela and Pereira, 2022; Das, A 2024b**). Pesticides and herbicides have a relatively high severity due to their neurotoxic effects, endocrine-disrupting properties, and potential carcinogenicity, particularly with prolonged or repeated exposure.

PFAS stands out with the highest severity score, reflecting its persistence in the environment, resistance to conventional water treatment, bioaccumulation in the human body, and long-term impacts such as liver damage, cancer, and developmental issues in children (**Zhou and Lee, 2021**). The graph highlights that the severity of health risks is not only dependent on the concentration of contaminants but also on their chemical stability, bio accumulative potential, and susceptibility to conventional water treatment methods (Das, A 2022).

This visualization underscores the critical need for targeted monitoring, stricter regulatory standards, and the adoption of advanced treatment technologies such as AOPs and reverse osmosis to mitigate these risks (**Kümmerer, et al. 2020; Das, A 2026**). Moreover, it emphasizes the importance of public awareness and research into the cumulative and long-term health impacts of exposure to ECs, particularly for vulnerable populations such as infants, children, pregnant women, and immunocompromised individuals. Overall, Figure 2 serves as a clear representation of the relative health hazards posed by different emerging contaminants, guiding policymakers, water treatment authorities, and researchers in prioritizing interventions for the most severe and persistent pollutants.

8. Conclusion

New drinking water contaminants are a major social health concern, which needs greater attention. Emerging contaminants (ECs), including pharmaceuticals, personal care products, PFAS, pesticides, and endocrine-disrupting chemicals, are increasingly being detected in drinking water sources at trace levels, yet even low concentrations can have significant long-term health impacts, such as endocrine disruption, neurotoxicity, reproductive disorders, and cancer. This paper has indicated that although the traditional treatment means are not efficient in eliminating most ECs, the sophisticated treatment technologies such as AOPs and reverse osmosis can be used in this situation. AOPs utilize highly reactive hydroxyl radicals to degrade persistent organic compounds, while reverse osmosis employs semi-permeable membranes to physically remove a wide range of dissolved contaminants, including highly stable substances like PFAS and pharmaceuticals.

Since ECs are very common in drinking water systems worldwide, there is a critical need for ongoing research to understand their long-term health impacts, cumulative effects, and potential ecological consequences. Developing more cost-effective and energy-efficient treatment solutions is also essential to ensure that advanced technologies can be implemented on a large scale, particularly in regions with limited resources. Moreover, it is important to establish regulatory standards and monitoring frameworks for ECs to safeguard public health, guide treatment priorities, and support evidence-based policymaking.

This study contributes to achieving several Sustainable Development Goals (SDGs), particularly, SDG - 3 (Good Health and Well-being) by addressing chemical hazards in drinking water and minimizing health risks; SDG - 6 (Clean Water and Sanitation) by highlighting advanced treatment methods for safe water supply; and SDG - 12 (Responsible Consumption and Production) by identifying the sources and impacts of persistent contaminants, encouraging sustainable practices in pharmaceuticals, agriculture, and industrial processes. By combining the assessment of contaminant prevalence, evaluation of treatment efficiencies, and discussion of health risks, this research provides a comprehensive framework for policymakers, water authorities, and researchers to enhance drinking water safety and ensure sustainable water management.

Overall, this study emphasizes that the proactive identification, treatment, and regulation of ECs are critical for protecting public health, promoting environmental sustainability, and fulfilling global commitments to clean and safe water for all.

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Credit authorship contribution statement

Dr. Abhijeet Das: Study conception, Conceptualization, Material preparation, Data collection, Analysis, Interpretation, Methodology, Resources, Writing – Original draft, Formal analysis, Investigation, Supervision, Writing – review and editing. Kumbhakarna Mallik: Conceptualization, Material preparation, Data collection, Analysis, Interpretation; Dr. Krishna Pada Bauri: Investigation, Supervision, Writing – review and editing. The corresponding author have read and agreed to the published version of the manuscript.

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