Nanotechnology and Emerging Contaminants in Drinking Water

Advanced Solutions for Purification

Edited by
Sesan Abiodun Aransiola,
Yakubu Adekunle Alli,
Kondakindi Venkateswar Reddy,
and Naga Raju Maddela

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Nanotechnology and Emerging Contaminants in Drinking Water

This book delves into the cutting-edge application of nanotechnology for the detection, removal, and degradation of emerging contaminants in drinking water. It covers a wide range of nanomaterials detailing their synthesis, functionalization, and deployment in water treatment processes. It presents case studies and pilot projects that demonstrate the scalability of these technologies, providing valuable insights into the challenges and opportunities associated with integrating nanomaterials into existing water infrastructure.

Features:

- Discusses the concept of emerging contaminants in drinking water, such as pharmaceuticals, personal care products, and microplastics.
- Provides an overview of traditional water treatment methods and their limitations in removing these contaminants.
- Examines nanomaterials as a promising solution for capturing and degrading contaminants at the molecular level in drinking water.
- Establishes strong connections between theoretical mechanisms and nanotechnology applications.
- Presents the current state of nanomaterial-based water treatment technologies in real-world applications, including industrial and municipal water treatment plants.

This book is aimed at graduate students and researchers in environmental and chemical engineering, and water treatment.

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Foreword

Chukwuma C. Ogbaga

Water is life. Yet, in today's rapidly changing world, ensuring access to safe and clean drinking water has become one of humanity's most pressing challenges. Beyond traditional pollutants, we now face a new generation of threats: emerging contaminants, micropollutants, pharmaceuticals, personal care products, heavy metals, and microplastics that are often invisible, persistent, and difficult to remove using conventional water treatment methods. These challenges affect not only human health but also ecosystems, agriculture, and the sustainability of our natural resources.

Nanotechnology and Emerging Contaminants in Drinking Water: Advanced Solutions for Purification is a timely and groundbreaking work that addresses these critical issues. By harnessing the extraordinary properties of nanomaterials, from metal and metal oxide nanoparticles to carbon-based nanostructures, the book demonstrates how innovative technologies can detect, capture, and neutralize contaminants in ways previously unimaginable. It bridges the gap between complex scientific research and practical, real-world solutions, showing how cutting-edge science can make a tangible difference in the quality of life for communities worldwide.

What makes this book especially remarkable is its holistic approach. It does not merely focus on the technical aspects of nanotechnology; it places these innovations within the broader context of environmental sustainability, public health, and global water security. Readers will gain insight into both the promise and the challenges of applying nanotechnology for water purification, including considerations of safety, scalability, and environmental impact. This work is a vital resource for scientists, engineers, policymakers, students, and anyone passionate about protecting our planet and ensuring access to one of humanity's most fundamental resources. More than a technical guide, it is a source of inspiration, demonstrating that with innovation, determination, and collaboration, we can overcome even the most daunting challenges. The authors' vision and scholarship offer hope and a clear path toward a future where clean and safe drinking water is not a privilege, but a universal reality.

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7 September 2025

Preface

Water is the most essential natural resource for sustaining life on earth. It plays a critical role in human health, agricultural productivity, industrial development, and ecological balance. Safe and clean drinking water is fundamental to human survival and well-being. However, contamination of water resources has become one of the most pressing global challenges in the 21st century. Among these, the presence of emerging contaminants including pharmaceuticals, personal care products, pesticides, microplastics, endocrine-disrupting compounds, and other synthetic chemicals has raised unprecedented concern. Emerging contaminants in drinking water are particularly problematic due to their persistence, resistance to conventional treatment methods, and potential for bioaccumulation. Even at trace levels, these contaminants can interfere with human hormonal systems, cause oxidative stress, and contribute to chronic diseases such as cancer, reproductive disorders, and developmental abnormalities. Moreover, their continuous release into aquatic environments threatens aquatic ecosystems, reduces water quality, and complicates global water security efforts. Conventional purification technologies often prove inadequate in eliminating these pollutants, underscoring the urgent need for advanced, sustainable, and innovative solutions.

Nanotechnology has emerged as a transformative tool to address these challenges. Engineered nanomaterials with unique surface properties, tunable porosity, high reactivity, and multifunctional capabilities offer new opportunities for the efficient removal, degradation, and monitoring of emerging contaminants in drinking water. By leveraging nanotechnology-based adsorption, photocatalysis, filtration, and sensing systems, researchers and engineers are pushing the frontiers of water purification technologies. These advanced solutions not only promise enhanced efficiency but also align with global efforts to achieve safe, accessible, and contaminant-free water for all. The sustainability of global drinking water resources is crucial in meeting the demands of a rapidly growing population and in securing the future of human health. Providing contaminant-free water has become more complex in light of emerging pollutants, but also more urgent. One such critical issue is the long-term ecological and health risks posed by persistent organic and inorganic contaminants. Although present in minute concentrations, their continuous release and resistance to natural degradation make them a serious environmental and public health threat. These concerns have been critically explored and addressed in this volume with the latest scientific insights and technological innovations available in the literature.

In addition, this book is organized into three comprehensive sections: ("Introduction to Water Contaminants and Purification Methods," "Traditional and Nanotechnology-Based Water Purification," and "Health Risks, Regulations, and Future Perspectives") with four, six, and nine chapters in Sections I, II, and III, respectively, making up 19 chapters in total. Each section is systematically structured to address vital challenges, technological developments, and forward-looking strategies in the field of water purification. Also, Scopus AI (Elsevier software), Deep Seek, Grammarly, and ChatGPT-OpenAI were used to create preliminary, contextual literature searches, correct the flow and detect redundancies, correct English mistakes and to improve the writing tone and to generate the structural outline especially for Chapters 1, 4, and 16.

The chapters were contributed by 75 leading academics, scientists, and researchers from diverse regions of the world including Nigeria, India, the United States, South Africa, Morocco, Mexico, Kazakhstan, Algeria, the United Kingdom, Ecuador, Brazil, Poland, Zimbabwe, Taiwan, and Pakistan reflecting a truly global perspective on one of humanity's most urgent concerns.

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We express our profound gratitude to all the contributors to this chapter, whose expertise, timely input, and unwavering commitment have been instrumental in bringing this book to fruition. The enthusiasm, generosity, and collaborative spirit of each contributor ensured that this work was completed efficiently and to the highest standard. We also extend our sincere appreciation to the anonymous reviewers, whose insightful and constructive feedback significantly enhanced the quality of this book by encouraging the inclusion of additional expert perspectives. Our heartfelt thanks go to the CRC Press team and the production staff, whose guidance, professionalism, and support were critical in ensuring the timely and successful completion of this project. Collaborating with such dedicated professionals has been both an honor and a privilege. Finally, we wish to acknowledge the invaluable support of the management and colleagues at the University of Abuja (Nigeria), Nelson Mandela University (South Africa), Jawaharlal Nehru Technological University (India), and Universidad Técnica de Manabí (Ecuador), whose encouragement and assistance throughout the proposal, preparation, and publication process have been indispensable.

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Sesan Abiodun Aransiola is a lecturer at the Department of Microbiology, University of Abuja, Nigeria. He obtained his B.Tech, M.Tech, and Ph.D. in Environmental Microbiology from the Federal University of Technology, Minna, Nigeria. He has demonstrated his research expert in the production of vermicasts from vermicomposting of organic wastes to assist plants in the remediation of polluted soil with heavy metals. His expertise spans environmental health, phytoremediation, vermicomposting, marine resources, and bioremediation of pollutants in the soil. Aransiola's research is deeply rooted in innovative solutions for soil and water remediation, with significant contributions to microbial biotechnology and waste management. He is an award-winning researcher and has over 100 publications including book chapters, research and review articles of good international repute with high-impact factors. He has co-edited scientific books of global interest which include microbial biotechnology for bioenergy, marine bioresources: prospects and obstacles; marine bioresources: prospects and obstacles; marine microbial products: applications and opportunities. Ecological interplays in microbial enzymology, prospects for soil regeneration and its impact on environmental protection, soil microbiome in green technology sustainability, marine bioprospecting for sustainable blue-bioeconomy, vermitechnology: economic, environmental, and agricultural sustainability, white pollution: biodiversity and hazards in marine plastisphere, wetland ecosystems: conservation strategies, policy management, and applications. Microbial biofilms—applications and control, marine greens: environmental, agricultural, industrial, and biomedical applications, environmental footprint of bioplastic additives, emerging contaminants in food and food products, phytoremediation in food safety: risks and prospects, biotoxins in food: threats and benefits, fuel cells in environmental sustainability, biotechnology of climate-smart agriculture in food security and sustainable farming (CRC Press) with many more in the process. Also, he rose to the rank of assistant chief scientific officer at National Biotechnology Research and Development Agency, Nigeria, for years where he was involved in the uses of vinasse (a by-product of ethanol) as bio-fertilizer to reclaim polluted soil for agricultural purposes before joining the university. Dr. Aransiola's academic journey is complemented by robust research (with some grants won), teaching career (with proper mentoring and supervising both undergraduate and postgraduate students), and active involvement in community services, where he leverages his knowledge to foster sustainability. His contributions continue to impact both academia and the broader environmental sciences community. He is a member of Nigerian Society for Microbiology, Association of Environmental Impact Assessment of Nigeria (Affiliation of International Association for Impact Assessment), and American Society for Microbiology.

Yakubu Adekunle Alli is a distinguished postdoctoral researcher at Nelson Mandela University, specializing in the design of multifunctional nanomaterials for CO_2 conversion, N_2 reduction, renewable energy, and antimicrobial drug development. His work integrates photocatalysis, electrocatalysis, environmental remediation, and advanced additive manufacturing to develop sustainable solutions for energy, climate, and health challenges. Dr. Alli has published 60 high-impact articles with nearly 1,000 citations (h-index 19) and serves as an editor and a reviewer for leading journals, including *Nature Communications*, *Chemical Engineering Journal*, and *ACS Sustainable Chemistry & Engineering*. He has held prestigious fellowships, including the Nelson Mandela Postdoctoral Fellowship, National Research Funds, South Africa, Coimbra Group Scholarship, AOARD Postdoctoral Fellowship, and Peculiar Ultimate Concerns Limited Postdoctoral Scholarship, alongside the Islamic Development Bank Merit Scholarship. His postdoctoral research spans smart 4D printing at International Islamic University Malaysia and CO_2 conversion at the French National Centre for Scientific Research. He also lectures at Ahman Pategi University, Nigeria, mentoring future scientists. A member of the Royal Society of Chemistry, the Chemical Society of Nigeria, and the International Younger Chemists Network, Dr. Alli drives interdisciplinary research at the nexus of nanomaterials, sustainability, and innovative technologies with global impact.

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Section I

Introduction to Water Contaminants and Purification Methods

1 Sources and Types of Emerging Contaminants in Drinking Water

Stella Suanu, Leh-Togi Zobeashia, and Tarimoboere Agbalalah

1.1 INTRODUCTION

Emerging contaminants (ECs), also recognized as contaminants of emerging concern, include a growing challenge in global environmental science and public health. These ECs include a wide range of substances such as pharmaceuticals, microplastics, personal care products, per- and polyfluoroalkyl substances (PFAS), nanomaterials, pesticides, endocrine-disrupting compounds, manufacturing by-products, and flame retardants that are not usually monitored yet pose serious ecological and human health risks (Daughton and Ternes, 1999; Daughton, 2019). Unlike traditional pollutants, ECs usually escape detection or regulation standard by water processing and monitoring systems, which pose a key threat to the safety and sustainability of DW sources worldwide (Smith et al., 2023; Aransiola et al., 2024). The label "emerging" does not indicate that these materials are newly produced, rather, developments in analytical techniques have enabled their identification often at minimal levels that were previously undetectable and that, increasing scientific documentation connects these contaminants to possible adverse impacts to health and environment. Many ECs are persistent, capable of bioaccumulation, and toxic; some interfere with endocrine functions, contribute to antimicrobial resistance, or cause long-term harmful effects (Jones et al., 2024; Sharma et al., 2024). Their diverse origins include urban wastewater, agricultural runoff, improper drug disposal, personal care products, and industrial effluents, collectively contributing to their widespread occurrence in surface water, groundwater, and ultimately drinking water supplies (Kumar et al., 2023). Concern over ECs globally stems from their extensive human health implication and water sustainability. Consumption of contaminated drinking water exposes populations to complex chemical mixtures whose chronic effects remain poorly understood yet may be cumulative, transgenerational, or delayed (Wang et al., 2023). Infants and children are particularly vulnerable due to higher intake per body weight and greater sensitivity to toxic exposures. Furthermore, ECs contamination disproportionately impacts developing and economically disadvantaged areas, where accelerated industrialization, limited sewage treatment, and regulatory gaps dominate (Garcia et al., 2023). Such disparities endanger public wellness advancement, intensify socio-environmental inequalities, and obstruct achievement of United Nations Sustainable Development Goals for clean water and sanitation (Lee et al., 2023). Policy and technological measures remain disconnected despite increasing recognition. Numerous countries are only starting to integrate ECs into water quality standard, limited by chemical variety, absence of standardized analytical techniques, and incomplete toxicological assessments. Policy examinations demonstrate the requirement for coordinated global administration, enhanced surveillance, preventive pollution control, and advanced processing methods including sophisticated oxidation, membrane separation, and nanomaterial-based networks (Patel et al., 2023). In the United States, the Environmental Protection Agency (EPA) has launched coordinated investigation initiatives to characterize sources, destiny, and health

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effects, while advocacy organizations demand precautionary oversight and increased public openness (Johnson et al., 2023). The chapter review the sources and the different types of ECs in global drinking water systems, detailing their contamination routes and also grouping important pollutants. It also indicates their environmental behavior, physicochemical properties, and resistance to removal by standard treatment processes. The chapter aims to aid decision-making in water quality management, protect the health of the public, and direct future research efforts by advocating for a coordinated, multidisciplinary approaches to tackle this complex issue, ensuring safe and sustainable drinking water for present and future generations.

1.1.1 Overview of Emerging Contaminants

Emerging contaminants are acknowledged by their growing prominence in environmental research and by the restricted or newly accepted evidence linking them to toxic effects on the health of human and the ecosystems. A substance is typically classified as an ECs when concerns arise about its environmental and biological impact, but regulatory oversight remains limited due to insufficient data or detection challenges. Classification evolves with ongoing research, with major categories including pharmaceuticals and personal care products (PPCPs), industrial chemicals, pesticides, microplastics, engineered nanomaterials, and naturally occurring toxins such as cyanotoxins. These categories are based on their sources, chemical structures, and typical environmental pathways (Smith et al., 2023; U.S. EPA et al., 2023). PPCPs infiltrate waterways primarily through municipal discharges, agricultural runoff, and disposal of unused products, including compounds such as antibiotics, synthetic hormones, and microbial agents. Industrial substances like PFAS persist due to their extraordinary stability and resistance to degradation. Pest control chemical differs in persistence, with some rapidly degrading while others linger in sediments and biota. Plastics microparticles and nanomaterials present a particulate type of contamination with distinct biological absorption and transport processes (Smith et al., 2023; Jones et al., 2024).

The ecological future of ECs depends upon their chemical and physical properties, which determine persistence, movement, and removal potential. Several emerging pollutants withstand standard treatment techniques because of their minimal water-repelling nature, restricted biodegradability, and stable molecular structures including the carbon–fluorine bonds in PFAS that provide extended persistence in water environments and sediment deposits. Their persistence receives additional support from sediment binding, distribution across water and organic compartments, and conversion to derivative compounds that might maintain or surpass the harmfulness of the original substance. Environmental systems frequently function as extended storage sites, enabling slow discharge and continuous contact (Patel et al., 2024; Kumar et al., 2025). These characteristics encourage bio-accumulation in aquatic creatures and concentration increases throughout food web, disrupting natural functions like breeding, nutrient recycling, and species equilibrium. Amplifying these dangers are attributes including hormone interference, harmful impacts at minute amounts, and the enhancement of antibiotic resistance (Smith et al., 2023; Jones et al., 2024). The human health consequences extend beyond immediate poisoning, prolonged consumption of minute drug residues, hormonal compounds, and lasting industrial contaminants through potable water connects to hormonal system malfunction, decreased reproductive capacity, growing antibiotic resistance, and increased malignancy probability. Vulnerable populations particularly infants, pregnant women, and immune-compromised individuals encounter intensified risks due to physiological sensitivity and exposure intensity. From an ecological standpoint, ECs disrupt growth, reproduction, and behavior of aquatic organisms, occasionally causing population reductions and modifying community composition. Recalcitrant substances such as PFAS can bioaccumulate to dangerous concentrations in apex predators, including humans. Residues of antibiotics in aquatic environments accelerate the emergence of resistant bacterial strains, reducing the efficacy of critical medicines (U.S. EPA et al., 2023; Patel et al., 2024). Incomplete toxicological assessments and developing evidence of combined effects emphasize the necessity for focused research, systematic monitoring, and flexible regulation. Preventive strategies must combine advanced detection technologies, innovative water treatment approaches, and cautionary policy frameworks to safeguard both public health and ecosystem stability in the presence of changing contamination challenges (Jones et al., 2024; Sharma et al., 2024; U.S. EPA et al., 2023).

1.2 SOURCES OF EMERGING CONTAMINANTS IN DRINKING WATER

Emerging contaminants in drinking water arise from multiple sources and follow complex pathways through which various pollutants enter and disperse within aquatic environments. These sources include agricultural runoffs, municipal sewage discharges, effluents from industrial organization, landfill leachate, municipal wastewater discharges, urban/metropolitan storm water runoff, and geological or naturally occurring sources. Understanding these origins remains vital for tackling contamination, enhancing water purification, and safeguarding human and environmental wellness (Khan et al., 2023a; Oluwaseun et al., 2024; Heis et al., 2025b).

1.2.1 Municipal Sewage Discharges

Municipal sewage serves as a principal channel introducing pharmaceuticals, personal hygiene products (PHPs), and plastic microparticles into aquatic systems. Wastewater treatment plants (WTPs) commonly process household and industrial wastewater containing traces of prescription medicines, over-the-counter medications, cosmetic products, and polymer microparticles from synthetic materials and personal hygiene products. Although WTPs reduce many contaminants, conventional treatment approaches often cannot completely remove these compounds, producing treated effluents that carry ECs to receiving waters (Oluwaseun et al., 2024). Studies have shown that antibiotics, analgesics, hormone chemicals, and antimicrobial agents are consistently detected in both treated and untreated wastewater outputs. Polymer microparticles, especially synthetic materials from manufactured textiles, also contribute significantly to pollution loads, originating from domestic laundry discharges and urban stormwater entering sewer systems. The continuous discharge from WTPs elevates ECs levels in rivers and lakes, posing risks for aquatic ecosystems and drinking water supplies (Oluwaseun et al., 2024; Mason et al., 2016).

1.2.2 Industrial Waste Streams

Industrial effluents constitute a major and varied sources of emerging contaminants, including colorants, chemical solutions, heavy metals, and enduring organic pollutants such as per- and polyfluoroalkyl compounds (PFAS). Processes including production facilities, surface treatment operations, chemical manufacturers, and fabric producers release intricate waste mixtures containing dangerous chemicals that frequently evade traditional wastewater treatment processes (Heis et al., 2025a). Heavy metals such as lead, cadmium, chromium, and mercury typically persist in manufacturing wastewater and concentrate in water environments, creating extended dangers through poisoning and bioaccumulation. PFAS, broadly used in manufacturing operations for their moisture- and flame-resistant characteristics, demonstrate remarkable persistence and are progressively found in water sources near manufacturing areas (Heis et al., 2025a; Afropolitan Journals, 2024). Current research suggests that uncontrolled or inadequately processed manufacturing discharges significantly contribute to drinking water pollution, demonstrating the critical requirement for enhanced regulatory controls and sophisticated treatment technologies specifically addressing these contaminants (Liang et al., 2023; Heis et al., 2025b).

1.2.3 Agricultural-Related Runoff

Agricultural activities release pesticides, livestock medicines, and nutrient supplements into surface and groundwater systems, constituting major origins of ECs. Pesticides broadly employed for plant protection including insecticides, herbicides, and fungicides regularly leak into adjacent water bodies during rainfall or irrigation, contaminating both surface waters and shallow groundwater aquifers (Khan et al., 2023b). Livestock pharmaceuticals administered to farm animals for disease control or growth promotion also enter water systems through waste and runoff. Remaining antimicrobials, hormonal substances, and parasite-fighting compounds used in livestock management have been discovered in farming drainage and subsurface water, with documentation that certain animal medication residues build up in soils and remain presentthroughout growing cycles (Song et al., 2010; Khan et al., 2023a). Plant nutrients from soil enhancers, especially nitrogen and phosphorus substances, promote excessive algae growth and can enable the movement of related chemical pollutants. These farming additions ultimately worsen contamination in drinking water resources, emphasizing the requirement for environmentally sound farming methods and improved management of agricultural chemicals (Song et al., 2010; Khan et al., 2023b).

1.2.4 Urban Stormwater Drainage

Urban stormwater runoff transports a variety of pollutants from impermeable surfaces, including hydrocarbons from vehicle exhaust, tire wear particles, and microplastics originating from urban debris and atmospheric fallout. These contaminants accumulate on streets, rooftops, and other hard surfaces, then rapidly enter water bodies during rain events, bypassing wastewater treatment facilities (Peterson et al., 2024a; Yonkos et al., 2014). Levels of microplastics mainly polyethylene and polypropylene fragments often surpass those in treated wastewater. Stormwater acts as a key conduit, carrying hydrocarbons, heavy metals, and particulates into freshwater ecosystems, where they can interact with other pollutants to amplify toxicity (Peterson et al., 2024c; Chen et al., 2022). Studies confirm urban drainage is a major contributor to pollutant loads in metropolitan drinking water supplies (Peterson et al., 2024b).

1.2.5 Landfill Leachate

Landfill leachate also known as refuse site seepage, produced by water filtering through waste accumulations, holds complicated combinations of organic and mineral pollutants, encompassing toxic metals, evaporating organic substances, and enduring chemicals. Since many landfill sites lack adequate containment or treatment systems, leachate can infiltrate soil and groundwater, leading to contamination of drinking water (Liang et al., 2023; ACTenviro, 2025). The composition of leachate varies with landfill age, waste types, and weather conditions but often contains hazardous substances such as phenolic compounds, ammonia, chlorinated solvents, and toxic metals. This complex mixture poses significant remediation difficulties due to its contaminants' high mobility, toxicity, and resistance to biodegradation (Liang et al., 2023; ACTenviro, 2025). Effective leachate management demands strong containment and advanced treatment technologies, underscoring its role as a critical emerging pollution source that calls for stricter regulation and innovative cleanup approaches (Liang et al., 2023).

1.2.6 Geological Sources

Natural geological sources release contaminants including arsenic, fluoride, and manganese into drinking water, primarily through geochemical processes in aquifers. Although these elements are naturally present in bedrock and soils, they may reach dangerous concentrations under specific hydrogeological conditions (Rahman et al., 2023b). Arsenic, found in arsenic-rich formations, has been associated with cancers and skin diseases after long-term exposure. Fluoride, beneficial in small amounts, can cause dental and skeletal fluorosis if concentrations become too high. Likewise, manganese, essential at trace levels, poses neurotoxic hazards when elevated (Rahman et al., 2023b; GAPMaps, 2024). Differentiating natural contamination from human-caused pollution is crucial for targeted interventions and accurate risk evaluation, especially in areas depending on untreated groundwater (Table 1.1) (Rahman et al., 2023a).

TABLE 1.1
Sources of Emerging Contaminants in Drinking Water

S/No	Sources	Main Contaminants	Impact	References
1.	Municipal sewage	Hormones, microplastics, antimicrobials	Persistent contamination of water	Oluwaseun et al. (2024)
2.	Industrial effluents	PFAS, heavy metals (Pb, Cd, Hg), solvents	Bioaccumulation, toxicity	Heis et al. (2025a)
3.	Agricultural runoff	Pesticides, fertilizers, animal drugs	Algal blooms, endocrine disruption	Khan et al. (2023a)
4.	Landfill leachate	Phenols, ammonia, chlorinated solvents, metals	Groundwater pollution	Liang et al. (2023)
5.	Urban stormwater	Hydrocarbons, tire particles, plastics	Rapid pollutant transport	Peterson et al. (2024c)
6.	Geological sources	Arsenic, fluoride, manganese	Cancer, fluorosis, neurological effects	Rahman et al. (2023b)

1.3 TYPES OF EMERGING CONTAMINANTS

1.3.1 Categories of Pharmaceutical and Personal Care Products (PPCPs)

Personal hygiene products (PHPs) and pharmaceuticals represent one of the most common categories of emerging contaminants identified in potable water. This group includes antibiotics, pain relievers, psychiatric drugs, endocrine compounds, sunscreen chemicals, scents, and numerous cosmetic components utilized for wellness, cleanliness, and beauty applications. These materials enter water environments mainly through urban wastewater discharges, improper disposal practices, and human and animal excretion (Heis et al., 2025a; URI, 2025; Amobonye et al., 2023). Drugs including antidepressants and antimicrobials have repeatedly been identified in trace amounts in surface waters, groundwater, and treated drinking water supplies. The presence of ECs creates public health concerns about antibiotic resistance development and potential chronic health impacts. Personal hygiene items and sunscreen chemicals discharge perfumes and synthetic UV-protective compounds that may disrupt aquatic organisms and bacterial populations. The intricacy of their chemical combinations and the impacts of minimal exposure levels challenge hazard evaluation, requiring extensive monitoring and thorough investigation (URI, 2025; Heis et al., 2025b).

1.3.2 Hormonal Disruption Compounds (HDCs)

Hormonal-disrupting compounds (HDCs) are chemicals substances that interfere with the endocrine systems of both humans and wildlife, potentially causing reproductive, developmental, neurological, and immune-related problems. Major EDCs found in drinking water include bisphenol A (BPA), plasticizers used to increase material flexibility, and synthetic hormones such as estrogens and contraceptive drugs (Zhang et al., 2023a; OECD, 2023). These substances originate from industrial manufacturing releases, agricultural runoff containing hormones from farm animals, and sewage discharges. They persist in aquatic environments due to their lipophilic nature and resistance to biological degradation.

1.3.3 Per- and Polyfluoroalkyl Compounds (PFAS)

PFAS, frequently called “eternal chemicals,” are a category of artificial fluorinated substances broadly utilized in non-adhesive cookware, stain-repelling materials, fire-suppression foams, and numerous manufacturing processes. They are distinguished by robust carbon-fluorine connections, making them extremely resistant to environmental breakdown and persistent in water systems globally (Nguyen et al., 2024). PFAS pollution in potable water has developed into a significant worldwide concern because of their bioaccumulative characteristics and connection with negative health consequences, including immune system toxicity, hormonal interference, and specific malignancies. Regulatory bodies have initiated setting guideline thresholds for combined PFAS and particular individual substances in potable water. Traditional water processing approaches are mostly ineffective against PFAS, encouraging the creation and implementation of sophisticated treatment methods including activated carbon absorption and high-pressure membrane separation (Nguyen et al., 2024; EEA, 2024).

1.3.4 Plastic Microparticles and Nanoparticles

Plastic microparticles (fragments <5 mm) and nanoparticles (<100 nm) have developed as extensive pollutants in potable water, stemming from the breakdown of larger plastic waste, artificial fabrics, packaging substances, and manufacturing items. These fragments infiltrate water resources through sewage releases, metropolitan drainage, and atmospheric settling (Peterson et al., 2024a; Schwaferts et al., 2019; Aransiola et al., 2024). Polyethylene, polypropylene, polystyrene, and polyethylene terephthalate are among the most commonly detected polymers in drinking water. Micro-particles from plastics create risks as physical debris but also as a form of vectors for hazardous chemicals and disease-causing microorganisms. Their minute size and varied morphologies facilitate transport and bioavailability which raises concerns about potential human exposure and its impacts on aquatic ecosystems. Thorough sampling protocols and standardization approaches remain crucial for accurately evaluating of plastics microparticle prevalence and associated dangers (Peterson et al., 2024b; Schwaferts et al., 2019; Musa et al., 2024; Auta et al., 2022).

1.3.5 Agricultural and Industrial Chemicals

A wide array of agricultural and industrial chemicals acts as emerging pollutants in drinking water. These include pesticides, herbicides, solvents, and flame retardants extensively applied in agriculture, manufacturing, and domestic settings (Khan et al., 2023a). Agricultural pesticides and herbicides can infiltrate water systems through runoff and leaching, causing risks such as carcinogenicity and endocrine disruption. Industrial solvents and flame retardants, including polybrominated diphenyl ethers (PBDEs), often withstand conventional water treatments and accumulate in food chains. Their persistence and toxicity underscore the need for strict monitoring, regulatory measures, and innovative treatment strategies (Khan et al., 2023b; Heis et al., 2025b).

1.3.6 Water Treatment By-Products (WTBPs)

Water treatment by-products (WTBPs) include chemical substances formed when sanitizing agents such as chlorine interact with occurring organic materials in water during processing procedures. The most widespread disinfectants of WTBPs are trihalomethanes (THMs) and haloacetic acids (HAAs), which commonly are known to appear in chlorinated DW systems worldwide (WHO, 2022; Manitoba Government, 2019). Although disinfection remains crucial to manage waterborne pathogens, extended exposure to certain WTBPs has been linked with elevated cancer and reproductive issues. Regulatory bodies establish maximum pollutant thresholds for WTBPs, and water utilities which aim to enhance processing procedures to reduce their creation, incorporating alternative sanitizing agents and precursor elimination methods (Manitoba Government, 2019; WHO, 2023).

1.3.7 Disease-Causing Microorganisms as Novel Pollutants

Novel pollutants also encompass disease-causing microorganisms and antibiotic-resistant bacteria and genetic material that multiply because of environmental pollution with antimicrobials and chemicals. These microorganisms create substantial health dangers through potable water, particularly where processing and sanitation infrastructure remain insufficient (Heis et al., 2025a; Koch et al., 2021). Antibiotic-resistant bacteria can withstand sewage processing procedures and establish populations in natural water systems. Lateral genetic exchange enables the distribution of resistance genes among microbial communities, intensifying global public wellness obstacles. Surveillance and reduction of microbial novel pollutants demand coordinated monitoring and enhancement in sewage processing and source protection (Heis et al., 2025b; Koch et al., 2021).

1.4 FACTORS INFLUENCING THE OCCURRENCE OF ECs IN DRINKING WATER

1.4.1 Chemical Persistence and Stability

An important factor affecting the presence of ECs in DW is the persistence and stability of the chemical in aquatic environments. Persistence means a substance's resistance to degradation, allowing it to remain in water systems for long durations. Highly persistent ECs can accumulate and disperse over wide geographic regions, resulting in extensive pollution (Zhang et al., 2023a). Many ECs resist natural attenuation due to their molecular structures. For example, per- and polyfluoroalkyl substances (PFAS) have strong carbon–fluorine bonds that make them extremely stable, earning the nickname forever chemicals. This durability hinders their removal by water treatment and supports their prolonged presence in surface and groundwater (Nguyen et al., 2024). Similarly, certain pharmaceuticals and personal care products like carbamazepine and triclosan are resistant to biodegradation and photolysis, which increases their persistence in aquatic environments (Zhang et al., 2023a). The stability of ECs also depends on properties such as sorption behavior, molecular weight, and solubility, which influence their distribution across water, sediments, and organisms. Hydrophobic compounds tend to bind to sediments, creating long-term contamination reservoirs, while low-molecular weight, hydrophilic substances remain dissolved and more bioavailable. Thus, these chemical traits strongly affect contaminant mobility, bioaccumulation potential, and exposure risks (Zhang et al., 2023b).

1.4.2 Effectiveness of Water Treatment Plants

The efficiency of water treatment plants (WTPs) significantly influences ECs levels in drinking water. Traditional treatments like sedimentation, coagulation, filtration, and disinfection efficiently remove many traditional pollutants but often do not fully eliminate ECs due to their chemical persistence and diversity (Olson et al., 2023;Rahman et al., 2023b). Removal success varies by technology; activated carbon adsorption and advanced oxidation processes (AOPs) achieve higher elimination rates for pharmaceuticals and organic micropollutants, whereas standard chlorination or filtration usually only partially reduce EC concentrations (Rahman et al., 2023b). Membrane technologies such as nanofiltration and reverse osmosis provide superior removal but are costly and energy demanding, limiting their broad application. Additionally, WTPs face challenges with transformation products generated during treatment, which may be persistent and toxic themselves. Partial degradation of parent compounds can produce metabolites with unclear toxic effects, complicating risk evaluations (Rahman et al., 2023b). Operational aspects like pollutant load, hydraulic retention time, temperature, and seasonal changes also affect treatment efficacy, causing fluctuating EC levels in treated water (Rahman et al., 2023a; Peterson et al., 2024a).

1.4.3 Temporal Patterns and Hydrological Conditions

Water-related elements and seasonal fluctuations substantially affect ECs presence in aquatic environments. Variations in precipitation, temperature, and current patterns influence transport, dilution, and biodegradation processes (Peterson et al., 2024b). Throughout rainy periods (wet season) or flooding incidents, enhanced surface drainage and stream flow can deliver surges of pollutants from agricultural, metropolitan, and manufacturing sources, raising ECs levels. Storm drainage may carry microparticles of plastics, pesticides, and petroleum products such as hydrocarbons, and additional contaminants into surface or subsurface water, impacting potable water standards (Peterson et al., 2024a). Alternatively, throughout arid or minimal-flow times, decreased dilution increase the levels of present contaminants, therefore intensifying their harmfulness and health dangers. Limited water quantities coupled with increased temperatures can also affect microbial processes and chemical conversion routes, influencing ECs longevity (Peterson et al., 2024b; Zhang et al., 2023b). Furthermore, cyclical trends in human activities/behaviors like heightened pesticide application during cultivation periods or changes in medication usage can create temporally dependent differences in pollutant contributions. These patterns emphasize the significance of extended surveillance to precisely evaluate contact and hazards (Peterson et al., 2024b).

1.4.4 Interconnections and Combined Effects

Persistence, temporal fluctuation, and treatment efficiency are interconnected factors that jointly influence the concentration of emerging contaminants in drinking water. For example, a contaminant that is highly persistent and poorly removed can build up seasonally from agricultural runoff, causing peak exposure periods. The interaction between contaminant chemistry and treatment methods may also produce harmful transformation products with different toxic effects. Seasonal changes in temperature and hydrology can either speed up or slow down these chemical and biological processes, increasing the complexity of managing ECs (Zhang et al., 2023a; Rahman et al., 2023a; Peterson et al., 2024b).

1.5 PUBLIC HEALTH AND ENVIRONMENTAL IMPLICATIONS

Emerging contaminants in drinking water poses a growing threat to public health and the ecosystem globally. These pollutants consist of a wide range of chemicals and microbial agents such as industrial chemicals, pharmaceuticals products, personal cosmetic care products, endocrine disruptors, and antibiotic-resistant bacteria, all detected at trace concentrations in water sources. Their complex behavioral nature and potential toxicity effects require immediate scientific focus and regulatory action (Heis et al., 2025b; Nguyen et al., 2023, 2024; Oluwaseun et al., 2024).

1.5.1 Human Health

The human health effects of emerging contaminants tend to be complex and remains under ongoing study which is as a result of the intricate exposure routes and typically low-dose, chronic exposure. Hormonal disruption is among the most important concerns, as some ECs mimic or interfere with natural hormones, influencing sexual development, reproductive health, and metabolism. Chemicals such as synthetic hormones, bisphenol A, plasticizers, and certain pharmaceuticals act as endocrine disruptors, potentially resulting developmental problems, fertility impairments, and heightened cancer risk (Zhang et al., 2023b; Heis et al., 2025a). Additionally, the pervasive presence of antimicrobials in aquatic environments drives antimicrobial resistance (AMR), a significant global health challenge recognized by the World Health Organization. Antibiotics resistance genes introduced through wastewater and agricultural runoff leads conditions that encourage the spread of resistance among microbial communities (Heis et al., 2025b). This thus threatens the effectiveness of antibiotics drugs important for treating infections in animals and humans. Cancer-causing potential is another significant worry connected to several ECs. Extended contact with specific water pollutants, including polycyclic aromatic hydrocarbons (PAHs), sanitization secondary products, and particular manufacturing chemicals, has been linked with heightened occurrences of diverse malignancies. While levels of individual pollutants may be minimal, the collective impacts, combinations, and transformation substances may worsen dangers (Heis et al., 2025b; Elliott et al., 2025).

1.5.2 Environmental Effects on Aquatic and Land-Based Life

Emerging contaminant negatively impacts aquatic and land-based environments by interrupting physiological and reproductive activities, modifying species relationships, and damaging biological diversity (Nguyen et al., 2024). Aquatic creatures including fish, amphibians, and invertebrates are extremely responsive to minimal levels of ECs, especially hormonal disruptors and medications. Contact has been demonstrated to cause modified sexual development, diminished fertility, behavioral modifications, and heightened death rates in important species (Nguyen et al., 2024). Plastic microparticles and nanoparticles create physical and chemical dangers to aquatic life. Their consumption can cause physical obstructions, decreased feeding, and biological concentration of harmful substances attached onto plastic surfaces. Furthermore, ECs can synergistically combine with additional pollutants, producing amplified ecological harm (Peterson et al., 2024a). Terrestrial organisms, including soil bacteria and animals, experience indirect effects through contaminated water and dietary sources. Persistent organic pollutants and heavy metals accumulate biologically, generating toxic effects at higher food chain positions. These implications threaten ecological stability and the vital environmental functions that sustain human health (Nguyen et al., 2024).

1.5.3 Potential for Biological Accumulation and Trophic Transfer

An important issue related to ECs involves their potential to accumulate biologically and move throughout food chains. Bioaccumulation happens when living organisms absorb contaminants faster than elimination processes, producing increased tissue concentrations across time. This mechanism proves especially important for enduring and fat-soluble pollutants including PFAS, polychlorinated biphenyls (PCBs), and specific pesticides (Oluwaseun et al., 2024). Trophic transfer also known as food web transfer explains the transport of these concentrated contaminants from consumed organisms to consumers, potentially creating biomagnification, where superior food chain organisms including humans contain the greatest pollutant burdens as reported by Oluwaseun et al. (2024) in water ecosystems, where aquatic species and crustaceans retain ECs, creating dangers for human consumption. The biological accumulation of ECs generates concerns beyond direct human contact through potable water but also through nutrition, emphasizing the connections between environmental pollution and community health hazards. This intricacy highlights the requirement for comprehensive evaluation methods to completely assess contact routes and potential consequences (Heis et al., 2025b; Oluwaseun et al., 2024).

1.5.4 Challenges and Research Needs

Although mounting evidence documents health and ecological risks associated with ECs, critical information gaps remain. Many pollutants lack comprehensive toxicological data, particularly concerning chronic low-level exposures and mixture effects. Emerging pollutants often occur in complex combinations that may interact unexpectedly, complicating risk assessments (Heis et al., 2025b). Additionally, regulatory frameworks trail scientific advancement, with most countries lacking standards or guidelines for many ECs. Surveillance programs are limited by analytical obstacles because of the minimal levels and chemical diversity of targets (Nguyen et al., 2024). Research priorities include creating responsive detection techniques, understanding toxicity mechanisms, exploring elimination effectiveness in water processing, and evaluating collective human and environmental contact. Advancing these areas will be vital for designing effective policies and interventions to manage the dangers of novel pollutants in potable water.

1.6 RESEARCH DEFICIENCIES AND FUTURE DIRECTIONS

Although ECs have become a rapidly expanding focus in environmental and public health sectors, significant knowledge gaps persist worldwide, especially in economically developing regions. These gaps impede effective management and reduction of these contaminants despite advances in detection technologies and growing awareness.

1.6.1 Insufficient Surveillance in Developing Countries

A major challenge in understanding and managing ECs is the lack of comprehensive surveillance data, particularly in developing nations (Rahman et al., 2023a). These areas often struggle with limited laboratory infrastructure, financial constraints, and shortages of trained personnel to carry out systematic monitoring of ECs in drinking water. As a result, the presence, concentration levels, and temporal patterns of many emerging pollutants remain poorly documented. This data scarcity undermines accurate risk assessment, policy formulation, and public health planning. It also exacerbates environmental health inequalities, as populations in resource-limited settings may face disproportionate exposure to untreated or inadequately treated water contaminated with hazardous ECs. Research indicates that pollution profiles differ in developing regions due to distinct industrial activities, agricultural practices, and consumption behaviors, making localized data critical to addressing unique local risks (Rahman et al., 2023a; Bakare-Abidola & Olaoye, 2025). Enhancing global cooperation and building local capacity are essential to closing these gaps, requiring investments in analytical infrastructure, training programs, and technology transfer. Affordable, durable monitoring methods designed for local conditions will be major to ensuring broad surveillance coverage and timely detection of ECs in these regions (Rahman et al., 2023a).

1.6.2 Need for Cost-Effective Detection Methods

Advanced analytical tools for EC detection, such as liquid chromatography coupled with mass spectrometry, offer high precision and sensitivity but are often expensive, technically demanding, and not readily available for routine monitoring in many regions (Qin et al., 2025; NIEHS, 2025). This technological obstacle restricts the surveillance scope and frequency, particularly for small-scale utilities and economically developing nations. There exists an immediate requirement for creating affordable, quick, and field-applicable identification techniques that can dependably evaluate a wide range of ECs at trace concentrations. Advances in sensor methods, nanotechnology-based examinations, biological sensors, and molecular identification components demonstrate potential in delivering economical and portable options for on-location water quality assessment (Noguera-Oviedo & Aga, 2016). Merging advanced detection methods of ECs with data analysis and remote monitoring can improve early warning systems for water pollution. Furthermore, developing standardized protocols and validation structure for new sensing technologies is important to ensure data accuracy and regulatory approval, thereby facilitating wider implementation (Rahman et al., 2023a; Qin et al., 2025).

1.6.3 Long-Term Exposure Studies

While the observation of emerging contaminant in DW is becoming more frequent, there remains a significant gap in understanding the long-term health effect of chronic exposure (Heis et al., 2025b; Wang et al., 2020). Most toxicological data are derived from acute or high-dose studies, whereas human exposure typically involves low-level concentration of complex mixtures over long durations. Epidemiological research linking prolonged ECs exposure to effects such as endocrine disruption, cancer risk, neurotoxicity, and immune disorders is limited by difficulties in exposure measurement, confounding variables, and population differences (Heis et al., 2025b). There is an urgent need for more longitudinal cohort studies, biomonitoring programs, and sophisticated risk assessment models that consider mixture toxicity and susceptible groups. These efforts will guide regulatory limits, public health measures, and risk communication that reflects actual exposure scenarios (Heis et al., 2025b; Enyoh et al., 2023).

1.6.4 Integrated Research and Policy Needs

To address these knowledge gaps, it requires interdisciplinary strategies that combine toxicology, policy research environmental monitoring, engineering, and epidemiology. Establishing international research networks and fostering collaboration between developed and developing nations can accelerate advancements. Translating scientific findings into effective regulations and water management policies demands adaptive governance that evolves with new evidence. Policymakers should focus on innovating detection technologies, expanding monitoring systems, and applying precautionary principles to mitigate the uncertain risks associated with ECs (Bakare-Abidola & Olaoye, 2025; NIEHS, 2025).

1.7 CONCLUSION

Emerging contaminants in drinking water is growing setback for global water quality management and public health. These pollutants (microplastics, pharmaceuticals, personal, industrial, chemicals, among others) often resist the traditional treatment processes, allowing them to persist in water supplies. Their presence at trace levels, potential for chronic subjection, and complex environmental behaviors increase serious human health and ecological concerns. Sources include municipal wastewater, agricultural runoff, industrial discharges, landfill leachate, urban stormwater, and natural origins. Their occurrence depends on chemical persistence, treatment plant effectiveness, and seasonal factors. Public health risks involve endocrine disruption, carcinogenicity, and antimicrobial resistance, while ecological impacts include bioaccumulation and transfer through food webs. Important knowledge gaps persist, including limited monitoring in developing countries, need for affordable detection technologies, and insufficient long-term exposure studies, hindering risk assessments and protective regulations. Addressing these challenges requires interdisciplinary research, enhanced global surveillance, innovative detection and treatment technologies, and harmonized policy frameworks through collaborative efforts to safeguard drinking water quality and ensure sustainable access.

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