

Environmental Policy and Governance of Emerging Contaminants in Drinking Water: A Comparative Analysis of Global Regulations and Remediation Strategies

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DOI: [10.22178/pos.116-18](https://doi.org/10.22178/pos.116-18)

LCC Subject Category: QH1-278.5

Received 27.02.2025

Accepted 25.04.2025

Published online 30.04.2025

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Abstract. Emerging contaminants (ECs) in drinking water – such as pharmaceuticals, personal care products, endocrine-disrupting chemicals, and microplastics – pose growing challenges to environmental health and water governance. Despite increasing scientific attention to their occurrence and potential health risks, regulatory frameworks remain inconsistent across countries, with significant disparities in detection limits, priority substances, and remediation strategies. This review comprehensively analyses environmental policies and governance approaches addressing ECs in drinking water across major global regions. Drawing from peer-reviewed literature and international regulatory documents, we compare how entities such as the United States Environmental Protection Agency (EPA), the European Union, Canada, China, Australia, and several developing nations approach risk assessment, monitoring, and remediation of ECs. We also evaluate the effectiveness of current strategies, identify policy gaps, and examine the influence of socioeconomic, political, and technological factors on regulatory development. Furthermore, we explore adaptive governance models, public engagement, and cross-border cooperation as essential for advancing policy effectiveness. The review concludes with recommendations for harmonising global policy efforts and strengthening local governance structures to ensure safer drinking water systems in the face of evolving chemical threats.

Keywords: Emerging contaminants; drinking water; environmental governance; policy analysis; water regulations; global comparison; remediation strategies; water safety; chemical pollutants; adaptive policy.

INTRODUCTION

Emerging contaminants (ECs), also called contaminants of emerging concern (CECs), represent a diverse group of synthetic or naturally occurring chemicals not commonly monitored in the environment but capable of causing adverse ecological and human health effects. These include pharmaceuticals, personal care products, endocrine-disrupting compounds, industrial chemicals, and per- and poly-fluoroalkyl substances (PFAS) [1]. Their pervasive presence in drinking water systems worldwide has raised significant concerns regarding the adequacy of current environmental policies and regulatory frameworks.

Unlike conventional pollutants, ECs often evade standard water treatment processes due to their complex chemical properties and low concentration levels [2]. Many of these substances are persistent, bioaccumulative, and toxic, even at trace concentrations [3]. Recent advances in analytical technologies have led to increased detection of ECs in both surface and groundwater, highlighting the need for more responsive governance and management approaches [4].

The challenge of regulating ECs lies in the limited toxicological data, uncertainty about long-term exposure effects, and lack of globally harmonised regulatory limits. While developed countries

such as the United States, Canada, and members of the European Union have begun integrating ECs into water quality standards and risk assessments, many developing nations still face infrastructural, financial, and regulatory barriers [5, 6]. This global disparity underscores the importance of comparative policy analysis in identifying effective governance models and adaptable remediation strategies across varying socioeconomic contexts.

Environmental policies that govern ECs span from precautionary regulations and polluter-pay principles to integrated water resource management (IWRM) approaches [7]. For instance, the European Union's Water Framework Directive (WFD) mandates the inclusion of priority substances and watch lists, encouraging member states to update treatment systems and monitoring tools accordingly [8]. In contrast, regions like sub-Saharan Africa and Southeast Asia often rely on international guidelines, such as those provided by the WHO, due to the absence of robust domestic policies [9].

The lack of coordination between water, health, and environmental agencies and insufficient public awareness of EC-related risks further exacerbates governance challenges. Effective policy must, therefore, integrate scientific research, stakeholder engagement, economic incentives, and technological innovation to ensure sustainable management of ECs in drinking water [10].

This paper presents a comprehensive analysis of environmental policy frameworks addressing ECs in drinking water, focusing on comparative strategies in high- and low-income countries. It also explores the role of technological remediation, regulatory instruments, and governance mechanisms in shaping effective responses to EC pollution. By evaluating global case studies and emerging trends, the study aims to propose adaptable, science-driven strategies for mitigating the impacts of ECs on human and environmental health.

Literature Review

Emergence and Classification of Contaminants. Emerging contaminants (ECs) encompass a broad spectrum of anthropogenic and natural compounds increasingly detected in water sources due to enhanced analytical capabilities. These include pharmaceuticals, personal care products, endocrine-disrupting chemicals, pesti-

cides, microplastics, and industrial by-products such as PFAS (Per- And Polyfluoroalkyl) [1]. Many ECs are characterised by their persistence, bioaccumulation, and potential toxicity, even at trace concentrations [3]. These substances have raised serious environmental and public health concerns because traditional water treatment facilities cannot entirely remove them [2].

Detection and Occurrence in Drinking Water Systems. Advancements in analytical chemistry have enabled the detection of ECs at nanogram levels, uncovering their widespread presence in drinking water supplies across the globe. Studies in Europe, North America, and Asia have reported residues of antibiotics, hormones, and flame retardants in municipal water systems [1, 5]. In low-income regions, the lack of systematic monitoring and testing contributes to underreporting of EC prevalence, although indirect evidence through health and ecological impacts suggests significant exposure [9].

Environmental and Health Risks. Long-term exposure to ECs has been associated with endocrine disruption, antibiotic resistance, carcinogenicity, and reproductive toxicity [8]. Vulnerable populations, including infants, pregnant women, and immunocompromised individuals, face heightened risks. Moreover, ECs can impair aquatic ecosystems by altering reproductive cycles and bioaccumulating in the food chain [3].

Regulatory Frameworks and Global Disparities. Regulatory responses to ECs vary significantly across nations. The European Union's Water Framework Directive (WFD) provides a dynamic approach to managing ECs by incorporating a "Watch List" mechanism that is regularly updated with substances posing emerging risks [8]. The United States Environmental Protection Agency (EPA) uses the Unregulated Contaminant Monitoring Rule (UCMR) to gather occurrence data, informing potential regulation under the Safe Drinking Water Act [5].

In contrast, developing countries often lack dedicated EC policies due to limited infrastructure, data gaps, and funding constraints [6]. Reliance on international guidelines, such as WHO provisional limits, often replaces locally tailored regulatory standards. The absence of a unified global framework for EC regulation has led to uneven protections and exacerbated environmental injustices.

Governance Mechanisms and Institutional Coordination. Effective EC governance requires coordination between water utilities, environmental protection agencies, public health departments, and research institutions [10]. In practice, such coordination is often fragmented. Decentralised governance models may hinder rapid policy response, whereas centralised approaches can facilitate comprehensive risk assessments and integrated management.

Countries like Germany and the Netherlands have implemented precautionary regulatory instruments, investing in advanced treatment technologies and public awareness programs. Conversely, environmental governance in parts of Africa and Southeast Asia remains reactive and dependent on donor-funded interventions [9].

Technological and Policy Innovations. Recent innovations in EC mitigation include advanced oxidation processes (AOPs), membrane filtration, and nanotechnology-based adsorbents [2]. However, high costs and energy demands restrict their deployment in many regions. Countries aiming to address ECs at the source increasingly adopt policy innovations such as Extended Producer Responsibility (EPR), green procurement strategies, and public-private partnerships [7].

International efforts, such as the Strategic Approach to International Chemicals Management (SAICM), promote collaborative action toward safe chemical usage and waste disposal. However, the lack of enforceability limits their impact on national regulations.

METHOD

Research Design. This study employed a qualitative, comparative policy analysis approach to examine the global governance and regulatory frameworks related to emerging contaminants (ECs) in drinking water. The analysis draws from secondary data sources, including peer-reviewed scientific literature, international policy documents, and regulatory reports from key regions, including North America, Europe, Asia, and Africa.

Search Strategy. A systematic literature search used scientific databases such as Scopus, Web of Science, ScienceDirect, and Google Scholar. Search terms included combinations of "emerging contaminants," "drinking water," "regulations," "governance," "environmental policy," "PFAS," "pharmaceuticals in water," "water quali-

ty directives," and region-specific terms like "EPA," "EU Water Framework Directive," and "WHO guidelines." The search is limited to publications from 2010 to 2024 to ensure contemporary relevance.

Inclusion and Exclusion Criteria. Inclusion criteria: a) Articles and reports discussing EC occurrence, regulation, or policy governance in drinking water systems; b) Studies published in English. Between 2010 and 2024; c) Peer-reviewed papers, regulatory documents, white papers, and NGO/governmental reports.

Exclusion criteria: a) Studies focusing solely on ECs in wastewater or surface water without a link to drinking water; b) Articles lacking regulatory or governance insights; c) Non-English literature due to translation constraints.

Data Extraction and Synthesis. Key information extracted from the selected documents included: 1) Country or region of study; 2) Types of ECs discussed; 3) Regulatory frameworks or guidelines in place; 4) Governance mechanisms and institutional actors; 5) Technological or policy responses to EC management.

The researchers then categorised the data thematically to identify patterns, gaps, and variations in global regulatory responses. They compared high-income and low-income countries to highlight disparities and best practices.

Validity and Reliability. To ensure validity, triangulation was employed by cross-referencing findings from multiple sources, including government publications, peer-reviewed journals, and international guidelines. Reliability was strengthened through consistent application of inclusion criteria and review by two independent researchers to minimise bias in data selection and interpretation.

RESULTS AND DISCUSSION

The analysis of global regulations and governance strategies for emerging contaminants (ECs) in drinking water revealed several key trends and disparities across different regions. The following are the main findings from the comparative analysis:

Regulatory Frameworks

North America (United States and Canada): In the United States, the Environmental Protection Agency (EPA) has taken a proactive role in regu-

lating several ECs, particularly per- and polyfluoroalkyl substances (PFAS), pharmaceuticals, and personal care products (PPCPs). The Safe Drinking Water Act (SDWA) mandates the establishment of maximum contaminant levels (MCLs) for pollutants in drinking water, specifically focusing on chemicals known to have public health impacts.

Canada has frameworks similar to the Canadian Environmental Protection Act (CEPA), focusing on a precautionary approach for emerging pollutants such as microplastics, pharmaceuticals, and industrial chemicals. However, Canada has lagged in regulating certain ECs like PFAS compared to the United States.

Europe: The European Union (EU) has a comprehensive regulatory framework under the Water Framework Directive (WFD), which addresses water quality and ecological status across member states. The EU's regulations include specific measures for monitoring and controlling ECs, particularly endocrine-disrupting chemicals (EDCs), pharmaceuticals, and PPCPs. A significant initiative was the revision of the Directive 2020/2184 on the quality of water intended for human consumption, which includes monitoring ECs like pharmaceuticals and hormones.

Additionally, the EU has been instrumental in fostering regional collaborations on managing ECs, such as the European Union Water Initiative (EUWI), which has focused on capacity-building and knowledge sharing across member states and neighbouring countries.

Asia: In countries like China and India, regulatory frameworks for ECs in drinking water are still emerging. China has established regulations under the National Environmental Protection Agency for monitoring heavy metals and specific industrial contaminants, but lacks comprehensive guidelines for emerging pollutants like pharmaceuticals and microplastics.

In India, the Bureau of Indian Standards (BIS) is responsible for water quality standards, though EC regulation is still being developed. Recent studies have noted high levels of pharmaceutical residues in water supplies, but regulatory responses remain insufficient compared to Western countries.

Africa: In Africa, regulatory frameworks for ECs in drinking water are largely underdeveloped. Some countries, such as South Africa, have established water quality regulations focusing on tra-

ditional pollutants like heavy metals and microbial contaminants. Still, emerging contaminants such as pharmaceuticals, microplastics, and PFAS are not comprehensively regulated.

The African Ministers' Council on Water (AMCOW) has promoted regional cooperation on water quality, though the implementation of EC-specific regulations remains inconsistent across the continent. Many parts of Africa rely on international guidelines, such as those from the World Health Organisation (WHO), rather than local regulations.

Governance Mechanisms and Institutional Actors

United States: In collaboration with state-level agencies, the US EPA plays a central role in the governance of ECs in drinking water. Scientific research, public health assessments, and community feedback inform regulatory decisions. However, there is ongoing debate over the sufficiency of the EPA's regulatory actions, especially regarding PFAS.

European Union: European governance is multi-layered, involving EU institutions such as the European Commission, national regulatory bodies, and local municipalities. The EU also integrates input from various non-governmental organisations (NGOs) and scientific bodies, such as the European Environment Agency (EEA), in decision-making processes. The region's strong emphasis on public participation and transparency in environmental decision-making sets a model for global governance.

Asia: In countries like China and India, governance mechanisms are often centralised, with the Ministry of Ecology and Environment (MEE) in China and the Ministry of Environment, Forest and Climate Change (MOEFCC) in India overseeing regulatory matters. However, both countries face challenges in enforcing policies effectively due to rapid industrialisation and insufficient monitoring infrastructure.

Africa: In Africa, governance structures are fragmented, with many countries lacking dedicated agencies to manage water quality issues, including emerging contaminants. AMCOW promotes policy development across the continent, but political and financial constraints limit the capacity for enforcing regulations.

Technological and Policy Responses

Technological Responses: Advanced water treatment technologies, such as membrane filtration, reverse osmosis, and activated carbon adsorption, are widely utilised in high-income regions like North America and Europe to remove ECs from drinking water. However, the high costs associated with these technologies limit their application in developing countries.

Emerging technologies such as nanomaterials and bioremediation are being explored in several regions, particularly for removing pharmaceuticals and EDCs from drinking water.

Policy Responses: Policy responses in high-income countries often focus on setting strict regulatory standards and enforcing compliance through penalties and incentives. The US has initiated several PFAS action plans, while the EU has set maximum levels for certain pharmaceuticals in drinking water.

In contrast, many low-income countries struggle with the lack of specific regulations for ECs and rely heavily on international organisations, such as the WHO and UN Environment, for guidance on managing water quality.

Gaps and Future Directions. Despite substantial progress in high-income regions, there are significant gaps in the regulation and governance of ECs in drinking water in many low- and middle-income countries. There is a critical need for capacity-building initiatives and the development of region-specific guidelines.

Research on innovative and cost-effective water treatment technologies is crucial, especially for regions with limited access to advanced infrastructure. Additionally, there is an urgent need for greater international cooperation to address the global challenge of emerging contaminants.

The findings from this comparative analysis of global regulations and governance mechanisms for emerging contaminants (ECs) in drinking water highlight the diverse challenges and responses across different regions. While some countries, particularly North America and Europe, have made considerable strides in developing comprehensive frameworks for regulating ECs, other areas, especially Asia and Africa, continue to face significant regulatory and governance challenges.

Variability in Regulatory Approaches

. The regulatory approaches to ECs in drinking water are highly variable across regions. North

American countries like the United States and Canada have relatively advanced regulatory frameworks with established maximum contaminant levels (MCLs) for several ECs, particularly pharmaceuticals, microplastics, and PFAS [11]. These nations also benefit from extensive monitoring systems, enabling them to proactively identify and address emerging risks [12]. However, regulatory processes in these regions are often slow, with long timelines between identifying a contaminant as emerging and its subsequent regulation. This regulatory lag is a significant challenge for public health protection, exposing populations to potentially harmful contaminants for extended periods [13].

In contrast, many regions in Asia and Africa are only beginning to address ECs in their drinking water. The lack of robust regulations in countries like China, India, and several African nations reflects the challenges posed by rapid industrialisation, limited infrastructure, and insufficient scientific data [14, 15]. While some countries have regulations targeting traditional pollutants, such as heavy metals and pesticides, ECs like microplastics, pharmaceuticals, and personal care products remain largely unregulated [16]. This gap in regulation underscores the need for global collaboration and the establishment of internationally recognised standards that can be adapted to local contexts [17].

Governance Challenges and Opportunities. Effective governance is critical for ensuring the safety of drinking water in the face of emerging contaminants. The governance structures in North America and Europe are generally well-organised, with a multi-level approach that includes national, regional, and local authorities. These regions also benefit from active participation from non-governmental organisations (NGOs) and public health bodies in decision-making [18]. However, challenges persist in these regions, particularly about enforcement and the need for greater public awareness [19].

In Asia and Africa, governance is often more fragmented and less equipped to handle the complexity of ECs. Many countries lack dedicated agencies for water quality management and rely on international guidelines for direction [20]. Political instability, financial constraints, and capacity-building are significant obstacles to developing effective governance mechanisms [21]. However, there are opportunities for improvement through regional collaborations, as seen with ini-

tiatives like the European Union Water Initiative (EUWI) and the African Ministers' Council on Water (AMCOW), which promote information sharing and capacity building [22].

Technological and Policy Solutions. Technological solutions, such as advanced water treatment methods, are central to managing ECs in drinking water. In high-income countries, technologies like reverse osmosis, activated carbon adsorption, and membrane filtration have proven effective at removing ECs, including PFAS and pharmaceuticals [23]. However, these technologies are often expensive and may not be viable for low-income regions. As such, research into affordable and scalable technologies that can be deployed in areas with limited resources is urgently needed [24].

From a policy perspective, stricter regulations and enforcement mechanisms are necessary for high-income countries to close the gap between the identification of ECs and their regulation [1]. Meanwhile, in low-income regions, policy development should focus on establishing basic water quality standards and monitoring systems. International organisations, such as the WHO and the UN Environment Programme, are crucial in providing technical support to these countries as they develop regulatory frameworks and governance structures [17].

CONCLUSIONS

This study highlights the critical role of regulatory frameworks and governance mechanisms in addressing the risks associated with emerging contaminants (ECs) in drinking water. The findings show that high-income regions such as North America and Europe have significantly progressed in regulating and monitoring ECs. However, challenges remain regarding enforcing existing regulations and the slow pace at which new contaminants are identified and controlled. On the other hand, regions in Asia and Africa are lagging in regulatory development, which is exacerbated by issues such as limited scientific data, weak governance structures, and financial constraints.

While technological advancements in water treatment have proven effective in removing ECs in developed countries, applying these technologies in low-income regions remains challenging due to cost barriers and lack of infrastructure. Moreover, the varying levels of public awareness

and engagement in the regulatory process further complicate efforts to manage ECs effectively.

Overall, there is an urgent need for stronger regulation in high-income countries and comprehensive policy development in low-income regions. Moreover, fostering international collaboration, knowledge sharing, and capacity building will be essential in addressing the global challenge of ECs in drinking water.

Based on the findings of this study, the following recommendations are proposed to improve the regulation, governance, and management of emerging contaminants in drinking water globally:

Strengthening Regulatory Frameworks: Countries, particularly those in low- and middle-income regions, should prioritise the development of robust regulations for ECs in drinking water; this includes establishing guidelines, setting permissible limits for various ECs, and creating effective monitoring systems.

Regulatory agencies in high-income countries must rapidly update their frameworks to address new contaminants, such as pharmaceuticals, personal care products, and microplastics, and reduce the regulatory lag.

Increasing Public Awareness and Engagement: Public awareness campaigns should be launched to educate communities about the risks of ECs and the importance of water quality management. These initiatives should target consumers and local policymakers, empowering communities to demand safer drinking water.

Governments should encourage greater transparency in decision-making, allowing public participation in discussions about EC regulation and water safety.

Promoting International Collaboration: The global community should prioritise collaboration among countries, primarily through international organisations such as the WHO, the UN Environment Programme, and the World Bank, to share knowledge, best practices, and technological solutions for managing ECs.

Developed countries can assist developing nations by providing technical and financial support to build capacity for monitoring and regulating ECs.

Enhancing Water Treatment Technologies: Governments and research institutions should invest in developing cost-effective and scalable water

treatment technologies suitable for low- and middle-income countries. Innovations in filtration and treatment technologies, such as low-cost activated carbon filters and solar-powered water purification systems, should be promoted.

Furthermore, a global initiative to standardise and promote affordable technologies that remove ECs from drinking water should be explored, ensuring all regions can access safe water.

Strengthening Governance Structures: Governance structures responsible for water quality management should be strengthened, particularly in regions with fragmented or weak institutions. Clear accountability, enhanced technical expertise, and strengthened enforcement mech-

anisms are critical to ensuring the safety of drinking water.

Creating independent regulatory bodies to monitor water quality and enforce regulations will be crucial in addressing ECs effectively.

Fostering Research and Data Collection: More research is needed to identify emerging contaminants and assess their impact on human health and ecosystems. Countries should invest in scientific studies to understand the sources, pathways, and long-term effects of ECs in drinking water. Building a global database of emerging contaminants and their health impacts will enable informed decision-making and regulatory actions.

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