A COMPREHENSIVE REVIEW OF THE CURRENT STATE OF ORGANIC EMERGING CONTAMINANTS MANAGEMENT IN DRINKING WATER: REGULATORY LANDSCAPE, PROPERTIES, HEALTH IMPACTS, TREATMENT METHODS

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This study provides a comprehensive assessment of the growing challenge posed by organic emerging contaminants in drinking water systems. A comparative analysis is conducted on key pollutants, including per- and polyfluoroalkyl substances, pesticides, bisphenol A, nonylphenol, 1,4-dioxane, and β-estradiol, focusing on their occurrence, physicochemical characteristics, environmental persistence, and health impacts on both ecosystems and human populations. These substances frequently exhibit similar traits such as hydrophobicity, low volatility, and resistance to conventional water treatment processes, thereby significantly complicating their effective removal using standard technologies. Regulatory frameworks in the European Union, the United States, China, and Ukraine are critically examined, with attention to both recent regulatory advancements and persistent gaps that hinder uniform international control. In addition, a detailed assessment of current water treatment technologies, including adsorption, ion exchange, and membrane filtration, which demonstrate a fairly high efficiency in pollutant removal under optimized operational conditions, is provided. However, challenges remain related to the regeneration of spent sorbents, membrane fouling, operational costs, and safe waste management. Oxidative methods, such as ozonation, UV irradiation, and advanced oxidation processes, are effective for the destruction of organic micropollutants, although the formation of potentially hazardous by-products, such as aldehydes, carboxylic acids, or halogenated organics, requires further water treatment. The effective removal of organic micropollutants from water requires the integration of strategies for both physical removal and chemical or biological degradation. Degradation technologies, such as incineration, electrochemical degradation, supercritical water oxidation, and biodegradation, demonstrate varying efficiency and levels of environmental sustainability and are often limited by high energy consumption, high operational costs, or incomplete mineralization of pollutants. The findings highlight the pressing need for further enhancement of international regulations, the development of cost-effective, energy-efficient, and sustainable advanced treatment technologies, and the adoption of integrated water management strategies to ensure the long-term protection of public health and drinking water resources globally.

Keywords: *adsorption, drinking water, emerging contaminant, legislation, organic micropollutants, reverse osmosis*

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1. Introduction

The pollution of water bodies with organic micropollutants has become a growing global issue, driven by rapid population growth and industrialization. These contaminants include such anthropogenic chemicals as pharmaceuticals, pesticides, industrial chemicals, surfactants, and personal care products. Advanced analytical methods like

LC-MS/MS have detected these substances in aquatic environments at trace levels, often in micrograms to picograms per liter. Many pollutants are persistent, bioaccumulative, and resistant to biodegradation, posing long-term environmental risks.

The terms "emerging contaminants" or "contaminants of emerging concern" (CECs) are frequently used to describe these substances, though there is no universal definition or fixed list of compounds classified under this category. The United States Environmental Protection Agency (US EPA) defines CECs as chemicals or materials that may pose a perceived, potential, or real threat to human health or the environment, or for which health standards are lacking (Gatz, 2021).

Importantly, the term "emerging" does not necessarily indicate newly developed chemicals. It can refer to newly identified exposure routes, increased awareness of risks, or improved detection methods (Stefanakis & Becker, 2020). CECs generally fall into three categories:

- Recently introduced chemicals, such as industrial chemicals like perfluoroalkyl substances;
- Long-standing pollutants only recently detected in drinking water and their significance started to attract interest, such as pharmaceuticals;
- Known substances with newly acknowledged adverse effects on human health or ecosystems, such as hormones.

There is no common approach to CECs classification. Key types of organic pollutants, considered as emerging contaminants, is presented in the Table 1 (Li et al., 2024).

Table 1. *Types of organic micropollutants considered as emerging contaminants*

CEC category	Definition	Sources of pollution	Examples
Persistent organic pollutants (POPs)	Toxic chemicals that persist for long periods of time in the environment and can accumulate and pass from one species to the next through the food chain	Industrial discharges, firefighting foams	Brominated flame retardants, per- and polyfluoroalkyl substances (PFAS), polycyclic aromatic hydrocarbons
Pharmaceuticals and personal care products (PPCPs)	Human and veterinary drugs, personal care products such as fragrances, lotions, and cosmetics	Improper disposal, wastewater discharges from pharmaceutical manufacturing plants, hospitals, and domestic sewage	Chemotherapy drugs, antidepressants, antibiotics, hormones, antiepileptics, painkillers, beta-blockers, parabens, polycyclic masks, UV filters, caffeine, nicotine
Endocrine-disrupting chemicals (EDCs)	Class of compounds that can mimic, block, or disrupt the action of natural hormones	Industrial agricultural runoff, consumer products	Bisphenol A, dioxins, phthalates, polychlorinated bisphenols, pesticides, alkylphenols

Table 1. *Types of organic micropollutants considered as emerging contaminants (continued)*

Disinfection by-products (DBPs)[1]	Chemical by-products that form when disinfectants react with organic and inorganic compounds in water	Appear within the drinking water system due to the combination of disinfection agents (especially chlorine) with precursors	Iodinated trihalomethanes, haloacetonitriles halonitromethanes, haloacetamides, halogenated furanones, nitrosodimethylamine, brominated and iodinated compounds

[1]Despite over three decades of research about disinfection by-products in drinking water, new health concerns continue to arise. Additionally, many water utilities are shifting from chlorine to alternative disinfectants like ozone, chlorine dioxide, and chloramines. While these alternatives typically lower concentrations of regulated trihalomethanes and haloacetic acids, they can also elevate levels of other potentially harmful by-products (Richardson, 2023).

CECs has been linked to various serious health issues, such as increased risks of cancer, liver dysfunction, cardiovascular problems, and reduced reproductive capabilities in both humans and animals. Conventional drinking water treatment processes have proven insufficient in effectively removing these pollutants. In response, stricter drinking water regulations are being implemented in many countries, requiring treatment facilities to upgrade their purification processes. Thus, the development of effective methods to eliminate these contaminants remains a critical objective within the field of drinking water treatment.

Increasing awareness of environmental pollution and the related health risks posed by CECs have driven extensive research in this area, resulting in a rapid surge in publications on the topic. The annual number of publications addressing “emerging contaminants” topic rose from fewer than 1,000 prior to 2006 to nearly 7,000 by 2022 as illustrated in Fig. 1 (Alam et al., 2025). China, the United States, and various European countries have emerged as key contributors to this field of research.

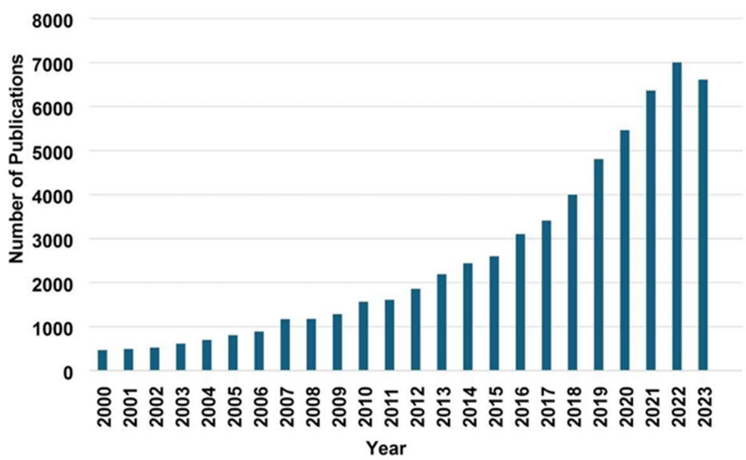

Fig. 2. *Trends in publications related to emerging contaminants from 2000 to 2023 by annual publications output.*

The purpose of this article is to provide a comprehensive overview of key organic micropollutants considered as CECs, along with their sources and associated health risks. It aims to examine the current status of drinking water regulations across various countries and evaluate both established and novel technologies for their removal from drinking water. This analysis will specifically focus on organic CECs that are either recently regulated or are likely to face regulatory action soon within the European Union, the United States, China, and Ukraine.

2. The current state of drinking water policies associated with emerging contaminants in drinking water

Since the 1970s, significant progress has been made in understanding water pollution as industrial practices evolve, new chemicals are introduced, detection technologies advance, and awareness of associated risks increases. Despite these improvements, most emerging contaminants remain unregulated. Only in recent years have governments started to make steps toward regulating these substances.

In December 2020, the European Commission adopted the updated Drinking Water Directive 2020/2184 to address CECs (European Parliament & Council of the European Union, 2020). This directive requires monitoring of 57 microbiological, chemical, and indicator parameters and was driven by the 2013 Right2Water initiative, which exercised European citizens' right to direct democracy by urging the European government to enhance access to safe drinking water across the EU and modernize the outdated Drinking Water Directive 98/83/EC (European Parliament & Council of the European Union, 1998). Alongside reinforcing existing standards, the new directive mandates the removal of specific organic CECs, including PFAS, bisphenol A, nonylphenol and β-estradiol. Moreover, despite long-standing pesticide regulations, full compliance remains a challenge due to enhanced detection methods revealing legacy contamination.

In the U.S., the Safe Drinking Water Act from1974, most recently amended in 2018, provides the main legal framework for regulating public drinking water (US Congress, 1974). Under this act, The National Primary Drinking Water Regulations, last updated in 2024, set health-based limits for 94 water quality indicators (U.S. Environmental Protection Agency, 2024a). Progress on new regulations has been notably slow. Despite long-standing PFAS concerns, enforceable national standards were only introduced in April 2024. Meanwhile, growing attention is now turning to 1,4-dioxane, with potential new federal guidelines coming (U.S. Environmental Protection Agency, 2024b).

In 2022, China revised its national drinking water regulation, known as The Standards for Drinking Water Quality of China, initially established in 1985, expanding the framework to include 97 water quality indices (State Administration for Market Regulation, 2022). This updated policy is now considered one of the most comprehensive and stringent drinking water regulations worldwide. However, China has yet to implement regulations targeting such critical CECs as PFAS and other persistent and endocrine disrupting chemicals.

In Ukraine, drinking water quality is governed by the Law of Ukraine No. 2918-III "On Drinking Water, Drinking Water Supply and Drainage" introduced in 2002, with the most recent amendment made in 2023 (Verkhovna Rada of Ukraine, 2002) and mandatory health-based standards comprising 86 water quality indices established under the State sanitary norms and rules DSanPin 2.2.4-171-10, last updated in 2024 (Ministry of Health of Ukraine, 2010). While Ukraine still has limited regulations related to CECs removal, it is important to understand the changes in Western countries regulations in the context of their further integration into national legislation.

A comparison of drinking water quality standards for organic CECs, recognized as emerging contaminants, is provided in the Table 2.

Table 2. *Comparison of drinking water quality standards for organic micropollutants considered as emerging contaminants in the European Union, USA, China and Ukraine*

CEC type	Parameter	Parametric value in micrograms per liter (μg/L)			
		EU	**USA**	**China**	**Ukraine**
POP	Benzo(a)pyrene	0.01	0.2	0.01	0.005
EDC, PPCP	Beta-estradiol	0.001[1]	-	-	-
EDC	Bisphenol A	2.5	-	10.0	-
POP	Carbon tetrachloride	-	5.0	2.0	2.0
POP	Chlorobenzene	-	100.0	300.0	-
POP	1,2-dibromoethane	0.05	0.05	-	-
other	1,4-dioxane	In some countries: 0.1 – DE, NL; 0.5 – SE	In some states: ≤1.0 – CA, FL, HI, KY, MN, NH, NY, NB; 3.0 – CT; 4.6 – ME; 7.2 - MI	-	-
EDC, POP	Dioxin	-	0.00003	0.00003	-
POP	Hexachlorobutadiene	-	-	0.6	-
DBP	Hexachlorocyclo-pentadiene	-	50.0	-	-
EDC	Nonylphenol	0.3[1]	-	-	-
EDC, POP	Pesticides	0.1 - individual 0.5 - total	0.2 – DBCP, Heptachlor epoxide, Lindane; 0.4 – Heptachlor; 1.0 – HCB, PCP; 2.0 – Alachlor, Chlordane, Dalapon, Endrin; 3.0 – Atrazine, Toxaphene; 4.0 – Carbofurane, Simazine; 7.0 – 2.4-D, Dinoseb; 20 – Diquat; 40 – Methoxychlor; 50 – 2,4,5-TP; 100 – Endothall; 200 – Oxamyl; 500 – Picloram; 700 – Glyphosate	0.01 – Geosmin; 0.4 – Heptachlor; 1.0 – Dichlorvos, DDT, HCB; 2.0 – Lindane, Atrazine; 3.0 – Parathion; 5.0 – HCH; 7.0 – Carbofuran; 9.0 – PCP; 10 – Chlorothalonil; 20 – Methyl parathion, Deltamethrin; 30 – Chlorpyrifos, 2,4–D; 80 – Dimethoate; 250 – Malathion; 300 – Bentazone; 700 - Glyphosate	0.1 - individual 0.5 - total

Table 2. *Comparison of drinking water quality standards for organic micropollutants considered as emerging contaminants in the European Union, USA, China and Ukraine (continued)*

EDC, POP	Per- and polyfluoroalkyl substances	0.1 - sum of 20 PFAS[2]; 0.5 – PFAS total	0.004 – PFOA, PFOS; 0.01 - PFHxS, PFNA, HFPO-DA	0,04 – PFOA; 0,08 - PFOS	-
EDC, POP	Polychlorinated biphenyls	In some countries: 0.5 – NL	0.5	0.5	-
EDC, POP	Polycyclic aromatic hydrocarbons	0.1	0.2	2.0	-
EDC	1,2,4-Trichlorobenzene	-	70.0	20.0	-
POP	Tetrachloroethylene	10.0	5.0	40.0	10.0
EDC	Thrichloroethylene	10.0	5.0	2.0	10.0
DBP	Trihalomethanes	100.0	80.0	100.0	100.0

[1]In accordance with Article 13(8) of Directive (EU) 2020/2184, 17-beta-estradiol and nonylphenol were included in the first watch list in view of their endocrine-disrupting properties and the risk they pose to human health.
[2]'Sum of 20 PFAS' is a subset of 'PFAS Total' substances that contain a perfluoroalkyl moiety with three or more carbons or a perfluoroalkylether moiety with two or more carbons (PFBA, PFPA, PFHxA, PFHpA, PFOA, PFNA, PFDA, PFUnDA, PFDoDA, PFTrDA, PFBS, PFPS, PFHxS, PFHpS, PFOS, PFNS, PFDS, PFUnDS, PFDoS, PFTrDS)

Table 3 presents drinking water quality standards for organic micropollutants that are not considered as CECs, but rather well-established and extensively studied.

Table 3. *Comparison of drinking water quality standards for organic micropollutants not considered as emerging contaminants, in the European Union, USA, China and Ukraine*

CEC type	**Parameter**	**Parametric value in micrograms per liter (µg/L)**			
		EU	**USA**	**China**	**Ukraine**
Industrial chemical	Benzene	1.0	5.0	10.0	1.0
Industrial chemical	o-Dichlorobenzene	-	600.0	1000.0	-
Industrial chemical	p-Dichlorobenzene	-	75.0	300.0	-
Industrial chemical	1,2-dichloroethane	3.0	5.0	30.0	3.0

Table 3. *Comparison of drinking water quality standards for organic micropollutants not considered as emerging contaminants, in the European Union, USA, China and Ukraine (continued)*

Industrial chemical	1,2-dichloroethylene	-	7.0	50.0	-
Industrial chemical	Dichloromethane	20.0	5.0	20.0	-
Industrial chemical	1,2-Dichloropropane	-	5.0	-	-
Industrial chemical	Diethylhexyl phthalate	-	6.0	8.0	-
Industrial chemical	Epichlorohydrin	0.1	2.0	0.4	-
Industrial chemical	Ethylbenzene	-	700.0	300.0	-
Industrial chemical	Styrene	-	100.0	20.0	-
Industrial chemical	2,4,6–trichlorophenol	-	-	200.0	-
Industrial chemical	Vinyl chloride	0.5	2.0	1.0	-
Industrial chemical	Vinylidene chloride	-	7.0	30.0	-
Industrial chemical	Xylene	-	10000.0	500.0	-

Despite global advancements in drinking water regulations, significant disparities remain in addressing CECs. While the EU, USA, China, and some other countries have already taken steps toward more comprehensive standards, regulatory frameworks continue to fall short of effectively mitigating long-term health and environmental risks.

3. Key organic emerging contaminants overview: physicochemical properties, occurrence and health impact

Organic CECs generally have similar characteristics that complicate their removal during water treatment processes. Many of these contaminants are, to varying extents, water-soluble, small to medium-sized, stable, non-volatile molecules, typically hydrophobic, with differing levels of polarity. The physicochemical properties of these contaminants influence their behavior and transport within the environment. Additionally, some organic CECs may degrade into metabolites, further complicating efforts to predict their environmental fate. Table 4 summarizes the key physical-chemical properties of these contaminants (National Center for Biotechnology Information, 2025).

Table 4. *Comparison of drinking water quality standards for organic micropollutants not considered as emerging contaminants, in the European Union, USA, China and Ukraine*

Pollutant	**Hydrophobicity**	**Charge**	**Molecular weight, Da**	**Solubility at 25°C, mg/l**	**Octanol-water partition coefficient Log Kow**	**Acid dissociation constant pKa**
Pesticides						
Glyphosate	hydrophilic	neutral	169.1	12.0	1.6	5.6
Atrazine	hydrophobic	neutral	215.7	27.5	2.6	15.8
2.4-D	hydrophilic	neutral	221.0	336.2	2.8	-4.9
Carbofuran	hydrophilic	neutral	221.2	351.0	2.3	12.3
Bentazone	hydrophobic	neutral	240.3	268.6	2.4	3.7
Imidacloprid	amphiphilic	neutral	255.7	0.06	0.6	1.6
Metolachlor	hydrophobic	neutral	283.8	530.0	2.3	n/a
Lindane	hydrophobic	neutral	290.8	7.3	3.7	n/a
Malathion	hydrophilic	neutral	330.4	143.0	2.4	7.7
Aldrin	hydrophobic	neutral	364.9	0.03	6.5	n/a
Heptachlor	hydrophobic	neutral	373.3	0.2	4.4	-10.0
Dieldrin	hydrophobic	neutral	380.9	0.2	5.4	-4.2
Endrin	hydrophobic	neutral	380.9	0.2	5.2	-4.2
Chlordane	hydrophobic	neutral	409.8	0.1	6.0	n/a
PFAS						
PFBA	hydrophobic	negative	214.0	765.7	2.4	1.6
PFBS	hydrophobic	negative	300.0	344.0	2.4	-3.3
PFHA	hydrophobic	negative	314.0	15,700.0	4.4	-0.2
PFHS	hydrophobic	negative	400.1	6.2	4.3	0.1

Table 4. *Comparison of drinking water quality standards for organic micropollutants not considered as emerging contaminants, in the European Union, USA, China and Ukraine (continued)*

PFNA	hydrophobic	negative	464.0	9,500.0	7.3	-0.2
PFOA	hydrophobic	negative	414.1	9,500.0	4.8	-4.2
PFOS	hydrophobic	negative	500.1	680.0	4.5	0.1
Other						
1,4-Dioxane	hydrophilic	neutral	88.1	130,640.0	-0.3	-3.9
Nonylphenol	hydrophobic	neutral	220.3	7.0	5.8	10.7
Bisphenol A	hydrophobic	neutral	228.3	86.5	3.3	9.6
β-Estradiol	hydrophobic	neutral	272.4	3.9	4.0	10.1

The wide variability in the physicochemical properties of CECs, including solubility, polarity, and partitioning behavior, presents substantial challenges for their accurate detection and removal from the drinking water.

3.1. Pesticides

Pesticides are substances used to control pests and include insecticides, herbicides, fungicides and other types of chemicals. Modern agricultural systems rely heavily on chemical pesticides to ensure the stability and quantity of crop yields, playing a crucial role in maintaining food security.

Majority of modern pesticides are organic compounds, either synthetic or natural origin, though some are based on inorganic chemicals. Pesticides can be classified into several categories based on their chemical composition:

• Organochlorines - organic compounds containing five or more chlorine atoms. Examples include DDT, aldrin, dieldrin, heptachlor, chlordane.

• Organophosphates - derivatives of phosphorus acid. Examples include parathion, malathion, glyphosate.

• Carbamates - organic esters derived from N-methylcarbamic acid. Examples include carbafuran, aminocarb, carbaryl.

• Neonicotinoids - chemically similar to nicotine. Examples include imidacloprid, acetamiprid, dinotefuran, thiamethoxam

• Pyrethroids - synthetic analogs of natural pyrethrins. Examples include cypermethrin and permethrin

Organochlorines, organophosphates, and carbamates are highly toxic chemicals that can bioaccumulate. As a result, many of these substances have been banned or severely restricted in numerous countries. The use of neonicotinoids is also limited in some countries due to their neurotoxic effects and potential for bioaccumulation. In contrast, pyrethroids are generally considered less harmful.

Pesticides can degrade into metabolites through various chemical, biological, or physical processes, such as hydrolysis, oxidation, reduction, or enzymatic reactions.

Most pesticides undergo metabolic degradation in plant tissues, animal organisms, or the environment. Some metabolites can be more toxic than the parent compound, while others may present less environmental risk.

Widespread pesticide use is a major pollution source, contaminating both water and soil. The US Geological Survey found pesticides in over 90% of water samples nationwide (Covert et al., 2020). In the EU, 10–25% of surface water and 4–11% of groundwater sites exceed contamination thresholds (European Environment Agency, 2024). A large-scale biomonitoring study across five European countries detected at least two pesticides in 84% of participants, with higher levels in children (Ottenbros et al., 2023). China, the world's largest pesticide consumer, now accounts for over 43% of global use, with widespread water contamination reported (Zhang et al., 2022). In Ukraine, the destruction of the Kakhovka dam led to severe contamination by DDT, HCH, and their metabolites in the Zaporizhzhia region (Petrlik et al., 2023).

Human exposure to chemical pesticides is linked to chronic illnesses such as cancer, and respiratory, heart and neurological diseases (Kim et al., 2017).

3.2. Per- and polyfluoroalkyl substances

PFAS (per- and polyfluoroalkyl substances) refers to a large group of synthetic chemicals that include at least one fully fluorinated methyl group (-CF3) or methylene group (-CF2-), with no hydrogen, chlorine, bromine, or iodine atoms attached. The carbon-fluorine (C-F) bond is one of the strongest covalent bonds, which contributes to the exceptional stability of PFAS.

PFAS can be categorized into two main types: non-polymeric and polymeric, with non-polymeric PFAS already being regulated in drinking water in certain countries. Non-polymeric PFAS can be further divided into two primary groups: perfluoroalkyl substances, which have a completely fluorinated carbon chain, and polyfluoroalkyl substances, which contain a partially fluorinated carbon chain.

The characteristics of PFAS compounds are closely linked to the length of their carbon chains. These chemicals are classified into short-chain and long-chain compounds. Short-chain PFAS include perfluoroalkyl sulfonic acids with fewer than six carbon atoms and perfluoroalkyl carboxylic acids with fewer than seven carbon atoms. Long-chain PFAS, on the other hand, consist of perfluoroalkyl sulfonic acids with six or more carbon atoms and perfluoroalkyl carboxylic acids with seven or more carbon atoms. Long-chain PFAS are known to be persistent, bioaccumulative, and toxic, whereas short-chain PFAS are thought to have a lower potential for bioaccumulation. However, short-chain PFAS still possess other concerning properties and are already widely dispersed throughout the environment.

The durability of PFAS, along with their hydrophobic and lipophobic characteristics, make them highly valuable in industrial and commercial applications. These chemicals are used in a diverse range of products, such as food packaging, firefighting foams, textiles, electronics, medical implants, and more.

PFAS contamination of groundwater and surface water has become a major global concern. A 2022 Waterkeeper Alliance study found PFAS in 83% of U.S. waterways (Waterkeeper Alliance, 2022). Le Monde and partners identified over 17,000 PFAS sites across Europe, including more than 2,300 hotspots where PFAS concentrations exceed hazardous levels (Dagorn et al., 2023). As PFAS are phased out in many developed countries, China has emerged a leading producer and consumer, with extremely high levels detected in water bodies near fluorine chemical plants (Huang et al., 2025). In Ukraine, the war raises fears of PFAS contamination from munitions and firefighting foams (Hryhorczuk et al., 2024).

PFAS have been associated with a range of long-term health issues, including developmental, reproductive, liver, and cardiovascular problems (Domingo and Nadal, 2019).

3.3. Bisphenol A

Bisphenol A (BPA), or 2,2-bis(4-hydroxyphenyl)propane, is a chemical compound in alkylphenols group and consists of two phenol functional groups.

It is a man-made compound that has been widely utilized for many years in the production of materials like polycarbonate plastics and epoxy resins. These polymers retain trace amounts of BPA in the final products. BPA is found in numerous consumer goods, such as food containers, thermal receipts, inks, textiles, paints, adhesives, electronics, building materials, toys, CDs, automotive coatings, medical equipment, and dental products (Govarts et al., 2023).

Food is the main route of BPA exposure, as it leaches from packaging materials. A U.S. study found BPA in 52% of freshwater and 28% of marine samples across 40 states and territories (Staples et al., 2018). 92% of adults across 11 European countries tested positive for BPA in their bodies (Govarts et al., 2023). In China, BPA is widely found in water bodies near industrial sites (Liang et al., 2024). In 2025, the Interreg NEXT Poland–Ukraine Project began monitoring pollutants, including BPA, in drinking water sources (The Odessa Journal, 2025).

As an endocrine disruptor, BPA can interfere with the body’s hormonal functions, leading to potential health risks, including reproductive harm and negative effects on the immune system (Ma et al., 2019).

3.4. Nonylphenol

Nonylphenol (NP), or 4-(7-methyloctyl)phenol, is an alkylphenol made up of a polar phenol group and a hydrophobic hydrocarbon tail. It usually exists as a mix of isomers, with p-nonylphenol as the dominant form.

Nonylphenol is widely used in the production of phenol formaldehyde resins and nonylphenol ethoxylates. It is also used as an additive in fuels and lubricants.

In aquatic environments, nonylphenol mainly results from the breakdown of nonylphenol ethoxylates, commonly used as industrial surfactants. Its low solubility and high hydrophobicity cause it to accumulate in organic-rich areas like sewage sludge and sediments, where it can persist over time.

Due to its environmental impact, the EU has banned nonylphenol ethoxylates, and some other countries have imposed strict regulations. However, contamination remains widespread. In Europe, 184 water bodies exceeded NP limits, with half the cases reported in France (European Environment Agency, 2018). In California, NP was found in surface waters, sediments, and all stages of wastewater treatment plants (The Department of Toxic Substances Control, 2022). A study in Southwest China detected NP in 100% of tap water samples (Jie et al., 2017). In Eastern Ukraine, treated wastewater contained NP levels seven times above environmental standards (Vystavna et al., 2018).

Nonylphenol is a toxic xenobiotic and an endocrine disruptor, affecting the hormonal systems of various organisms. In the environment, it causes harm such as feminization of aquatic species, reduced male fertility, and lower juvenile survival rates (Funari Junior et al., 2024).

3.5. β-Estradiol

β-Estradiol (E2), or estra-1,3,5(10)-triene-3,17β-diol, is a corticosteroid with one aromatic ring. Very soluble in acetone, ethanol, dioxane and other organic solvents.

β-Estradiol is a natural human estrogen, produced mainly in the ovary. It is vital for the growth of breast and reproductive epithelia, maturation of long bones and development of secondary sexual characteristics.

It enters the environment due to human activities, particularly through sanitary and agricultural wastewater. In Europe, the highest concentrations are found in the Mediterranean Basin (Adeel et al., 2017). In China's Beijing-Tianjin-Hebei region, β-Estradiol was detected in 100% of river and urban wastewater effluent samples (Lei et al., 2020). In Ukraine, it was below detectable levels in most Dnipro water samples from the Kyiv region (Ho et al., 2020). There is limited recent data on β-Estradiol pollution in the USA.

Exposure to estrogens can have adverse effects on human health, including impacts on fertility, increased risk of obesity, and a higher susceptibility to certain cancers (Saito et al., 2015).

3.6. 1,4-Dioxane

1,4-Dioxane (1,4-D), also known as 1,4-diethylene oxide, is a cyclic organic compound characterized by two symmetrically positioned ether linkages. This chemical structure contributes to its high solubility in water and significant resistance to biodegradation.

1,4-D is widely used in industry as a solvent, stabilizer, and chemical intermediate, particularly in the production of rubber, plastics, pesticides, paints, and pharmaceuticals. It can also form as a by-product in the manufacture of cosmetic and personal care products like detergents, foaming agents, and emulsifiers, often remaining at trace levels in the final products.

Research on 1,4-D in aquatic environments is limited. In the U.S., it was detected in 21% of public water systems (Adamson et al., 2017). In Europe, contamination has been reported in German groundwater, linked to the historical use or production of chlorinated solvents (De Boer et al., 2022). In China, 1,4-dioxane was found in all samples from a river supplying Shanghai with drinking water (Wang et al., 2022). No data is available on 1,4-dioxane pollution in Ukraine.

Although 1,4-dioxane has been recognized as a drinking water pollutant since 1978, it remains an emerging concern due to its classification as a likely human carcinogen, the absence of enforceable drinking water standards in many countries, and the limited effectiveness of conventional water treatment processes in removing it (Sun et al., 2016).

3.7. Disinfection by-products

Haloacetic acids (HAAs) and trihalomethanes (THMs) are the two main types of chlorinated disinfection by-products (DBPs) found in drinking water. They form when chlorine-based disinfectants, such as chlorine, chloramine, and chlorine dioxide, react with precursors like natural and algal organic matter, brominated and iodinated compounds, and anthropogenic contaminants such as pesticides, pharmaceuticals, and detergents.

HAAs are halogenated aliphatic carboxylic acids with an acetic acid backbone and one or more halogen atoms, such as chlorine, bromine, or iodine. The five most common HAAs in treated water are monochloroacetic acid, dichloroacetic acid, trichloroacetic acid, monobromoacetic acid, and dibromoacetic acid. THMs are halogen-substituted single-carbon compounds with the formula CHX3, where X represents halogens like chlorine, bromine, fluorine, or iodine. The four most common THMs in treated water are chloroform, bromoform, bromodichloromethane, and dibromochloromethane.

DBP concentrations are generally higher in treated surface water than in groundwater, mainly due to the higher organic matter content in surface sources. Additionally, DBP levels tend to increase during warmer months, as higher temperatures accelerate the formation of these by-products.

Chlorine-based water disinfection, used since the early 20th century, has significantly reduced waterborne diseases. However, growing evidence links DBP to adverse health effects. In the U.S., DBP exposure is estimated to contribute to 6,800 new bladder cancer cases annually (Evans et al., 2020). In the EU, it is associated with 4.9% of bladder cancer cases (Evlampidou et al., 2020). A study in China also found increased cancer risk among children aged 9 months to 2 years (Zhao et al., 2023). In Ukraine's Zaporizhzhia region, THMs have been detected in river and drinking water, though concentrations remain within regulatory limits (Sokolovska & Petrusha, 2019). These findings emphasize the need for safer and more effective water disinfection methods to protect public health.

3.8. Conclusions

In summary, CECs pose significant environmental and public health challenges due to their diverse physicochemical properties, persistence, and widespread occurrence. Understanding their behavior, sources, and associated health risks is essential for developing targeted monitoring strategies and effective treatment solutions.

4. Emerging contaminants management in drinking water production

The treatment of CECs in raw water poses a significant challenge due to the diverse chemical characteristics of these substances. When managing CECs in drinking water, it is essential to consider both the efficiency of their removal and the management of waste streams from treatment plants, which are often loaded with these pollutants. Each available technology has its own benefits and limitations, making a thorough analysis crucial to identify the most effective solution for each specific case.

4.1. Emerging contaminants removal from drinking water

Unfortunately, conventional drinking water treatment methods, that involves a sequence of coagulation, flocculation, sedimentation, filtration, and disinfection, is often ineffective at removing organic CECs. It is a necessity to use advanced water treatment technologies, such as adsorption, ion exchange technology, membrane processes, destruction technologies etc.

Adsorption

Adsorption on activated carbon (AC) is the most common method of CECs removal due to its strong affinity for various compounds, high capacity, simple design, and regenerability. However, frequent reactivation or replacement may be needed. AC is typically available as granular (GAC), with particle sizes between 0.2 and 5 mm and powdered (PAC), with fine particles <0.18 mm. Adsorption is mainly driven by van der Waals forces and influenced by pore size, solubility, hydrophobicity, charge, functional groups, and molecular size of the pollutant. AC is particularly effective for hydrophobic and cationic compounds due to its hydrophobic nature and negative surface charge (Golovko et al., 2020).

Modified AC and composite adsorbents also show promise for removing CECs, though most research is still at the lab scale. Scaling up to industrial applications requires careful optimization and cost considerations. Modified AC is produced through chemical, physical, or biological processes to enhance AC adsorption performance. While composite adsorbents combine biopolymers, typically AC, with components like graphene, metal oxides, or carbon nanotubes, enhancing surface area and adsorption capacity, and addressing challenges in regeneration (Nazari et al., 2022).

Polymeric adsorbents are increasingly utilized due to their high surface area, controlled pore size distribution, chemical stability, and ease of regeneration. However, these materials are often expensive and tend to be effective only for a limited range of specific contaminants.

Ion exchange process

Ion exchange resins (IER) are widely used for water softening, demineralization, and selective removal of contaminants like metals and nitrates. They are gaining popularity for treating CECs due to their high selectivity, efficient regeneration, and long service life.

Specialized IERs are designed to remove pollutants such as 1,4-dioxane and PFAS, with tailored functional groups that enhance removal even at low concentrations. IER is proven to be more effective than AC for short-chain PFAS removal (Gagliano et al., 2020). However, in PFAS treatment, IER is typically single-use, requiring costly high-temperature incineration or landfilling, raising concerns about PFAS re-release into the environment.

Membrane processes

High-pressure membrane processes, such as nanofiltration (NF) and reverse osmosis (RO), are increasingly recognized by the municipal water sector as promising solutions for removing organic CECs. The primary removal mechanism for organic micropollutants with NF and RO is size exclusion, with larger and more branched molecules being removed more efficiently. Electrostatic repulsion and adsorption to the membrane’s active area also contribute to removal.

Removal effectiveness with membrane technologies depends on factors like the properties of the pollutant, pH, temperature, concentration, and the presence of other contaminants. For example, negatively charged pollutants are generally rejected more effectively than uncharged and positively charged pollutants of similar size (Ebrahimzadeh et al., 2021). While hydrophilic pollutants are generally better rejected than hydrophobic ones, except for small, uncharged molecules (Fujioka et al., 2020).

Recent research has focused on enhancing membrane selectivity by modifying surface properties to narrow pore-size distributions and adjust surface charges, improving selectivity for charged molecules via mechanisms like the Donnan effect and dielectric exclusion.

Oxidation

The oxidation process relies on reactive hydroxyl radicals (•OH) that degrade a wide range of organic pollutants, including emerging contaminants. Common oxidative technologies include:

• Ultraviolet (UV) radiation degrades contaminants that absorb UV light, though efficiency depends on the contaminant's structure and UV absorption properties.

• Ozone is powerful oxidant that can degrade organic compounds and microorganisms but has limitations such as low solubility in water and pH dependence.

• Advanced Oxidation Processes (AOP) combines ozone, UV, and/or hydrogen peroxide in different combinations to generate hydroxyl and sulfate radicals (SO4•-), enhancing the removal of organic micropollutants.

Despite effectiveness, oxidation processes are limited by high energy demands and the formation of harmful organic by-products such as aldehydes, ketones, trihalomethanes, and inorganic compounds such as nitrite and bromate (Ike et al., 2019). Post-treatment, such as granular activated carbon filtration, is necessary to remove these by-products (Stein et al., 2018).

Other treatment processes

Foam fractionation has emerged as an effective and cost-efficient method for removing and concentrating CECs. This process uses bubble-based foam generation to separate compounds from aqueous solutions and has proven particularly effective for the removal of surfactants and PFAS (Sochacki et al., 2024).

Biodegradation, employing genetically modified microbes, microbiomes, synthetic biology, nanomaterials, or biofilms, is also a promising approach. In this process, microbes break down organic compounds into less toxic or non-toxic residues, offering an eco-friendly solution for contaminant removal (Singh et al., 2024).

Comparison of emerging contaminants removal methods

Table 5 provides a comparison of organic CECs removal efficiencies by different methods.

Table 5. *Comparison of emerging contaminants removal rates by different methods, %*

Removal method	Pesticides	PFAS		BPA	NP	1,4-D	E2	DBP[1]	Reference
		Long chain	Short chain						
Conventional system	3-69	0-12	0-6	1	65	0	0-5	n/a	Van Pham et al., 2020; Rahman et al., 2014; Guerra et al., 2015; Carrera et al., 2019; Maher et al., 2019; Chen et al., 2013
MF, UF	2-63	0-1	0-1	8-29	5-18	4-9	12	36-95	Zahoor 2013; Rahman et al., 2014; Sun et al., 2022; Carrera et al., 2019; Imbrogno et al., 2017; Nguyen et al., 2021; Yang et al., 2015
NF	29-89	92-99	68-97	41-98	83-100	46	88-95	60-90	Rodríguez-Alegre et al., 2024; Zhi et al., 2022; Yüksel et al., 2013; Kowalska, 2014; Matarazzo et al., 2020; Aziz & Ojumu, 2020; Yang et al., 2017
RO	97	47-99	36-99	83-99	100	70-85	99	60-100	Rodríguez-Alegre et al., 2024; Yüksel et al., 2013; Garcia et al., 2013; Carrera et al., 2019; Aziz & Ojumu, 2020; Yang et al., 2015
Activated carbon	80-94	50-99	50-70	75-93	99	12	77-82	98-99	Njuoku et al., 2014; Mohammad & El-Refaey, 2023; McCleaf et al., 2017; Martín-Lara et al., 2020; Crini et al., 2021b; Carrera et al., 2019; Elias et al., 2021; Hasan & Makki, 2021
Polymeric adsorbent	77-88	98	95	95-99	78-81	90	99	n/a	Ronka, 2016; Tan et al., 2022; Ipek et al., 2017; Crini et al., 2021a; Woodard et al., 2014; Mohebbi et al., 2025

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Table 5. *Comparison of emerging contaminants removal rates by different methods, % (continued)*

Removal method	**Pesticides**	**PFAS**		**BPA**	**NP**	**1,4-D**	**E2**	**DBP**[1]	**Reference**
		Long chain	**Short chain**						
Ion exchange resins									Naushad et al., 2014; Van Pham et al., 2020; McCleaf et al., 2017; López-Ortiz et al., 2018; Imbrogno et al., 2017; Chen et al., 2014
Ozon									Tao et al., 2024; Franke et al., 2019; Liu at al., 2018; Barrera-Díaz et al., 2018; Carrera et al., 2019; Sun et al., 2019
UV									Ferhi et al., 2021; Dai et al., 2019; Liu et al., 2018; Kouakou et al., 2014; Ikehata et al., 2016; Huang et al., 2022a; Huang et al., 2022b
AOP									Bein et al., 2023; Dai et al., 2019; Liu at al., 2018; Sun et al., 2019; Carotenuto et al., 2019; Ikehata et al., 2016; Bennet et al., 2018; Huang et al., 2022b

[1]This table provides data on the removal of DBPs after their formation. An alternative strategy to manage DBPs involves reducing their formation by removing precursors, optimizing chlorine dosage and contact time, or using alternative disinfection methods like ozone, UV radiation, chloramines, or chlorine dioxide (Roque et al., 2023).

There is no "one-size-fits-all" solution for the removal of CECs. Each available method has specific advantages and limitations, and selecting the most appropriate technology requires a detailed analysis. Factors such as raw water composition, the properties of the targeted CECs, and the required removal efficiency must be carefully considered. Table 6 summarizes the key benefits and drawbacks of various advanced technologies used for the removal of CECs.

Table 6. *Advantages and disadvantages of key advanced technologies for emerging contaminants removal from drinking water*

Treatment	Advantages	Disadvantages
Adsorption	• Very efficient for wide range of CECs • Easy to use • Cost effective • Possible reactivation	• Possible fouling • Regular regeneration • Risk of desorption
Ion exchange	• Highly effective for specific CECs • Low energy	• Remove only some CECs • High capital cost • Possible fouling • Brine disposal
Membranes	• Very efficient for wide range of CECs • Fast process • Small footprint • Automatization	• High capital cost • High energy demand • Possible fouling • Waste concentrate disposal
Oxidation	• Very efficient for wide range of CECs • Rapid reaction time • Small footprint • No waste streams • Can work as disinfection	• High capital cost • Very high energy • Formation of toxic by-products

4.2. Waste stream management during the removal of emerging contaminants from drinking water

Separation methods such as adsorption, ion exchange, membrane filtration, and foam fractionation can effectively remove CECs, but they do not eliminate them. Instead, they transfer these contaminants from one media to another, creating a need for proper disposal of residual solids and liquids now contaminated with these substances.

Conventional water treatment plants typically discharge these residuals directly into water bodies, a practice known as direct discharge. Other waste management options include indirect discharge via sewer systems to wastewater treatment plants, land application, landfill disposal, and underground injection (U.S. Environmental Protection Agency, 2011).

However, when the waste stream contains high concentrations of pesticides, industrial chemicals, or substances like PFAS, traditional disposal methods may be restricted or even prohibited. In these cases, advanced waste treatment methods are necessary to protect human health and the environment. Residuals from advanced drinking water treatment systems, including brines from ion exchange regeneration, membrane rejects, spent backwash, exhausted ion exchange resins, and spent activated carbon, require careful disposal. Recommended disposal methods for these waste streams, which are contaminated with emerging pollutants, include hazardous waste landfills, hazardous waste incinerators, deep well injection, and thermal reactivation of activated carbon.

In the short term, conventional hazardous waste disposal methods for managing activated carbon, ion exchange resins, and membrane treatment residuals are likely to remain the most feasible options. However, utilities must take into account the limited availability of hazardous waste management infrastructure, the high costs associated with these methods, and the potential risks of re-releasing emerging contaminants into the environment. As a result, utilities should monitor advancements in destruction technologies and explore transitioning to more advanced solutions.

Novel destruction technologies like electrochemical oxidation, sonolysis, and supercritical water oxidation show promise but are still under development. These technologies face challenges related to high costs, energy demands, and potential toxic by-products. Electrochemical oxidation is particularly promising due to its low energy consumption and ability to operate at ambient conditions, while supercritical water oxidation is gaining attention, though it comes with higher costs and operational complexity.

Table 7 provides a comparison of key destruction technologies used to manage waste streams containing CECs (Meegoda et al., 2022; Hussain et al., 2025).

Table 7. *Comparison of destruction technologies for the management of waste streams containing emerging contaminants*

Technology	Destruction mechanism	Target waste streams	Stage of technology development	Advantages	Disadvantages
Incineration	Thermal degradation	Liquid streams, solid waste	Mature	• Existing infrastructure • The most mature method	• Very high energy demand • Risk of incomplete combustion • Harmful by-products
Electro-chemical degradation	Oxidation	Liquid streams	Demonstration	• Small footprint • Low energy demand	• Long residence time • Low effectiveness for short-chain PFAS • Harmful by-products

Table 7. *Comparison of destruction technologies for the management of waste streams containing emerging contaminants (continued)*

Supercritical water oxidation	High-temperature oxidation	Liquid streams, solid waste	Demonstration	• High efficiency • No harmful by-products	• Complicated operation • Frequent preventive maintenance
Plasma treatment	High-energy breakdown	Liquid streams	Piloting	High efficiency	• High energy demand • Harmful by-products
Photocatalysis	UV-induced degradation	Liquid streams	Piloting	Low energy demand	• High cost of catalyst replacement • Harmful by-products
Sonolysis	Ultrasound-induced breakdown	Liquid streams	Bench-scale	Simple operation	• Very high energy demand • Low effectiveness for short-chain PFAS
Bio-degradation	Microbial degradation	Liquid streams, solid waste	Bench-scale	Environmentally friendly	• Process duration • Limited studies

There is no single universally preferred solution for managing waste streams. Each situation requires a comprehensive analysis that considers the composition of the waste stream, destruction efficiency, operational complexity, environmental impact, and overall cost.

4. Conclusions

Organic CECs represent an increasing threat to drinking water safety due to their environmental persistence, complex physicochemical properties, and established health risks. Analysis indicates that although key pollutants, such as per- PFAS, pesticides, bisphenol A, nonylphenol, 1,4-dioxane, and β-estradiol, are progressively addressed through regulatory measures, implementation and enforcement remain inconsistent across countries. These contaminants commonly exhibit characteristics such as hydrophobicity, chemical stability, and bioaccumulative potential, which complicates their removal by conventional water treatment technologies.

Treatment methods including adsorption, ion exchange, membrane filtration, and advanced oxidation processes have demonstrated effectiveness in CECsremoval. However, challenges related to media regeneration, membrane fouling, and residual waste management persist. Oxidative techniques, such as ozonation, UV, and AOP, are being explored for breaking down resistant pollutants, although the formation of potentially hazardous by-products necessitates efficient post-treatment controls. The effective management of CECs requires the integration of removal and destruction strategies. Destruction technologies, such as incineration, electrochemical degradation, supercritical water oxidation, and biodegradation, exhibit varying degrees of efficacy and environmental sustainability, often constrained by energy demand and incomplete mineralization.

Advancing global regulatory frameworks, in conjunction with the implementation of multi-barrier treatment approaches and international research collaboration, is critical for mitigating the risks posed by CECs and safeguarding public and ecological health.

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КОМПЛЕКСНИЙ АНАЛІЗ СУЧАСНОГО СТАНУ УПРАВЛІННЯ ОРГАНІЧНИМИ МІКРОЗАБРУДНЮВАЧАМИ, ЩО ВИКЛИКАЮТЬ ЗАНЕПОКОЄННЯ, У ПИТНІЙ ВОДІ: НОРМАТИВНЕ РЕГУЛЮВАННЯ, ФІЗИКО-ХІМІЧНІ ВЛАСТИВОСТІ, РИЗИКИ ДЛЯ ЗДОРОВ'Я, МЕТОДИ ВИДАЛЕННЯ

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У цьому дослідженні представлено всебічну оцінку зростаючої загрози, яку становлять органічні пріоритетні та нові забруднювачі у системах питного водопостачання. Проведено порівняльний аналіз основних забруднюючих речовин, зокрема пер- та поліфторалкільних сполук, пестицидів, бісфенолу А, нонілфенолу, 1,4-діоксану та β-естрадіолу, з акцентом на їхнє поширення, фізико-хімічні характеристики, стійкість у довкіллі та вплив на здоров'я як екосистем, так і людського населення. Ці речовини часто мають подібні властивості, зокрема гідрофобність, низьку леткість та стійкість до традиційних методів очищення води, що суттєво ускладнює їх ефективне видалення за допомогою стандартних технологій. Критично розглянуто нормативно-правові підходи Європейського Союзу, Сполучених Штатів, Китаю та України з акцентом на останні регуляторні досягнення та стійкі прогалини, які перешкоджають запровадженню єдиної міжнародної політики. Крім того, детально оцінено сучасні технології очищення води, зокрема адсорбцію, іонний обмін та мембранну фільтрацію, які демонструють досить високу ефективність за оптимальних умов експлуатації. Водночас залишаються проблеми, пов'язані з регенерацією використаних сорбентів, забрудненням мембран, експлуатаційними витратами та безпечним управлінням відходами. Окислювальні методи, такі як озонування, УФ-опромінення та процеси передової оксидації, ефективні для руйнування органічних мікрозабруднювачів, хоча утворення потенційно небезпечних побічних продуктів, зокрема альдегідів, карбонових кислот чи галогеновмісних органічних сполук, потребує додаткового очищення. Ефективне видалення таких забруднювачів вимагає інтеграції стратегій як фізичного усунення, так і хімічного чи біологічного розкладу. Технології деградації, зокрема спалювання, електрохімічне розкладання, окиснення у надкритичній воді та біодеградація, демонструють різну ефективність і рівень екологічної сталості, але часто обмежуються високими енергозатратами, значними витратами або неповним мінералізаційним ефектом. Отримані результати підкреслюють нагальну потребу в посиленні міжнародного регулювання, розвитку економічно доцільних, енергоефективних та сталих технологій очищення, а також впровадженні інтегрованих підходів до управління водними ресурсами з метою довгострокового захисту здоров'я населення та джерел питного водопостачання в усьому світі.

Ключові слова: *адсорбція, забруднювачі що викликають занепокоєння, законодавство, зворотній осмос, органічні мікрозабруднювачі, питна вода*