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Occurrence, sustainable treatment technologies, potential sources, and future prospects of emerging pollutants in aquatic environments: a review

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Emerging contaminants (ECs), such as polyfluorinated compounds, antibiotics, microplastics, and nonylphenol, continue to challenge environmental management practices due to their persistence and bioaccumulation potential. This review articulates the critical pathways and environmental risks posed by these contaminants, setting the stage for an in-depth exploration of innovative removal technologies. We spotlight groundbreaking methods that are reshaping the landscape of ECs remediation: membrane filtration technology, constructed wetlands, adsorptive materials, algae-based systems, biological treatments, and advanced oxidation processes. Each method is evaluated for its efficacy in removing ECs, with particular emphasis on sustainability and economic viability. Our findings reveal that integrating these technologies can significantly enhance removal efficiency, offering new directions for environmental policy and practical applications. This article positions these advanced removal technologies at the forefront of the fight against ECs, advocating for their broader adoption to safeguard environmental and public health.

KEYWORDS

emerging contaminants, risk assessment, removal technologies, environmental pollution, sustainable development

1 Introduction

In the past hundred years, the world has experienced great development. The rapid development of industry, agriculture, and urbanization have brought economic benefits and aggravated environmental issues (Mafi et al., 2013). For instance, deleterious solid waste, inadequate sewage treatment, the utilization of non-biodegradable materials, and detrimental greenhouse gases constitute contemporary environmental concerns. Historically, prevalent pollutants encompassed heavy metals, organochlorine pesticides, sulfur dioxide, $PM_{2.5}$, and other contaminants. Subsequently, there are many kinds of pollutants without relevant laws and regulations, called emerging contaminants. Many classes of drugs are essential to modern society, such as antibiotics, endocrine disruptors, fluorocarbon and others.

A typical example is antibiotics, which have led to the antibiotic revolution since the discovery of penicillin by Alexander Fleming in 1929, as well as the subsequent development of purification of penicillin by Howard Florey and the Bavarian chain company Ernest of

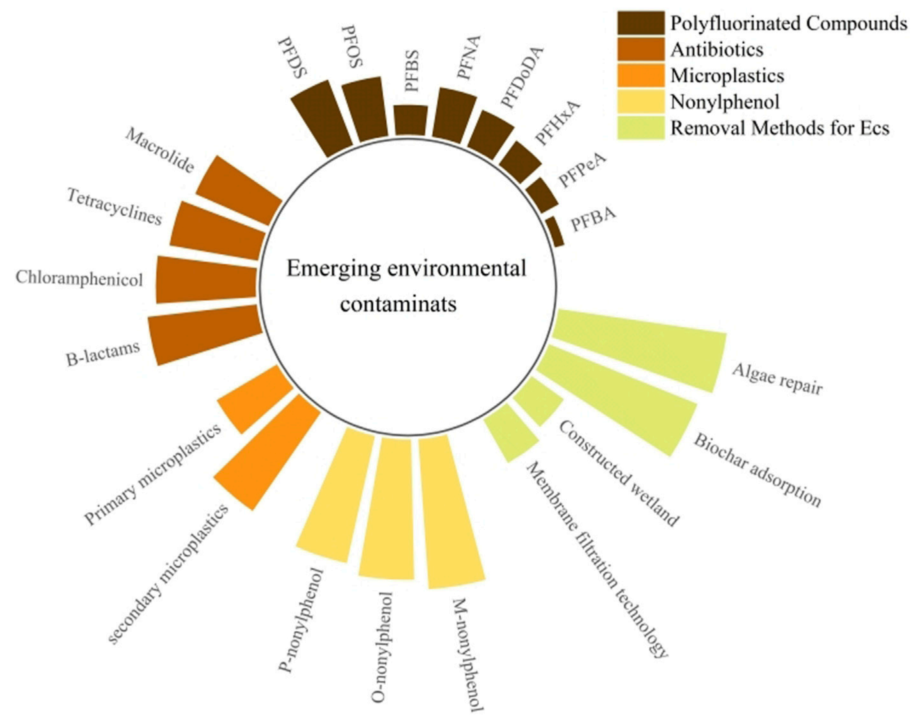


FIGURE 1
Some examples of major emerging contaminants.

Bavaria chain during World War II (Carvalho and Santos, 2016). Antibiotics are present in rivers, lakes, and oceans globally, causing problems such as resistance genes and endocrine disorders. However, for China or some developing countries, these pollutants may not be officially classified as such due to economic, legal, or other considerations. Take antibiotics or perfluorooctane sulfonate (PFOS) for instance, which has been detected in estuarine sediments and water bodies worldwide, as well as in mammalian tissues and human serum, and is widely recognized for its persistence in the environment (Fernandes et al., 2020).

In addition, some endocrine disruptors are the main factors causing pollution today. In 1995, endocrine disruptors became a scientific concept and it was discovered that these pollutants can cause harm to the biological reproductive system and hormone function (Seralini and Jungers, 2021). Artificial sweeteners (ASs) are widely used as sugar substitutes in human diet and animal feed due to their high intensity of sweetness. The use of ASs in all foods was banned by the US Food and Drug Administration (FDA) in 1970, because of its potential carcinogenic effect on experimental animals. However, in Asia, for example, China is the main user of artificial sweeteners (Luo et al., 2019). Although ASs have been found in various environmental media worldwide due to their extensive and sustained use, their ecological toxicity has not received much attention (Buerge et al., 2024). Under the attention of scholars from around the world, the toxicity of some ECs can be estimated using formulas. With the attention of scholars from all over the world, the toxicity of some ECs can be estimated using formulas. However, current research on the mixed toxicity of ECs remains unclear. While acknowledging the role of predictive models in estimating the toxicity of certain ECs, it is imperative to also consider the extensive toxicity data that exists. Additionally, the assertion that research on mixed toxicity is unclear may not fully represent ongoing efforts in the field, as evidenced by recent studies which contribute to our understanding of combined toxic effects (Chen et al., 2022a). While advanced methodologies for the systematic detection and management of ECs have been developed, their practical application is hindered by economic and regulatory challenges, particularly at the real-scale deployment stage. This nuance is essential for a comprehensive discussion on the state of ECs management and research.

In recent years, the study of ECs has covered various aspects, and scholars' opinions constitute a valuable source of information. As can be seen in Figure 1, research related to emerging contaminants/ emerging contaminants removal has been steadily increasing over the past decade. Nevertheless, owing to the extensive reach, myriad origins, and intricate pollution mechanisms of emerging contaminants, effective control and investigation require collaborative efforts across various sectors to mitigate potential and immediate risks to both human health and ecological integrity. In light of these circumstances, the objective of this study is to assemble a comprehensive inventory of emerging pollutants and delve into their toxicity profiles, as well as explore methodologies for their removal and mitigation.

2 Sources and routes of emerging contaminants

Emerging contaminants are known to be toxic, resistant to degradation, prone to bioaccumulation, and often capable of

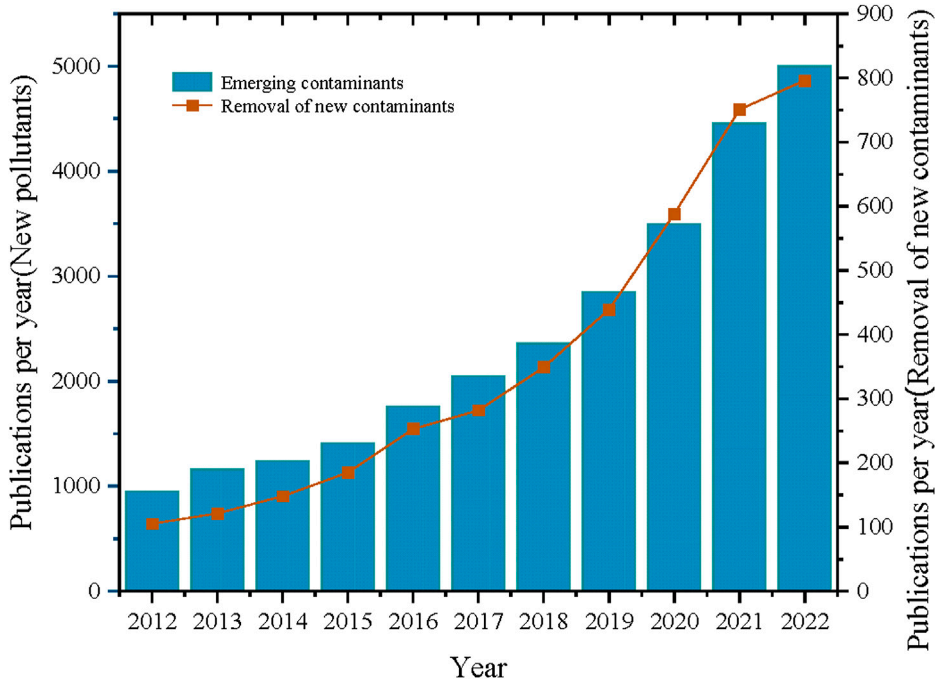


FIGURE 2
Evolution of the number of ECs and new pollutant removal publications between 2012 and 2022(The data comes from the web of sciense).

crossing international borders via air, water, and migratory species. Figure 2 illustrates the sources of emerging contaminants. They can deposit far from their emission sites and subsequently accumulate in terrestrial and aquatic ecosystems. Industries such as pharmaceuticals, printing, electroplating, beauty products, chemical manufacturing, antibiotics, and cleaning agents contribute to the release of these pollutants into water, soil, and air. Similar to traditional sources of pollution, they pose significant threats to the environment. The toxicity and physicochemical properties of these substances, regardless of their form or source, play crucial roles in determining how they interact within the biosphere and influence natural transformation processes.

It is evident that wastewater pollution sources and the infiltration into groundwater significantly contribute to the presence of ECs in natural water bodies, particularly in areas with poor wastewater treatment oversight and underdeveloped regions. Hospitals, pharmaceutical companies, domestic sewage, industrial wastewater, and aquaculture are major sources of ECs. Furthermore, due to the complex physicochemical properties of ECs, wastewater treatment plants struggle to effectively remove them. For instance, an antibiotic concentration of 13.6 μg/L was detected in a wastewater treatment plant in Wisconsin, USA (Sarmah et al., 2006). Landfill leachate is also a significant pollution pathway and serves as a major reservoir for microplastics, which substantially increase environmental threats (V et al., 2023). Besides posing environmental risks, ECs also facilitate the spread of antibiotic resistance genes. Through the exchange of surface water and groundwater runoff, ECs can cause additive or synergistic toxic effects, necessitating appropriate regulatory oversight or the development of treatment technologies.

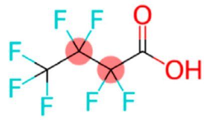
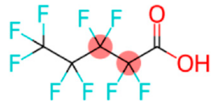
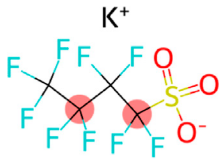
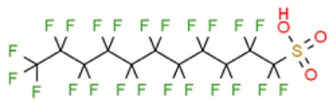
3 Known and emerging contaminants

Emerging contaminants, released into the environment, exhibit biotoxicity, environmental persistence, and bioaccumulative properties, thus representing significant risks to ecological health and human wellbeing. This category includes perfluorinated compounds, recognized as persistent organic pollutants under the Stockholm Convention and used predominantly as flame retardants. Additionally, other substances such as bisphenol A (an endocrine disruptor), pharmaceuticals (notably antibiotics), and microplastics, although not listed by the Convention, are of paramount concern. Their widespread prevalence, coupled with the complexities involved in their detection and the necessity for extensive pretreatment processes, underscores the critical importance of continued research and management efforts concerning these contaminants.

3.1 Polyfluorinated compounds

Polyfluorinated Compounds (PFCs) are a new type of persistent organic pollutants. Each hydrogen atom in the carbon chain of a compound molecule is replaced by a fluorine atom (Table 1). The general formula is F(CF2) N-R, where R is the hydrophilic functional group. PFCs have excellent physical and chemical properties and are widely used in industrial production and daily life. They have been detected in the atmosphere, water, soil, sediment, organisms and even polar ice fields. The majority of per- and polyfluoroalkyl substances exhibit extraordinary durability, as they resist hydrolysis, photodegradation, and

TABLE 1 Structural diagram of perfluorinated compounds.

Type	Name	Abbreviation	Chemical structure
PFCA	Perfluorobutanoic acid	PFBA	
	Perfluoropentanoic acid	PFPeA	
	Perfluorohexanoic acid	PFHxA	
	Perfluorododecanoic acid	PFDoDA	
	Perfluorononanoic acid	PFNA	
PFSA	Perfluorobutane sulfonic acid	PFBS	
	Perfluorohexane sulfonic acid	PFHxS	
	Perfluorooctane sulfonic acid	PFOS	
	Perfluorodecane sulfonic acid	PFDS	

biodegradation across a spectrum of environmental conditions (Le et al., 2018). It is evident that the likelihood of detecting PFAS in aquatic ecosystems is notably elevated, owing to significant discharges into rivers, lakes, groundwater, and various other aquatic habitats. Beyond these aquatic domains, PFAS compounds are frequently encountered in other environmental matrices such as suspended particulate matter, sediment, and similar substrates (Liu et al., 2021). PFCs are highly bioaccumulative and potentially toxic to reproduction. The accumulation of PFCS in the environment also threatens the microbial community. The effect of long chain PFCs on soil bacterial community composition was greater than that of short chain PFCs. The results showed that PFCS pollution also greatly affected the survival of several major bacterial genera in aquatic ecosystems (Wu et al., 2021). The solubility of PFCs in water plays an important role in its toxicity. In fact, slow dissolution processes may lead to slow accumulation and metabolism, as well as an increase in the half-life of PFC. It is imperative to underscore that, apart from their high affinity for organics dispersed in water and aquatic species, the omnipresence and enduring nature of PFCs in aquatic environments present formidable challenges. For instance, the half-life periods of perfluorooctanoic acid and perfluorooctane sulfonate (PFOS) are approximately 40 and 90 years, respectively, underscoring the formidable persistence of these molecules. Eradicating them poses significant difficulties. Moreover, in aquatic organisms, half-lives can vary depending on metabolic pathways and are particularly influenced by the functional groups present (Savoca and Pace, 2021). Furthermore, the half-life of these compounds may also vary based on the size and species of the organism, owing to cumulative effects within the food chain. For instance, the half-life of PFOS is reported to be 5 months in dolphins and 29–31 days in marbled flounder (Chisaki, 2005; Sakurai et al., 2013).

3.2 Antibiotic

The development of modern antibiotics dates back to pivotal moments in the late 1920s and 1930s. In 1929, Fleming's discovery of penicillin marked a significant milestone, followed by the revelation of sulfonamide (SAs) as the inaugural broad-spectrum antibiotic in clinical practice in 1935. The industrial-scale production and commercialization of penicillin began in 1946, marking the beginning of the era widely recognized as the antibiotic age. Subsequently, a plethora of antibiotics emerged, revolutionizing the field of medicine (Carvalho and Santos, 2016). The antibiotics that are currently the most widely used and abundant in the environment include: tetracyclines, sulfonamides, quinolones, and macrolide. The presence of these antibiotics in the environment is mainly affected by factors such as human activities, animal husbandry and medical wastewater.

The aquatic presence of many antibiotics manifests as amphoteric ions, attributable to their distinct pk_a values, which intricately influence adsorption mechanisms and consequent environmental distribution. For example, tetracycline has three different pk_a values and is readily adsorbed on different solid particles and sediments. Compared to other antibiotics, sulfonamides have fewer functional groups, exhibit weaker interactions with soil and sediment, and possess lower biodegradability, making them more frequently detected in water (Fan et al., 2010). Notably, the solubility of antibiotics in water constitutes another pivotal determinant. For sulfonamide, the solubility of sulfadimidine in water is significantly higher than that of Sulfamethoxazole (1,500 and 610 mg/L, respectively). In contrast, fluoroquinolones and Macrolide are less soluble in water and can't be permanently present in surface water. At all events, these antibiotics can be strongly adsorbed on sediment particles, which means that sediment eventually becomes a sink for antibiotics. For example, this is observed in mangrove forests in Takahashi, China (Li Y. et al., 2016).

Much literature has emphasized the influence of temperature on antibiotics, However, in natural settings, a variety of factors can affect the presence of antibiotics, even unstable β-lactam antibiotics, the longest half-life under natural conditions can also reach 27 days. The breakdown of antibiotics is highly dependent on pH, temperature, and the presence of hydrolysis-sensitive functional groups in the antibiotic structure (Mitchell et al., 2013). pH affects the adsorption and desorption of antibiotics mainly by affecting the existing form of ions. For example, norfloxacin may repel Ca^{2+} and Mg^{2+} ions in water, leading to its detection in large quantities in aquatic environments. In natural water samples, tetracycline and oxytetracycline inhibited photodegradation at pH 7.3, but the presence of Ca^{2+} and Mg^{2+} made tetracycline and oxytetracycline form metal ion complexes. The kinetics of antibiotics in water are related to their adsorptive solubility, and the degradation rate is largely dependent on the contribution of possible hydroxyl radicals and other unidentified reactive substances (Bahnmueller et al., 2014). Complex adsorption mechanisms, including hydrogen bonding and ion exchange, also contribute to antibiotic migration (Chen and Zhou, 2014). However, the specific mechanisms and reasons for the degradation or adsorption of different antibiotics need to be further studied.

3.3 Microplastics

Plastics with a diameter of less than 5 mm are classified as microplastics (MPs). Microplastics may originate from the degradation of personal care products and larger plastic items. Concurrently, owing to inadequate management, plastic waste undergoes photolysis, fragmentation, and microbial decomposition, generating secondary microplastics (Laskar and Kumar, 2019). Plastic fragments smaller than 100 nm are classified as nanoplastics. Despite the relatively large specific surface area of MPs, which facilitates adsorption across diverse environmental media and their migration, nanoplastics are not readily removed by standard water purification processes (Chen et al., 2022b). Figure 3 illustrates the path of microplastics production and the associated management practices. Physical separation in wastewater treatment plants remains the primary method for removing polyethylene (Yu et al., 2023). Regrettably, sludge from physical separation is often recycled for landfill or agricultural applications, leading to the re-introduction of MPs into water systems (Chen et al., 2022c). According to Sharma, nanoplastics are considered more harmful than microplastics. The aquatic environment may be subject to more complex contamination due to the possible adsorption of heavy metals or organic pollutants on the surfaces of microplastics and nanomaterials. More seriously, nanoplastic particles are small in size and can act as adherents to microbial surfaces, or enter microorganisms, affecting local microbial communities or generating cascading toxicity (Sharma et al., 2022). Owing to the absence of efficient microplastic removal techniques in sewage treatment, numerous microplastics continue to enter aquatic environments through this process. In addition, the MP removed from wastewater treatment is mainly retained in bottom sludge, which is mostly directly buried or further processed as farmland fertilizer. Consequently, these microplastics may reenter natural water bodies via soil erosion or surface runoff.

3.4 Nonylphenol

Nonylphenol (NP) represents a broad class of isomeric compounds, each characterized by a nine-carbon alkyl chain bonded to a phenol ring, with the chemical formula $C_{15}H_{25}O$. The primary derivative of NP is nonylphenol ethoxylates (NPE). Organic compounds with a phenol group attached to a nine-carbon tail. The general formula is: $C_{15}H_{24}O$+ (OCH_2CH_2) nOH, where n may range from 1 to 100, but most NPE contains 6 to 12 ethoxy groups. NP is recognized as a potential endocrine-disrupting chemical impacting both human health and the environment. Nonylphenol was first synthesized in 1940 and its production and application continue to this day. Annually, the United States produces approximately 1,54,200 tons of NP, compared to 73,500 tons in Europe, 16,500 tons in Japan, and 16,000 tons in China. Current research indicates that China is a major producer of nonylphenol (Bhandari et al., 2021) (Figure 5). The most prevalent form of NP in the environment is branched-chain 4-nonylphenol. As a critical component in the production of nonionic surfactants, nonylphenol is commonly detected in water. However, water

FIGURE 3
Sources and transmission pathways of emerging contaminants (Wang et al., 2024).

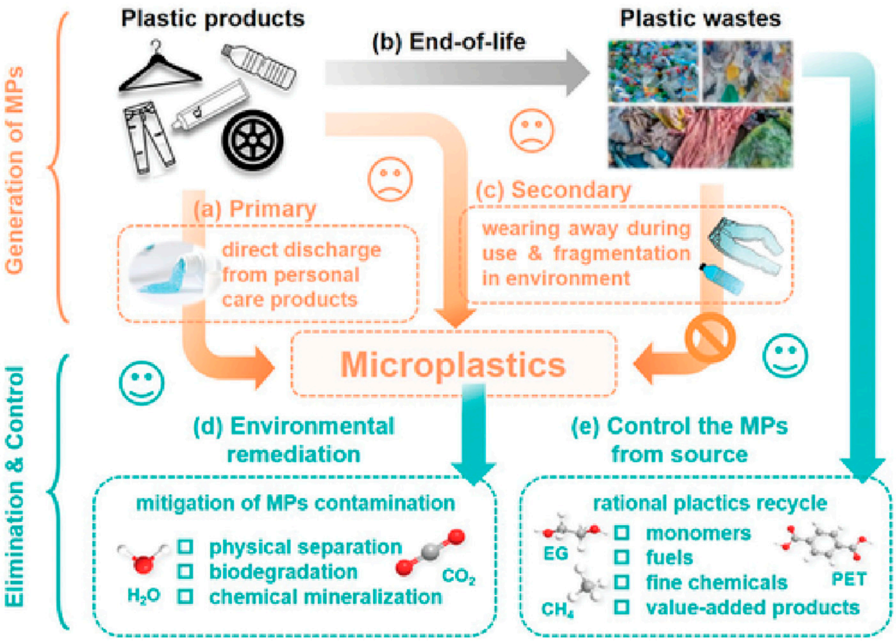


FIGURE 4
Microplastics production way, explain the process and management (Chen et al., 2022b).

samples frequently underestimate the quantities of hydrophobic organic matter transported to sediments by particles. In addition, one-time or infrequent surface water sampling does not explain the temporal variation in potential toxic concentrations (Crane, 2021). Unlike some countries, in Japan, nonylphenol is designated as a criterion within the environmental quality standards for water pollution (Hong et al., 2020).

4 Risk assessment of ECs

The chemical structure of a substance dictates its molecular and reactive properties, which in turn affect its toxicity and toxicological effects on humans, animals, and the environment. Specifically, the factors that affect the toxic properties of toxins include the following (Parida et al., 2021): 1. The functional groups and types of chemical bonds; 2. The spatial structure of the chemical substance; 3. The water-solubility and fat-solubility of the chemical substance; 4. Chemical substances with electrical properties, such as strong acids and bases, are prone to stimulation, while strong oxidants can cause oxidative stress reactions.

4.1 Ecological and environmental risks

The toxic substances that are excreted and left in the water body will become one of the main sources of antibiotics in the aquatic ecosystem. Research has shown that chemical compounds in water impact a variety of fungi, aquatic animals, and plants to varying degrees, including algae, fish, and nitrifying bacteria. In general, Predicted no-effect concentration (PNEC) values for different classes of antibiotics can be calculated using ECOSAR models or literature values to derive the extent to which antibiotics affect aquatic organisms (Formula 1).

$$RQ = \frac{MEC}{PNEC} \tag{1}$$

Where MEC is the measured environmental concentration and PNEC is the predicted unaffected concentration, PENC can be expressed as follows:

$$PNEC = EC_{50} or LC_{50}/1000 \tag{2}$$

This was determined using the ECOSAR model (Formula 2) (United States Environmental Protection Agency, 2011), which is widely used by researchers to assess the toxicity of organic compounds to aquatic organisms. General risk can be classified into three levels: high risk (RQ > 1), moderate risk (0.1 < RQ < 1), and low risk (0.01 < RQ < 0.1) (Krkstrm et al., 2020).

Enrofloxacin and Ciprofloxacin have been identified as posing significant risks to aquatic organisms in Laizhou Bay (Zhang et al., 2012). In fact, singular models are inadequate for predicting actual harm, as multiple compounds coexist in water and certain antibiotic combinations exhibit pronounced synergies. Liu et al. (2011) found that the coexistence of erythromycin, Ciprofloxacin and Sulfamethoxazole significantly reduced the growth rate, chlorophyll content, and photosynthetic rate of the freshwater algae Selenastrum capricornutum. A recent study indicates thatsildenafil (RQ = 3,048), lovastatin (RQ = 320), and trimethoprim (RQ = 74) in hospital wastewater pose high risks to animals and plants in the water body; However, the elevated risk associated with some compounds is attributed to their high concentrations, particularly those with significant ecotoxicological potential (Rodriguez-Rodriguez et al., 2023). In general, algae are the most sensitive species to antibiotics in water due to their high PNEC.

4.2 Hazards to human health

For certain ECs, the adjusted concentration can be calculated based on the Toxicity Equivalence Factor (TEF), and the lifetime lung cancer risk can be calculated using the WHO method.

The calculation of noncarcinogenic risk is as follows, divided into inhalation (Formula 3), nondietary intake (Formula 4), and skin contact (Formula 5). Common carcinogenic risks include substances such as polycyclic aromatic hydrocarbons, pesticides, and endocrine disruptors, among others.

$$\frac{CDI_{Inhalation} \times \left(\sqrt[3]{\frac{BW}{70}}\right) \times IR_{Inhalation} \times EF \times ED}{BW \times AF \times PEF} \tag{3}$$

$$\frac{CDI_{Dermal} \times \left(Unsupported\sqrt[3]{\frac{BW}{70}}\right) \times SA \times AF \times ABS \times EF \times ED}{BW \times AT \times 10^6} \tag{4}$$

$$\frac{CDI_{Ingestion} \times \left(Unsupported\sqrt[3]{\frac{BW}{70}}\right) \times IR_{Ingestion} \times EF \times ED}{BW \times AT \times 10^6} \tag{5}$$

5 Interaction of new pollutants and reactions with metals

The complexation of antibiotics with metals is influenced by numerous factors, resulting in diverse coordination outcomes. The main influencing factors include pH value, temperature, natural organic matter, salinity, properties of microplastics and coordination metal ions, among others. Different types of β-lactamases can render new-generation β-lactam antibiotics ineffective, among which metallo-β-lactamases (MBLs) are one of the main causes of widespread antibacterial resistance to carbapenem antibiotics. These metallohydrolases require at least one metal ion at the active site to coordinate with the essential nucleophile for hydrolysis (Möhler et al., 2017). Macrolide antibiotics typically function as monodentate ligands, binding to metal ions via hydroxyl groups on their smaller rings, in contrast to most other antibiotics, which are multidentate ligands (Wang et al., 2022). Tetracycline possesses multiple metal-binding sites, and its pharmacological activity largely depends on metal coordination. Berton found that the proportion of antibiotics that do not bind to proteins in plasma occurs almost exclusively in the form of calcium and magnesium complexes. Within cells, however, these drugs primarily coordinate with magnesium (II) ions, while calcium ions influence the absorption and bioavailability of tetracycline (Wendell et al., 2016).

Microplastic-mediated effects have also been reported. For example, it may play a mediating role between polycyclic hydrocarbons and antibiotics under multiple adsorption interactions. The surfaces of microplastics are capable of adsorbing polycyclic aromatic hydrocarbons and antibiotics, thereby facilitating their physical and chemical interactions. This medium may alter the distribution, transportation, and bioavailability of these substances, thereby affecting the ecosystem in the environment. Tong found that in the presence of Cu, there was a significant change in the adsorption of tetracycline and ciprofloxacin on microplastics, due to Cu-induced strong complexation between tetracycline and ciprofloxacin (Tong et al., 2023). Zhang employed ultraviolet light to simulate solar aging of microplastics, discovering that this aging significantly enhanced their capacity to adsorb levofloxacin hydrochloride. When the concentration of heavy metals in the environment is higher than that of antibiotics, heavy metals act as cation bridges and can form levofloxacin chromium complexes with levofloxacin, thereby promoting the adsorption process (Zhang et al., 2023; Zhou et al., 2022). Research indicates a significant positive correlation between microplastics and antibiotics resistance genes (ARGs), with microplastics increasing the frequency of bacterial gene transfer by 1.4–1.7 times, suggesting they may exacerbate the spread of antibiotic resistance genes in the environment (Yu et al., 2023). However, given the complexity of natural environments, the interactions among ECs warrant further investigation.

6 Removal methods for ECs

With the increasing maturity of technological means, there are various technologies for the treatment of new pollutants, such as metal-organic frameworks and biochar adsorption of organics, among others. The following chapters summarize and analyze various methods for the removal of pollutants.

6.1 Membrane filtration technology

A typical case provides comprehensive data on the occurrence of 19 antibiotics, 10 antibiotic-resistant bacteria, and 15 ARGs in the initial influent and different treatment stages of conventional activated sludge (CAS) and membrane Bioreactor (MBR) systems. Compared with CAS, MBR systems demonstrate superior removal efficiency. Specifically, Amoxicillin, Ciprofloxacin, Chloramphenicol, Meropenem, Minocycline, Azithromycin, Oxytetracycline, Sulfadimidine, and Vancomycin exhibited the highest removal rates in both CAS and MBR systems, with a median removal efficiency of 70%. No antibiotic-resistant bacteria were detected in the microfiltration permeate of the MBR system (Le et al., 2018). Compared with conventional membrane treatment technologies, electrochemical membrane filtration (EMF), a combination of electrochemical advanced oxidation process and low-pressure membrane filtration—has proven effective in degrading organic pollutants in wastewater, particularly persistent organic and micro-pollutants. This technology effectively removes pollutants in wastewater. The conventional membrane merely block the flow, while the electrochemical membrane can produce free radicals to degrade the pollutants and mineralize the pollutants into small molecules (Table 2). For instance, the high conductivity of carbon nanotubes facilitates their integration into hollow fiber membranes for combined membrane filtration and electrochemical processes (Yang et al., 2019). Compared with membrane filtration alone, the permeation flux of electrochemically assisted Carbon Nanotubes (CNTs)/AL_2O_3 membrane filtration was increased by 1.6 times, and the natural organic matter removal efficiency improved by 300% (Yang et al., 2019).

6.2 Constructed wetland

Constructed wetland (CW) are a sustainable treatment technology used for removing various metal and organic pollutants from wastewater. This technology requires without the need for additional energy sources and features low operating costs. Figures 5, 6 illustrates the principles of constructed wetlands for pollutant removal. It has been employed in landfill leachate treatment, hospital wastewater, municipal wastewater, among applications. For example, Hanwell investigated the impact of active aeration on the removal of selected drugs in a simulated wetland. It was found that continuous aeration can remove about 99% of the two-meta duality and Sagastan, and at the same time, Atenolol and Pesor were still effectively removed (75% and 50%, respectively) among the high-concentration drugs detected at the hospital site (Auvinen et al., 2017). Sabri employed the CW for Sewage Treatment wastewater and has found significant treatment with antibiotics, with an overall removal rate of 28%–100%, depending on the type of antibiotic (Sabri et al., 2021). The CWs are multifunctional systems that improve water quality, act as hydrological buffers, and support natural habitats and recreational areas.By simulating natural wetland systems, such as wetland plants, soil, and soil microorganisms, continuous water treatment can remove various pollutants from different wastewater sources. Initially, constructed wetlands were primarily utilized for secondary and tertiary treatment of domestic and urban sewage; however, further research has expanded their capability to effectively address a broader spectrum of pollutants, with efficiency varying by substrate material. Considering various objectives, such as hydraulic penetration, pollutant types, and treatment needs, substrates of varying diameters are utilized in CWs. Biological processes (biodegradation, plant absorption, etc.) and physicochemical processes (adsorption, oxidation, chemical degradation, optical degradation, volatilization, and hydrolysis, etc.) also influence pollutant removal in CWs (Ji et al., 2022).

6.3 Adsorption material

Biochar is a kind of material with multi-layer and fibrous porous structure, which is usually pyrolyzed under oxygen-limited conditions. Based on temperature, three primary pyrolysis processes are identified: fast pyrolysis (temperature >500°C), moderate pyrolysis (temperature 300°C–500°C) and slow pyrolysis (temperature <300°C) (Luo et al., 2022). In the process of adsorption, both physical and chemical adsorptions take place, with the dominant mechanism varying according to the type of pollutant involved (Figure 7). Significant electron donor-acceptor (EDA) interactions typically occur between the aromatic ring of the π donor and the π protonated adsorbent on the surface of the modified biochar. Additionally, electrostatic interactions, hydrogen bonding, surface complexation, cation exchange, and non-specific van der Waals forces may all contribute to the adsorption process (Peiris et al., 2017). For example, a coke made from olive oil waste from the biochar-thermal carbonization process, which removes triclosan, ibuprofen, and diclofenac from wastewater. Similar to activated carbon, the efficiency of biochar adsorption is influenced by the physical and chemical properties of the pollutants, the pK_a of the adsorbent, and the temperature. Under the influence of oxygen-containing functional groups and solution pH, triclosan removal efficiency can reach up to 98% (Delgado-Moreno et al., 2021). Owing to the limitations in the application of original biochar for environmental remediation, an increasing number of

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TABLE 2 Removal of new contaminants by membrane treatment.

Types of pollutants	Membrane	Influent concentration (μg/L)	Time(h)	Removal efficiency (%)	Current density (mA/cm^2)	Reference
Tetracycline Sulfamethoxazole	CeO_2@CNT-NaClO	-	30 30	98.0 99.0	2.0 2.0	Ni et al. (2023)
Sulfamethoxazole Ciprofloxacin Tetracycline carbamazepine	CeO_2@CNT	-	240	91.3 94.4 99.3 89.4	0.5	Ma et al. (2023)
Sulfamethoxazole Trimethoprim	Electrochemical membrane aeration biofilm reactor	50	2,160	40.1 32.8	2.0	Ren et al. (2021)
Benzotriazole	Titanium dioxide ceramic membrane	14,200	30	98.1	20	Wang et al. (2022)
Tetrabromobisphenol A	F-doped Tiso electroactive film	3.5	90	99.7	7.8	Pei et al. (2021)
Bisphenol A	Coal-based carbon film	50	0.88	97	2	Pan et al. (2019)

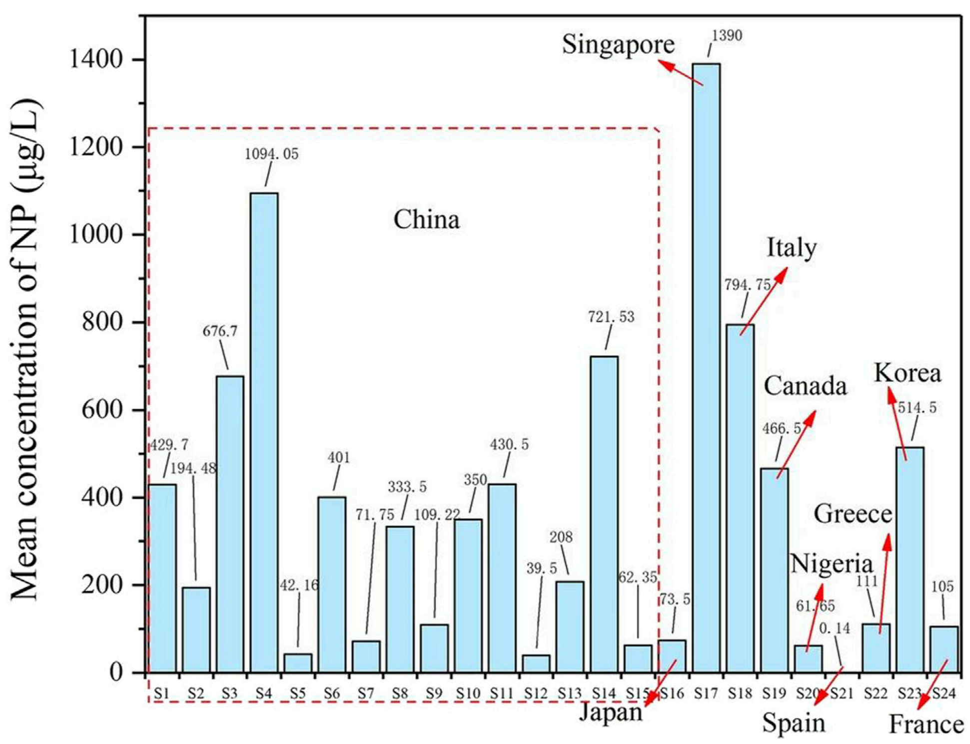

FIGURE 5
Distribution of nonylphenol in water environment of China and other countries. NP: nonylphenol. (S1: Yangtze River (Nanjing Section), S2: Yangtze River, S3: Yellow River, S4: Liao River−River, S5: Liao River-Reservoir, S6: Pearl River−River, S7: Pearl River-Reservoir, S8: Haihe-River, S9: Haihe-Reservoir, S10: Daliao River Estuary-Seawater, S11: Daliao River Estuary-Freshwater, S12: Sishili Bay and Taozi Bay-Seawater, S13: Sishili Bay and Taozi Bay-Freshwater, S14: Taihu Lake, S15: Chaohu Lake, S16: Japan, S17: Singapore, S18: Italy, S19: Canada, S20: Nigeria, S21: Spain, S22: Greece, S23: Korea, S24: France) (Hong et al., 2020).

researchers are turning to the production of biochar-based composites. These composites incorporate techniques such as liquid precipitation, nano-composite materials, and magnetic fields. However, magnetic biochar composites are predominantly employed for metal adsorption (Liang et al., 2021). Additionally, biochar derived from animal manure, chicken bones, bamboo and other raw materials is also popular because of its environmental characteristics (Patel et al., 2022). The pyrolytic calcium-rich biochar made from crab shells shows great advantages in the removal of chlortetracycline. At low concentrations, adsorption predominates; however, as concentrations increase, the adsorption capacity escalates impressively to 5,048 mg/g,

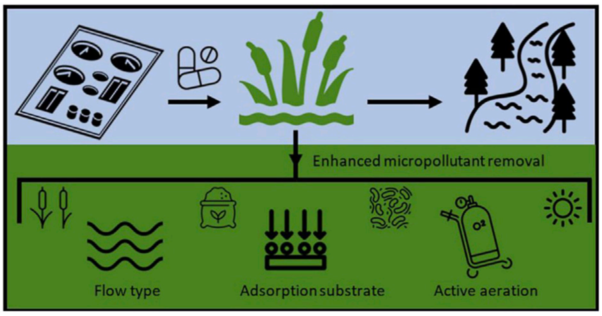

FIGURE 6
Constructed wetlands remove pollutants (Wagner et al., 2023).

combining both adsorption and flocculation mechanisms. Remarkably, the system maintained enhanced removal efficiency even after five operational cycles (Xu et al., 2020).In terms of Polycyclic aromatic hydrocarbon, pyrolysis of biochar using sludge from a groundwater treatment plant can be very effective, with a degradation efficiency of 87%. Biochar produced at 700°C predominantly undergoes degradation through Fenton oxidation, where Fe^{3+}/Fe^{2+} and Mn^{3+}/Mn^{2+} redox pairs catalyze the formation of O^{2-}• and HO• radical (Hung et al., 2020). In recent years, the research progress of biochar modification to remove organic pollutants has been recorded. Further research is necessary to develop targeted biocarbons with clear interactions that enable precise on-off regulation of cyclic remediation processes (Patel et al., 2022).

In fact, an increasing number of adsorbent materials, such as metal-organic frameworks (MOFs), nanomaterials, and metal oxide nanocomposites, are receiving significant attention from scholars. Several cases of MOFs removing emerging contaminants (ECs) have been reported, including MIL-101 adsorbing tetracycline (Hu et al., 2017), and MOF-5 adsorbing ciprofloxacin (Gadipelly et al., 2018). Due to their large surface area, customizable pore structure, diverse topologies, and ease of regeneration, MOFs are key to achieving complex applications in environmentally-friendly adsorption. However, the instability of MOFs in aqueous solutions is a crucial factor to consider, as studies have shown that currently no MOFs can effectively adsorb multiple pollutants simultaneously (Jeong et al., 2023). Experiments have found that the principles of adsorption are often electrostatic adsorption, hydrogen bonding, or π-π interactions. This is consistent with the study by Zhang et al., who investigated the adsorption of sulfamethoxazole using carbon nanotubes (Zhang et al., 2011). Lv developed high-performance coal gasification slag-based adsorbents from waste coal gasification slag through optimized preparation processes to adsorb microplastics, finding a maximum adsorption capacity exceeding 1,400 mg/g and an adsorption removal efficiency of up to 99.2% (Lv et al., 2025). Bele investigated the production of graphene oxide from hydrazine hydrate; at optimal reduction levels, the enhanced π-π interactions between the adsorbent and adsorbate led to an adsorption capacity for bisphenol A of 94.06 mg/L (Bele et al., 2016). Overall, providing surface functional groups and adsorption sites on adsorbents remains key to improving adsorption efficiency. Since adsorption can be combined with other processes to enhance efficiency, it is considered one of the green processes for removing ECs from wastewater resources (Sophia and Lima, 2018).

6.4 Algae repair

The most important processes in algal reactions are biodegradation, photodegradation, volatilization and adsorption (Gondi et al., 2022). Generally, biodegradation and photodegradation are the primary methods for removing organic micropollutants in urban wastewater (Matamoros et al., 2015). For instance, algal-mediated removal of five pharmaceutical and personal care products species (Trimethoprim, Sulfamethoxazole, carbamazepine, Ciprofloxacin and triclosan) from lake water has

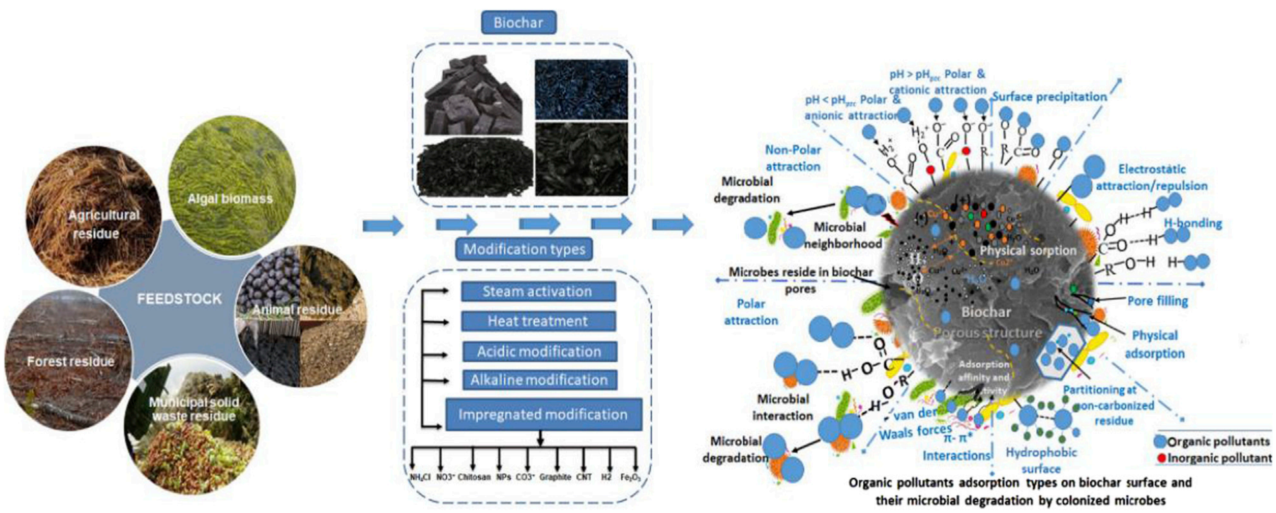

FIGURE 7
Biochar removes organic matter (Patel et al., 2022).

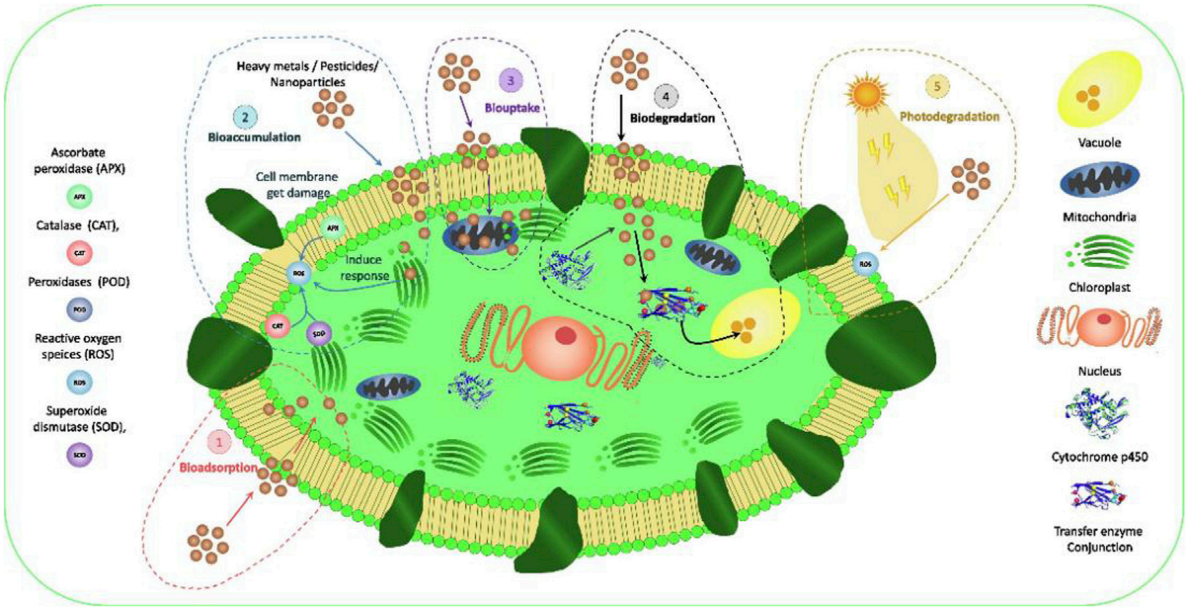

FIGURE 8
Mechanisms of bioremediation of new pollutants through microalgae-based treatment systems: (1) EP crosses the algal cell wall and binds to intracellular proteins in living cells during biouptake; And (2) in inactive cells during bioaccumulation (3) EP is adsorbed to algal cell wall or extra polymer(EPS) during bioadsorption (4) complex EP is decomposed into simpler and less toxic compounds during biodegradation (5) EP is exposed to UV light during direct or photodegradation (Gondi et al.,2022).

been documented. Significant removal efficiency was demonstrated under light conditions, with Ciprofloxacin and Triclosan being highly sensitive to light resulting in a 100% removal efficiency (Bai and Acharya, 2017). Zhang et al. (2021) found that intertidal algal blooms could remove bisphenol A and NP at ambient concentrations, with Ulva pertusa proving most efficient. The removal mechanism involves initial rapid biosorption, followed by slow bioaccumulation and biodegradation (Zhang et al., 2021). In addition, biosorption and bioaccumulation are also important ways to remove the concentration of organic pollutants in the environment. The difference lies in whether pollutants accumulate on the surface or are assimilated into the cytoplasm (Figure 8). Microalgae can continue to grow even after absorbing pollutants. Clearly, bioaccumulation necessitates that microalgae remain viable, as opposed to merely living, which is more suitable for removing dyes and heavy metals (Ratnasari et al., 2022). Consequently, owing to the metabolic activity of the cell wall and physicochemical processes on its surface, various organic compounds in wastewater and algal culture ingredients may facilitate distinct organic removal mechanisms.

6.5 Biological treatment technologies

Conventional activated sludge treatment technology is commonly employed in municipal wastewater treatment plants, featuring three main degradation pathways: microbial processes (biodegradation, metabolism, or co-metabolism), sludge flocculation adsorption, and volatilization (primarily during aeration). Generally, pollutants exist in different ionic forms under varying pH conditions, and since log D is pH-dependent, the log D value is a critical factor to consider for adsorptive removal of pollutants (Grandclement et al., 2017). Some studies have proposed using activated sludge technology to remove new pollutants (Coccia and Bontempi, 2023; Fan et al., 2022; Verlicchi et al., 2013), however, emerging contaminants (ECs) often exist in trace amounts and their complex physicochemical properties restrict degradation capabilities. Research has shown that activated sludge can remove acetaminophen, fluconazole, and ibuprofen with efficiencies of 99.9%, 97%, and 99.9% respectively (Dos Santos et al., 2022), but shows poorer removal for ofloxacin, penicillin V, sulfamethoxazole, and methoxybenzamine (Blair et al., 2015). Thus, developing integrated technologies is the future direction for treating ECs, such as a wastewater treatment system combining aquatic foxtail algae with activated sludge, where forming a biofilm post-inoculation significantly enhanced the removal efficiency of pollutants in the wastewater (Guo et al., 2019). Another study applied a static magnetic field (SMF) to the activated sludge process to enhance tetracycline removal from swine wastewater. The SMF increased electrostatic interactions between activated sludge and tetracycline, providing more binding sites and promoting the growth of ammonia-oxidizing bacteria, tetracycline-degrading bacteria, and aromatic compound-degrading bacteria. Additionally, SMF mitigated the enrichment and spread of antibiotic resistance genes by reducing the potential host abundance and suppressing the upregulation of genes encoding ABC transporters and hypothetical transposases (Zhu et al., 2024). Therefore, the application of magnetic fields (MF) in biological wastewater treatment has garnered significant attention due to its sustainability, cost-effectiveness, and eco-friendliness (Li et al., 2024).

Generally, pollutants are adsorbed onto the lipid structures of bacterial communities and the fatty parts of wastewater sludge through hydrophobic interactions (e.g., aromatic and aliphatic). Moreover, they can also be adsorbed onto the negatively charged polysaccharide structures outside bacterial cells through electrostatic interactions (e.g., amino groups). Given the ubiquity of bacteria, protozoa, and fungi in aquatic environments, microbial degradation often represents the most critical process in the mass balance of environmental transformation.

Additionally, the Membrane Bioreactor (MBR) represents another prevalent technology for biowastewater treatment. According to previous reports, MBR has demonstrated effective removal of nonylphenol and certain hormones (Gonzalez et al., 2006), yet it appears to be less effective for antibiotics (Kim et al., 2007). Although MBR has well-recognized advantages, the accumulation of fouling on the membrane surface reduces membrane flux, necessitating the use of corrosive chemicals for cleaning and thus posing a significant challenge due to secondary pollution. Ashish suggests that pharmaceuticals can alter the secretion patterns of various contaminants, such as disrupting cellular structures, thereby forcing the release of intracellular polymers. All these factors contribute to the accelerated fouling propensity in MBR systems (Sengar and Vijayanandan, 2022).

6.6 Advanced oxidation technology

The electrochemical treatment process involves the mineralization of pollutants through two primary pathways: direct anodic oxidation at the main electrodes (anode and cathode) or indirect oxidation via reactive oxygen species in the solution and reduction reactions at the cathode. For example, Tang employed a silver-plated titanium (Ti/Ag) anode for the electrochemical degradation of perfluorinated compounds (PFCs) in the effluent from a municipal wastewater treatment plant. Their study demonstrated excellent PFCs removal efficiencies, with maximum removal efficiencies of approximately 70.8% for short-chain PFCs (CF < 7), 91.5% for long-chain PFCs (CF ≥ 7), and 92.0% for chemical oxygen demand (COD) (Tang et al., 2021). Generally, the removal rate increases with the increase in current density. This rule applies not only to perfluorinated compounds but also to the removal of pharmaceutical residues, such as ciprofloxacin, in a pilot-scale pulsed corona discharge system, where the removal efficiency increased from 29% to 100% as the nominal power increased from 30 W to 250 W (Ajo et al., 2018). Due to the oxygen release reaction potential in electrochemical systems, the environmental friendliness of electrode materials is crucial. The electrochemical oxidation efficiency of the anode largely depends on the electrode material itself, where weak interactions between the electrode and reactive oxygen species result in high chemical reactivity, leading to the complete mineralization or oxidation of organic pollutants. Electrochemical oxidation systems are considered a viable option for the treatment of pharmaceutical pollutants (Ganthavee and Trzcinski, 2023; Li et al., 2016a).

Another effective and environmentally friendly removal method is photocatalysis. As an emerging green technology, it primarily accelerates reactions by generating electrons and holes upon light irradiation. Efficient photocatalysis involves a broad light absorption spectrum and high separation efficiency of photogenerated charge carriers. Under ideal conditions, molecular oxygen can be excited by electrons to produce superoxide anion radicals and hydrogen peroxide, which can completely decompose organic pollutants into non-toxic CO_2 and H_2O without generating harmful by-products (Rajaitha et al., 2022). Photocatalysis has been applied to various materials, such as carbon nanotubes and titanium dioxide. Baran et al. found that TiO_2 photocatalysis can effectively remove sulfamethoxazole and its by-products, with the resulting by-products being less toxic to Chlorella vulgaris and easier to degrade (Baran et al., 2006). In the context of microplastic photocatalysis, Nabi et al. discovered that after 12 h of UV irradiation at 254 nm, the degradation rate of 5 mm polystyrene microplastics reached 44.6% under liquid phase conditions and increased to 99% in the solid phase (Nabi et al., 2020).Xu suggested that lower pH and lower temperatures are more conducive to photocatalysis during degradation, as low pH can introduce ions into the reaction process, and low temperatures can facilitate the fragmentation of microplastics (Xu et al., 2021).

Despite the availability of numerous advanced oxidation-reduction methods for the removal of emerging pollutants, we must consider the discrepancies between laboratory-simulated experiments and actual complex water bodies. Additionally, whether the experimental process incurs additional costs remains uncertain. More importantly, the stability and recyclability of materials are critical factors that need to be considered.

7 Conclusion

The scope of new pollutants has been expanding over time, and in addition to those mentioned in the article, it also includes a large number of compounds such as polychlorobenzenes, polycyclic aromatic hydrocarbons, etc. With large-scale production and use, they are ubiquitous in the environment. Although there are many reports of their presence, the relative concentrations are higher in Asia and Europe. There are many studies in treatment technology, lack of corresponding innovation is also a huge problem. It is worth noting that the current research on the deprivation of new pollutants is mainly concentrated in the simulation of the laboratory. And despite the fruitful results, the effects of de-priming trace pollutants in the actual aqueous environment as well as coping with complex environmental matrices are yet to be investigated, and intermediates produced by the degradation of parent neopollutants, for example, are likely to be more toxic. Considering the current situation, several factors need to be considered:

1. Regulation: As understanding of neo-pollutants deepens and monitoring technologies advance, regulatory systems will become more comprehensive and refined. Future regulations will increasingly focus on real-time monitoring and data sharing to promptly detect and address the emergence of new pollutants. Simultaneously, there will be a strengthened emphasis on international cooperation and information sharing to effectively tackle transboundary pollution.
2. Removal technologies: Future research directions for removal technologies will focus on enhancing efficiency, environmental compatibility, and economic feasibility. With technological

advancements, it is anticipated that more sophisticated methods for pollutant elimination will be developed. Furthermore, there will be a heightened emphasis on the practical deployment and sustainability of these technologies. While the primary findings of this research highlight promising approaches for contaminant removal, certain limitations exist, such as the synergistic effects of various technologies and the yet unclear implications of certain byproducts. Indeed, enhancing energy efficiency at the source to mitigate environmental impacts represents a vital strategy for sustainable development, encompassing the innovation of new materials and the formulation of less toxic pharmaceuticals.

3. Environmental hazards: Future research will be more in-depth and comprehensive in response to the potential environmental hazards of new pollutants. The focus of research may include studies on the ecotoxicity, bioaccumulation and potential long-term effects of pollutants to comprehensively assess their impacts on the ecosystem and develop corresponding countermeasures.

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QZ: Investigation, Writing–original draft, Writing–review and editing. HC: Funding acquisition, Writing–review and editing. GL: Writing–review and editing. XW: Data curation, Funding acquisition, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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