Review

Environmental Chemistry and Safety
DOI: 10.26599/ECS.2026.9600031
2026, 2, 9600031

Contaminants of emerging concern (CECs) in aquatic and terrestrial environments: Sources, impacts, and remediation strategies

M. Ky Nguyen[1*], S. Wong Chang[2], and D. Duc Nguyen[2*]

[1]Faculty of Environment and Natural Resources, Nong Lam University, Hamlet 33, Linh Xuan Ward, Ho Chi Minh City 700000, Vietnam
[2]Department of Civil & Energy Systems Engineering, Kyonggi University, Suwon 16227, South Korea

Abstract: Contaminants of emerging concern (CECs) refer to various synthetic chemicals—such as pharmaceuticals and personal care products (PPCPs), pesticides, per- and polyfluoroalkyl substances (PFASs), micro/nanoplastics, and nanomaterials—that pose a threat to both environmental and human well-being. These pollutants primarily originate from industrial activities, wastewater effluents, household waste, and agricultural runoff. Anthropogenic CECs are recognized as a new class of micropollutants that contaminate aquatic environments and pose a threat to ecological and human health. Their continuous input from industrial, domestic, and agricultural sources results in chronic exposure and toxicity. Growing evidence of their health impacts calls for immediate and effective control measures to address CEC-induced hazards. This study outlines key sources, environmental implications, and innovative treatment solutions. Strengthening pollution control, treatment efficiency, and ecosystem protection helps governments resolve the water quality challenges of urbanization and move toward sustainable living. Yet, the removal of diverse and persistent CECs requires more advanced solutions, posing a significant challenge.

Key words: micro/nanoplastic; pharmaceutical; ecological risk; micropollutant; PFAS; health hazard.

Citation: Nguyen M. Ky, Chang S. Wong, Nguyen D. Duc. Contaminants of emerging concern (CECs) in aquatic and terrestrial environments: Sources, impacts, and remediation strategies. *Environmental Chemistry and Safety*, 2026, 2, 9600031. https://doi.org/10.26599/ECS.2026.9600031

1. Introduction

Contaminants of emerging concern (CECs) are defined as substances that are not routinely monitored in environmental systems but may be included in future legislation owing to their persistence, bioaccumulation potential, and harmful effects on ecosystems and human health [1]. According to the United States Geological Survey (USGS), they are defined as manufactured or naturally occurring chemicals or microbes that are not routinely monitored in the environment but are capable of causing known or suspected ecological or human health impacts [2, 3]. CECs' classification has progressed in response to industrial growth, pollutant discharge characteristics, technological advances in wastewater treatment, and evolving regulatory frameworks [4]. Rising global concern regarding the widespread presence of various CECs, such as, plasticizers, disinfectants, flame retardants, herbicides, insecticides, corrosion inhibitors, and synthetic dyes — in industrial effluents, agricultural drainage, and stormwater runoff has led to growing research efforts focused on their removal and mitigation [5]. CECs primarily enter the environment through two major routes: wastewater treatment plants (WWTPs) and surface runoff. For example, a monitoring campaign in the semi-arid Mediterranean basin of Kasserine, Tunisia, detected a total of 101 emerging contaminants in both surface water and groundwater, providing a comprehensive overview of pollution in the basin [6]. Most pollutants were detected more frequently and at higher concentrations in surface waters, suggesting that wastewater discharges into watercourses are the main source of these contaminants. Further, during rainfall, contaminants are washed from various urban and non-urban surfaces, contributing to their dispersion in aquatic ecosystems.

Due to their persistence and tendency to accumulate in water bodies, CECs have been recognized as potential hazards to human and ecological health, even at low concentrations [7]. As newly emerging contaminants, CECs have drawn considerable interest owing to their potential risks and toxicological impacts [8, 9]. The presence of CECs in aquatic systems can disrupt hormonal balance, impair reproduction, and lead to bioaccumulation in the food chain, potentially causing chronic health impacts on humans. In aquaculture systems, CECs are commonly detected in water, sediments, and cultured species, particularly antibiotics, antifoulants, and disinfectants [8]. By accumulating in food crops and transferring through the food web, CECs may compromise food safety and environmental quality, presenting significant implications for wastewater treatment and its reuse in agricultural systems [10-12].

To mitigate the adverse effects of CECs and protect aquatic ecosystems, various technologies for treating aquaculture effluents have been investigated, including physical, chemi-

Correspondence to: Nguyen M. Ky, nmky@hcmuaf.edu.vn; Nguyen D. Duc, nguyensyduc@gmail.com

Received: January 30, 2026; Revised: April 24, 2026; Accepted: May 3, 2026

cal, and biological methods [4, 8, 13]. This review seeks to advance the development of more efficient and sustainable approaches for managing CECs, thereby enhancing environmental and public health protection. The study encompasses a wide range of CECs, including pharmaceuticals and personal care products (PPCPs), pesticides, per- and polyfluoroalkyl substances (PFASs), micro/nanoplastics, and nanomaterials. It examines their sources, environmental pathways, and ecological and human health impacts. The study also reviews current and emerging remediation technologies, such as biological and nature-based approaches and advanced treatment technologies. Overall, it aims to highlight innovative and sustainable strategies for mitigating CEC pollution in both aquatic and terrestrial environments.

2. Sources and occurrence of major CECs

The release of industrial effluents containing chemical additives and manufacturing by-products partly explains the presence of hazardous compounds in aquatic systems. Over recent decades, the range of sources contributing to CEC contamination in wastewater and freshwater environments has expanded beyond classical pollutants, as depicted in Fig. 1.

Sources of CECs include point discharges from industrial, municipal, and hospital WWTPs, diffuse inputs such as stormwater runoff and atmospheric fallout, and unintentional releases caused by leakage or accidental events [13, 14]. Even at low concentrations, CECs present notable ecological and health risks due to their ability to move, transform, and persist in environmental media. Municipal effluents, containing organic contaminants from both household and industrial sources, serve as the primary entry route for CECs into the aquatic environment. Livestock production facilities can introduce substantial amounts of pollutants—such as veterinary hormones, antibiotic residues, and nutrients—into surrounding ecosystems through the discharge of animal waste.

2.1. Pharmaceuticals and personal care products (PPCPs)

The widespread daily use of pharmaceuticals and personal care products (PPCPs) results in their release into aquatic systems through multiple routes, primarily via municipal and industrial discharges. Effluents from treatment plants, pharmaceutical industries, and hospital waste streams play a major role in their distribution across aquatic and terrestrial environments [15, 16]. Household wastewater is a key contributor to PPCPs pollution in aquatic systems. Widely used in medicine, cosmetics, veterinary, and agricultural applications, PPCPs have become common environmental pollutants linked to ecological and human health risks. PPCPs originate from diverse residential and commercial sources, with domestic waste streams—such as urban dumps, household refuse, animal waste, and human excrement—playing a significant role in their environmental dissemination [15]. Further, agricultural runoff, particularly from the meat production sector, serves as a significant pathway for PPCPs contamination in the environment.

As an example, pharmaceuticals were first detected in river water in the 1970s. Pharmaceuticals are often present in elevated concentrations within solid waste and wastewater, making pharmaceutical manufacturing facilities a significant source of these compounds in the environment [17, 18]. Hospital wastewater significantly contributes to pharmaceutical contamination, while veterinary drugs used in livestock farming facilitate their entry into soil and aquatic systems. Pharmaceuticals are often found in surface waters at concentrations of ng/L, with several compounds commonly detected in significant amounts [19]. This group includes more than 4,000 chemicals used mainly for therapeutic purposes in humans and animals. Following use, these compounds are excreted as unmetabolized drugs or metabolites and transported through sewage systems [20], prompting extensive research on their occurrence and removal in aquatic systems and wastewater treatment.

2.2. Pesticides

Pesticides are chemical substances designed to control or eliminate pests, including insects, rodents, fungi, and weeds. Around one-third of global crop production involves their application. Pesticides remain crucial to agricultural practices, as they are used to control unwanted weeds and insect infestations, resulting in remarkable gains in crop yields [21]. On a global scale, total pesticide consumption in agriculture reached 3.73 million tonnes of active ingredients (Mt) in 2023, representing a 14% increase over the past decade and nearly

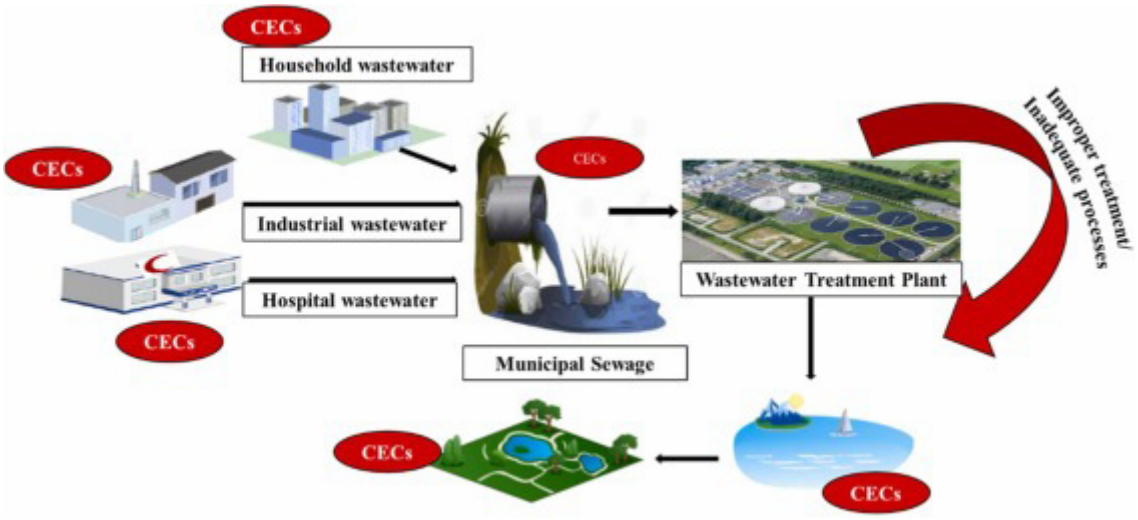

Fig. 1. Pathways of CECs entry from wastewater effluents into aquatic ecosystems. Reprinted from *Process Safety and Environmental Protection* [3].

double the level recorded in 1990 [22]. These substances are classified by their mode of action, molecular structure, risk potential, and practical applications [23].

Pesticides can penetrate aquatic ecosystems through different mechanisms, notably by intentional application to surface waters for the suppression of weeds, pest species, or crop-related diseases [24]. Additionally, pesticides can enter the atmosphere through volatilization and long-distance transport before being deposited elsewhere. The primary sources of pesticides are agricultural applications, such as spraying on crops and soils, followed by runoff and leaching that introduce residues into the surrounding environment. Additional inputs arise from urban landscaping, household pesticide use, and vector control operations. Contamination may also arise from industrial production, leakage during storage, and inadequate disposal practices.

2.3. PFASs

PFASs represent a large class of synthetic fluorinated organic substances noted for their chemical inertness and environmental persistence. The group comprises over 14,000 compounds, including partially and fully fluorinated molecules with diverse structural types—branched, linear, or cyclic [25, 26]. Environmental PFAS inputs can be broadly classified as direct or indirect. Direct emissions, PFASs are commonly used in fire-retardant foams, adhesives, metal finishing, cosmetics, and paper products, serving as stain- and water-resistant additives in the textile manufacturing process [27]. Importantly, the textile industry consumes considerable amounts of PFASs and precursor chemicals, which are then used in paper packaging and aftermarket goods [28]. Regarding indirect PFAS emissions, they arise from landfill leachate and WWTPs effluent [29]. Industrial emissions, especially waste and wastewater outputs from manufacturing processes, constitute the main route by which novel PFASs are introduced into ecosystems. Leachate from landfills and discharges from industrial and municipal WWTPs act as secondary pathways introducing PFASs into aquatic ecosystems.

2.4. Micro/nanoplastics

Microplastics (< 5 mm) and nanoplastics (< 1 μm) are small plastic particles that result from the breakdown of larger plastic debris or are directly manufactured at microscopic scales [30]. Micro/nanoplastics originate from primary sources, including cosmetic microbeads and industrial pellets, as well as secondary sources formed through the degradation of larger plastics through physical, chemical, and biological degradation processes in nature [31-33]. They are released into the environment through wastewater, runoff, and airborne deposition, exacerbating global contamination (Fig. 2).

Currently, around 367 million tons of plastic are produced annually worldwide. Their widespread use across industries stems from their affordability, flexibility, and ease of manufacture; however, poor waste management has led to **s**evere accumulation in marine, terrestrial, and landfill environments. Examples include plastic bags, bottles, and fishing nets that accumulate in rivers and oceans, eventually fragmenting into micro/nanoplastics. Moreover, plastics serve as a dominant packaging material in the food sector [35]. Despite their benefits, plastics can fragment over time, releasing micro/nanoplastics that contaminate food chains and environmental systems.

2.5. Nanomaterials

Nanomaterials specifically refer to particles ranging in size from 1 to 100 nanometers in at least one dimension [36], which imparts them with distinct physical, chemical, and biological properties. Originating from natural (e.g., volcanic ash, sea spray) and anthropogenic sources (e.g., industrial processes, cosmetic products, electronic manufacturing, and wastewater), these particles raise growing concerns about their persistence and potential environmental toxicity.

In contemporary society, nanomaterials constitute a fundamental component of numerous disciplines, finding broad util-

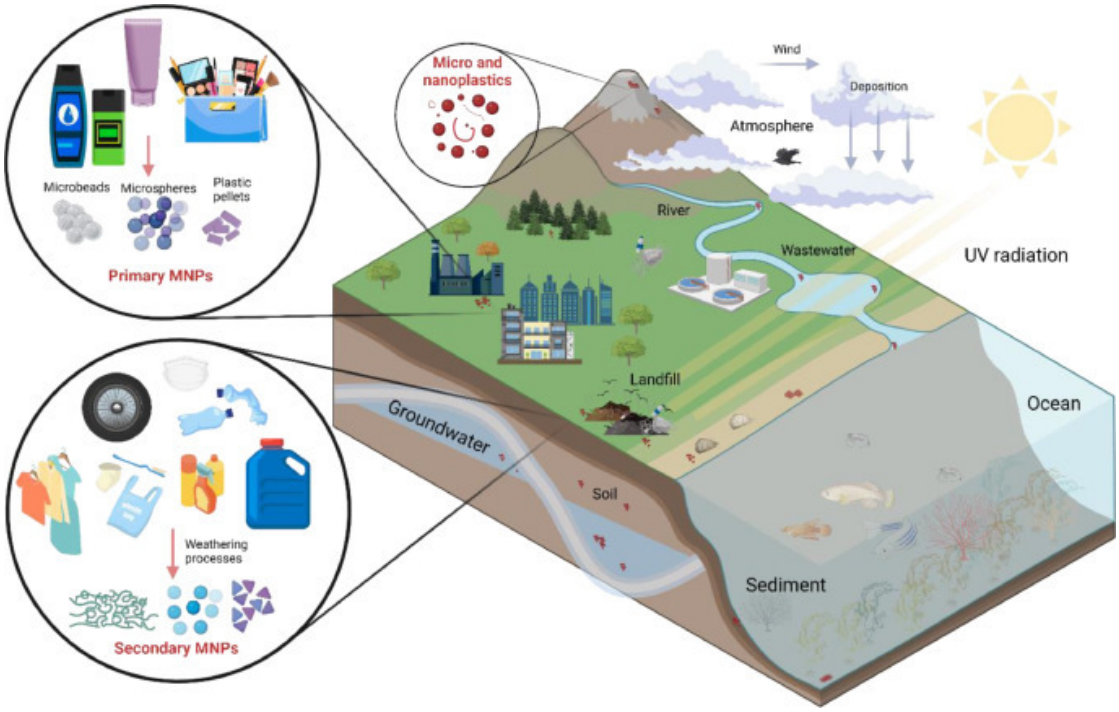

Fig. 2. Sources and transport routes of micro/nanoplastics pollution. Reprinted from *Green Analytical Chemistry* [34].

ity in scientific innovation, medical and pharmaceutical advancements, industrial manufacturing, and electronic communication technologies [36]. Through the precise manipulation of nanoscale materials, nanotechnology finds broad applications in both domestic utilities and industrial processes, underscoring its growing technological and economic significance [37]. It involves the synthesis of various nanomaterials designed for use in biomedical, veterinary, and animal husbandry applications [38, 39].

3. Ecological and human health impacts

CECs are human-made substances with persistence and bioaccumulation in environmental compartments, with evidence indicating that even low concentrations may pose hazards to both ecological and human health [7]. CECs can persist for extended periods in sediments, where they are taken up by benthic organisms and subsequently transferred through the aquatic food web to higher trophic levels, such as fish [40, 41]. Their levels may increase through trophic transfer and biomagnification, resulting in top predators exhibiting contaminant levels several orders of magnitude higher than those in surrounding waters. Consequently, the concentrations of CECs in fish tissues serve as important indicators of aquatic ecosystem health and potential risks to human health through fish consumption. Additionally, the USEPA categorizes several chemicals as CECs, including confirmed or suspected endocrine-disrupting chemicals. Their occurrence raises significant concerns, highlighting the need for ongoing monitoring and mitigation strategies.

3.1. Pharmaceuticals and personal care products (PPCPs)

Environmental contamination by PPCPs presents serious hazards to flora, fauna, and humans. PPCPs, a significant class of CECs, persist in the environment and may disrupt target receptor physiology [3]. The release of industrial effluents, including bioactive compounds utilized in PPCP manufacturing, is a primary pathway by which these substances enter aquatic ecosystems. Additionally, global pharmaceutical consumption continues to increase, supporting the health of both humans and animals, but this has led to emerging contaminant pollution. Pharmaceuticals represent one of the most persistent classes of environmental pollutants, potentially posing serious risks to human health and aquatic biota [42, 43]. For example, as primary producers in the food chain, plants can act as a major pathway for the transfer of pharmaceutical contaminants; when consumed by humans and animals, these compounds may bioaccumulate in tissues and pose potential health risks, including the emergence of antibiotic resistance [42, 44]. Exposure of aquatic organisms to pharmaceuticals can lead to a range of adverse effects, including oxidative stress, inhibited growth and development, premature mortality, and inflammatory responses [45].

The persistence, bioaccumulative potential, and toxicity of PPCPs contribute to their detrimental effects on aquatic organisms, with some compounds further influencing growth and developmental processes [46]. Exposure to PPCPs can disrupt reproduction in aquatic organisms, affecting not only small species such as *Daphnia* spp., but also fish [47]. Experimental studies have shown that PPCPs, including triclosan, tonalide, and galactoside, exhibit limited translocation in plants such as carrot (*Daucus carota* sativus) and barley (*Hordeum vulgare*) [48]. Triclosan has been reported to exhibit toxicity toward several bacterial species, while high concentrations of alkylbenzene sulfonates have been shown to alter microbial communities in surface waters [49]. Experimental evidence suggests that PPCP exposure increases stress indicators and activates detoxification pathways in *Cucumis sativus* [50]. Exposure of cucumber seedlings to a mixture of 17 PPCPs at 550 μg/L resulted in a decline in photosynthetic pigment content and substantial accumulation of these compounds in the root tissues [51].

Moreover, the environmental impact of antibiotics, beyond that of conventional CECs, is increasingly recognized. These pharmaceuticals can interfere with ecological processes, adversely affect wildlife, and facilitate the emergence and dissemination of antibiotic-resistant bacteria (ARB) and antibiotic-resistant genes (ARG). Chronic exposure to antibiotics facilitates the development of antibiotic resistance, thereby presenting significant threats to human health [52]. Due to their largely non-biodegradable nature, these micropollutants persist over prolonged periods in the environment. More importantly, the cumulative impact of these global trends has amplified pollution. Pharmaceutical residues, combined with other pollutants such as microplastics, are now widespread in various ecosystems, posing considerable environmental and management challenges [53].

3.2. Pesticides

Despite their utility in enhancing crop yields and managing pests, pesticides contribute significantly to environmental degradation and public health concerns [54]. Persistent environmental contamination by pesticides has led to widespread exposure in air, water, food, and soil, creating acute and chronic health hazards. Acute toxicity may occur following substantial inhalation, ingestion, or dermal exposure, while repeated or long-term exposure can result in chronic toxic effects. Exposure to pesticides has been linked to diverse toxicological outcomes, including neurotoxicity, mutagenicity, carcinogenicity, teratogenicity, and disruption of the endocrine system [54].

The intensive use of pesticides, combined with effluents from agricultural, industrial, and residential activities, ultimately results in their dissemination into aquatic ecosystems [55]. Through surface runoff, these pesticides reach water bodies, where they can be highly toxic to fish, crabs, lobsters, and turtles [23]. Exposure to pesticides in aquatic organisms results in pronounced oxidative stress and histopathological alterations. Off-target migration of these chemicals contributes to broader environmental pollution, with residues entering the human population through environmental and dietary pathways, potentially causing toxic effects.

The accumulation of pesticide residues and their metabolites in soils may lead to their dispersal via soil, water, and air, or persistence in agricultural produce, creating potential risks to human health [56, 57]. Exposure to these chemicals, whether acute or chronic, poses a significant public health concern, particularly in developing countries. In these countries, the intensive application of synthetic pesticides is primarily motivated by the imperative to maintain food security, as well as the accompanying economic and political considerations

[58]. Exposure to pesticides increases the production of reactive oxygen species (ROS), diminishing antioxidant defences and compromising the cellular ability to mitigate oxidative damage. Underexposure to chemical pesticides has been associated with adverse human health effects, such as carcinogenicity, cytotoxicity, and mutagenicity [59].

3.3. PFASs

Per- and polyfluoroalkyl substances (PFASs) are manufactured chemicals that have recently garnered substantial examination from environmental authorities and the general public due to their widespread distribution and associated health risks [27]. They are persistent synthetic chemicals that resist environmental degradation, often referred to as "forever chemicals." Due to their ability to accumulate in water, soil, and biota, PFASs pose long-term exposure risks. Their extensive contamination in water and wastewater systems represents a major environmental and public health challenge [25]. For example, some PFASs pose significant risks to water sources, and health issues need to be given more consideration.

The ubiquitous occurrence of PFASs constitutes significant environmental and human health challenges. PFASs represent a significant risk to terrestrial and aquatic organisms. In addition, variability in accumulation across trophic levels, influenced by habitat, exposure, and species-specific bioaccumulation, highlights ecological hazards [60]. Exposure to PFASs has been implicated in multiple adverse health outcomes, such as endocrine disruption, immunosuppression, and increased risk of specific cancers. Among these, perfluorooctanoic acid (PFOA) is particularly concerning due to its persistent, bioaccumulative, and widespread use. Also, the U.S. Environmental Protection Agency (EPA) Science Advisory Board has classified PFOA as a possible human carcinogen [61].

3.4. Micro/nanoplastics and nanomaterials

3.4.1. Micro/nanoplastics

Plastic pollution across environmental compartments poses significant risks to biota, ecological integrity, and economic systems [34]. The presence of plastic debris in marine ecosystems disrupts ecological balance and harms aquatic organisms and habitats [62]. The degradation of plastic waste into micro/nanoplastics facilitates environmental and biological interactions. These particles are consumed by organisms spanning multiple trophic levels, including phytoplankton, fish, birds, and mammals, amplifying their toxicity and ecological impact. In contrast, nanoplastics pose a greater hazard due to their small size and high permeability, which facilitate penetration into cells and tissues. Their widespread distribution presents significant risks to human health, including oxidative stress, inflammation, cellular damage, and potential carcinogenic effects [30, 63]. Polystyrene nanoplastics, for example, can cause DNA damage, mutagenic effects, and cytotoxicity [64].

The distribution of micro/nanoplastics in the environment has profound ecological and human health implications [65, 66]. Beyond their inherent toxicity, these particles can facilitate the transport of chemical contaminants and pathogenic organisms. An increasing number of studies highlight the accumulation of micro/nanoplastics in aquatic organisms, plants, and human tissues, raising concerns about the potential health effects of long-term exposure [67, 68]. Resembling certain types of zooplankton and food particles, these plastics are frequently ingested by fish, entering their digestive systems and potentially transferring up the food chain. The potential bioaccumulation of micro/nanoplastics is an emerging issue, and it poses a possible indirect pathway for human exposure through the ingestion of aquatic species [31, 69].

3.4.2. Nanomaterials

Nowadays, the pervasive deployment of nanoparticles unavoidably contributes to their dissemination across environmental compartments, promoting long-term persistence in ecosystems and accumulation within biota [36]. Owing to their unique properties and nanoscale size, nanoparticles can interact with wildlife and humans through multiple pathways [70]. They can infiltrate living organisms via diverse exposure routes, including dietary intake, soil contact, and water. This integration into food webs may induce genotoxic effects and perturb the homeostasis of reactive oxygen species and neutrophil activity [71]. Through interactions with cellular and microbial systems, nanomaterials can exert oxidative, inflammatory, and toxic effects on organisms.

Environmentally, they have the potential to disrupt microbial assemblages, bioaccumulate along trophic levels, and modify biogeochemical nutrient cycles. Processes like bioaccumulation and biosorption govern trophic transmission of nanoparticles in ecological networks. The accumulation of natural or engineered nanoparticles in biological systems can have various harmful effects [72]. Due to their nanoscale dimensions and chemical reactivity, nanoparticles exhibit potentially toxic properties, with their impact contingent on composition and concentration.

Thus, micro/nanoplastics and engineered nanomaterials are emerging pollutants of increasing concern due to their small size, persistence, and capacity to interact with biological systems. They can adsorb and transport toxic chemicals, thereby facilitating their entry into food webs. Upon ingestion or inhalation, micro/nanoplastics, as well as engineered nanomaterials, may elicit oxidative stress, inflammatory responses, and cellular injury. Their widespread distribution and intricate environmental dynamics pose significant threats to ecological systems and human well-being.

4. Remediation strategies

Conventional wastewater treatment processes are generally inadequate for effectively removing CECs before they are discharged into natural ecosystems. While advanced technologies, including biological and nature-based approaches, membrane filtration, and adsorbents, enhance the removal of these contaminants and can also mitigate their constraints in practical use. Additionally, nature-based systems such as constructed wetlands offer a sustainable, low-cost, and efficient treatment approach [73]. Techniques such as adsorption, membrane filtration, and biological degradation show great potential for removing CECs, including PFASs, pesticides, micro/nanoplastics, and PPCPs (Table 1) [3, 53, 55, 74]. Remediation strategies based on physical, chemical, and biological processes have also been implemented to achieve partial or complete removal of micropollutants, e.g., nanoparticles, from impacted ecosystems [36, 75].

4.1. Biological and nature-based approaches

Biological and nature-based approaches harness natural pro-

Table 1. Examples of strategies for the remediation of CECs

Pollutants	Describes	Efficiency	Remarks	Refs.
Per- and polyfluoroalkyl substances (PFASs)	Microalgal-based carbon-encapsulated iron nanoparticles (ME-nFe) Level 15 μg/L (industrial wastewater, landfill leachate)	> 60% PFOA (industrial wastewater, landfill leachate) >90% for medium- and long-chain PFASs	Promising adsorbent for PFAS remediation	[77]
Per- and polyfluoroalkyl substances (PFASs)	Electrocoagulation Landfill leachate Level 42 ± 3 μg/L (PFOS), 38 ± 4 μg/L (PFOA)	66% (PFOS) 28% (PFOA)	Offering practical guidance for PFAS treatment	[78]
Microplastics	Integrated Fixed-film Activated Sludge (IFAS) Membrane BioReactor (MBR) Level 10 mg/L (polyethylene)	> 99% (polyethylene)	Addressing multiple wastewater treatment targets Support sustainable wastewater treatment	[79]
Pharmaceuticals and personal care products (PPCPs)	Vertical flow constructed wetlands (*Phragmites australis* + *Iris pseudacorus*) Filled with expanded clay, mixed with admixtures Level 5 μg/L	> 84% (greywater)	Good performance in removing pollutants	[80]
Polyphenols and pesticides	Hydrochar and biochars (from coffee pulp and husk) Level 10-100 mg/L	Hydrochars ~ 100% (polyphenols) Biochars ~ 75% (pesticides)	Waste-derived chars to serve as sustainable adsorbents	[81]

cesses and organisms to mitigate pollution, restore ecosystems, and promote sustainable environmental management. Among the available treatment methods, biological processes are considered the most eco-friendly and sustainable for removing pollutants from the environment. For instance, constructed wetlands and microalgal-based systems are widely used bioremediation strategies for mitigating CEC pollution. Numerous nature-based solutions (NbS), such as. wetlands, rain gardens, swales, sedimentation ponds, and bioretention or hydrophyte systems—are now being implemented to efficiently treat pollutants [13, 76]. Major removal pathways include sorption, photodegradation, microbial biodegradation, and phytoremediation.

Overall, phytotechnology uses plants to absorb, immobilize, or break down hazardous pollutants present in water, air, and soil [82, 83]. Phytotechnology encompasses various processes, including photodegradation, phytovolatilization, phytotransformation, phytostabilization, and phytoextraction. Phytotechnology integrates several plant-based processes to reduce, degrade, or stabilize harmful pollutants with minimal secondary toxicity. It is highly effective for treating industrial and municipal wastewater in decentralized systems [84, 85]. Aquatic macrophytes are particularly effective in wastewater treatment systems because they grow rapidly, generate substantial biomass, and efficiently absorb and eliminate pollutants through continuous contact with contaminated water.

Typically, constructed wetlands represent one of the most promising NbS for improving water quality and managing CECs in aquatic ecosystems [13]. Constructed wetlands have demonstrated the ability to degrade diverse CECs, encompassing pesticides, PPCPs, endocrine-disrupting chemicals, and other organic pollutants such as polycyclic aromatic hydrocarbons (PAHs) and disinfection by-products [13]. For example, Fig. 3 illustrates the removal mechanisms of pharmaceuticals in constructed wetlands. They integrate natural processes involving vegetation, substrate, and microbial consortia to remediate contaminated water, representing an efficient, sustainable, and environmentally benign treatment system.

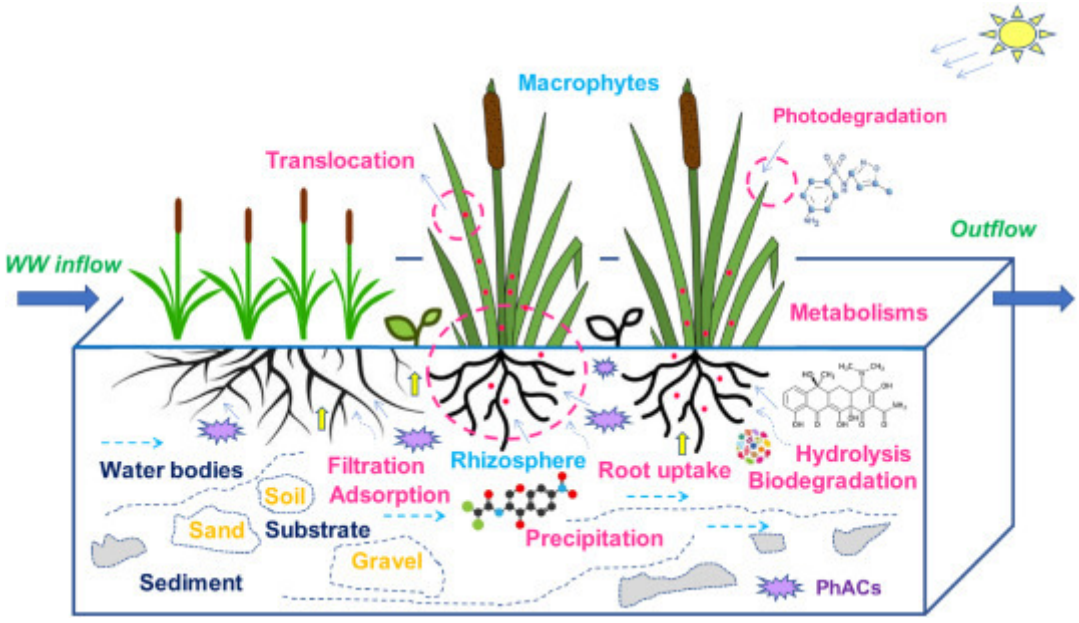

Fig. 3. Main mechanisms of pharmaceutical mitigation in constructed wetlands. Reprinted from *Chemosphere* [18]

These systems are composed of layered materials—including aggregates, soil, gravel, vegetation, and organic matter—that act as filter media for particle removal and provide support for plants [86, 87]. Contaminant removal occurs through natural attenuation, aided by plants and sediments, via mechanisms such as adsorption, absorption, biodegradation, and photolysis. These processes are influenced by hydrology, substrate characteristics, vegetation type, Log(Kow), compound structure and polarity, electron-donating groups, and the content of natural organic matter.

Up to now, constructed wetlands have been shown to achieve moderate to high removal performance for a diverse range of PPCPs, reflecting their potential as effective treatment systems for CECs [3]. Constructed wetland-based technologies provide an effective alternative to conventional treatment methods for removing PPCPs from the environment. Hybrid constructed wetlands systems have demonstrated satisfactory removal of compounds, including ibuprofen, naproxen, caffeine, and propylene glycol. Additionally, recent studies have shown that constructed wetlands can effectively treat wastewater contaminated with CuO nanoparticles, achieving removal efficiencies of 98-99% within a 300-day operational period [88]. These solutions exhibit high pollution removal efficiency, effective contaminant removal, and cost-effectiveness.

Further, microbial bioremediation utilizes fungi, algae, and bacteria to degrade hazardous environmental chemicals, converting them into energy or essential cellular components. *Ascomycete* fungi-based mycoremediation is an emerging approach for eliminating pesticides, PPCPs, and various plastics, including bioplastics [13]. Also, algal systems effectively remove various PPCPs such as antimicrobials, antibiotics, estrogenic hormones, and nonsteroidal anti-inflammatory drugs (NSAIDs) [89]. According to Escapa, et al. [17], *Chlorella sorokiniana* was able to tolerate paracetamol and salicylic acid, removing them with efficiencies of 69% and 98%, respectively. The extracellular molecules produced by microalgae generate hydroxyl radicals, which facilitate CEC degradation through photodegradation and volatilization [90]. Furthermore, enzymatic approaches offer a sustainable and efficient strategy for microplastic degradation, as specific enzymes can recognize and hydrolyze polymer bonds, accelerating the breakdown of plastic materials [34].

4.2. Advanced treatment technologies

Membrane filtration methods, including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), provide an effective means of eliminating PPCPs from wastewater [91, 92]. The NF process for treating PPCP-contaminated water is shown in Fig. 4. For example, the removal of pharmaceutical compounds by NF membranes primarily occurs through electrostatic interactions, steric hindrance, and adsorption processes [3, 53]. The efficiency of elimination varies substantially among individual compounds and is strongly governed by their physicochemical attributes, including hydrophobicity, polarity, solubility, and diffusivity. Remarkably, membrane bioreactor (MBR) systems have achieved removal efficiencies of up to 99% for pharmaceutical contaminants, underscoring their future potential in advanced wastewater treatment [18].

MBRs offer multiple benefits compared to traditional treatment technologies, including a compact design, improved effluent quality with extended solid retention times, higher removal rates of micropollutants, lower food-to-microorganism ratios, reduced sludge thickening, and lower sludge production [93, 94]. For instance, studies have demonstrated that MBRs outperform activated sludge systems, achieving removal efficiencies of 87% for ibuprofen and 56% for naproxen, in contrast to 50% and 6% obtained by conventional treatment, respectively [95]. Furthermore, integration of MF or UF membranes with advanced oxidation or biological treatment processes has demonstrated removal efficiencies exceeding 90% for caffeine [96, 97].

Among these methods, NF and RO generally exhibit higher removal efficiencies for dissolved CECs due to their smaller pore sizes and stronger rejection mechanisms. However, membrane processes often face limitations such as membrane fouling, high operational costs, and the generation of concentrated waste streams [92, 98, 99]. Consequently, membrane filtration is frequently integrated with other treatment technologies to enhance overall CEC removal efficiency. As an example, the use of activated carbon has been tested for CEC

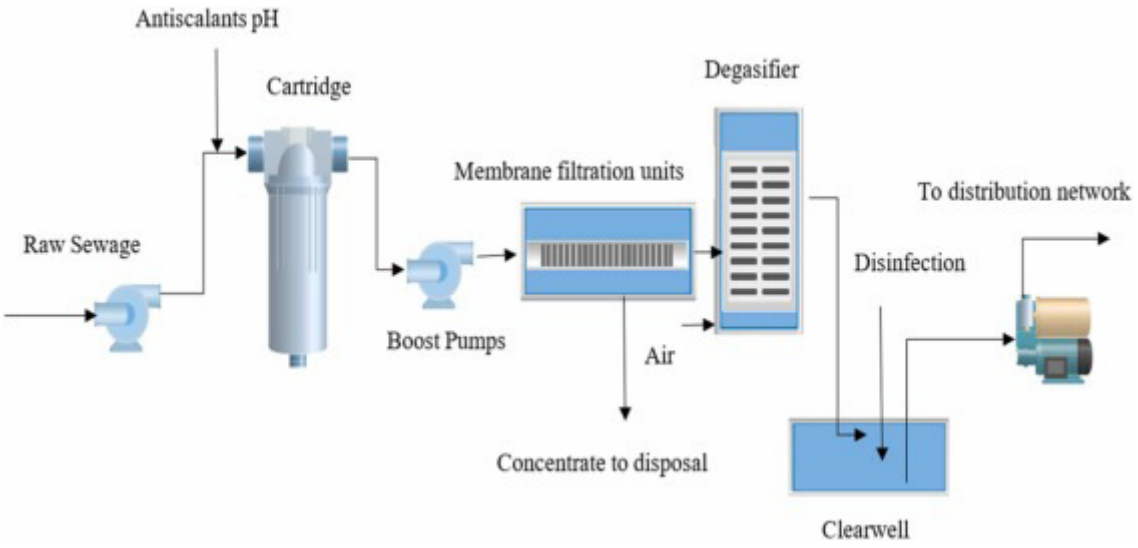

Fig. 4. Wastewater purification using nanofiltration to eliminate PPCPs. Reprinted from *Process Safety and Environmental Protection* [3].

removal, with studies indicating that adsorption onto activated carbon, applied before membrane filtration, can achieve a 90% reduction of pharmaceutical products [100]. Integrating poly aluminium chloride (PAC) adsorption with the physical separation provided by UF has been demonstrated to be an optimal approach for removing pharmaceutical pollutants from water. When integrated with nanotechnology, photocatalysis and advanced oxidation processes (AOPs) offer a promising approach for efficiently eliminating pharmaceutical contaminants from industrial wastewater [13].

Fig. 5 provides a comprehensive diagram of the MBR process employed for microplastic removal, highlighting its ability to capture microplastics and direct them to subsequent treatment stages for effective elimination [53]. The process typically begins with pre-treated streams entering the bioreactor, where organic matter undergoes biodegradation. The resulting mixed liquor is subsequently pumped through a semi-cross-flow filtration system, which separates and concentrates microplastic particles in the retentate.

As shown in Fig. 6, PFAS removal via adsorption involves

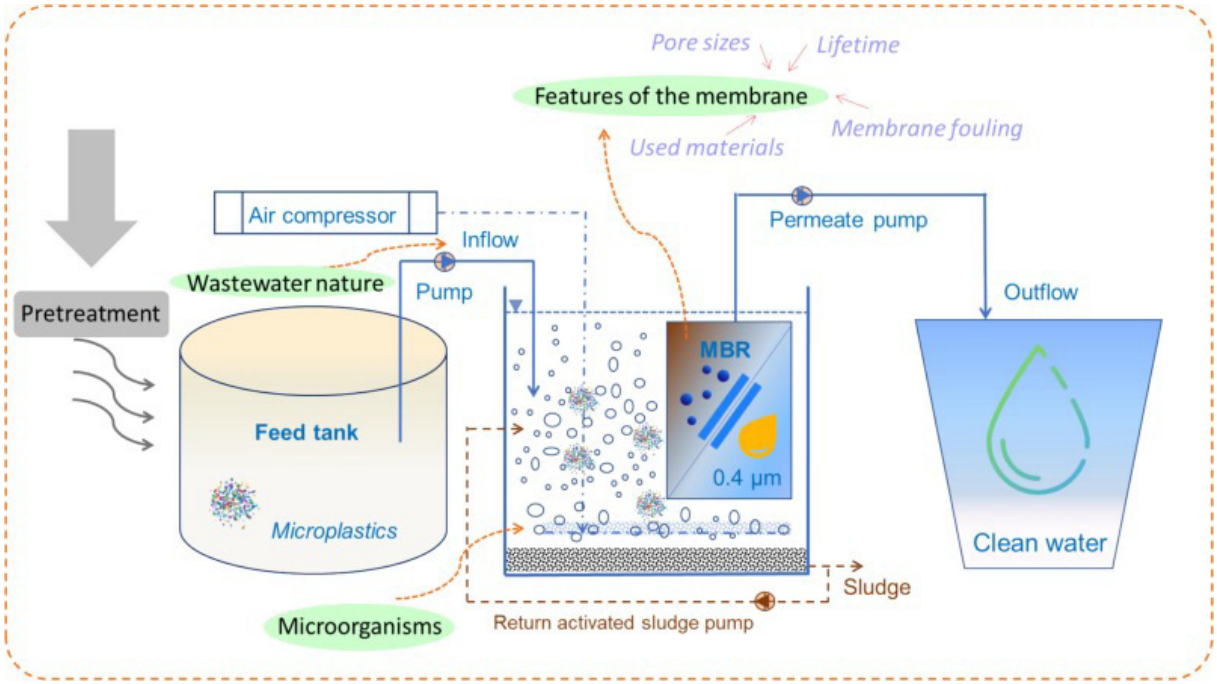

Fig. 5. Illustrative diagram of microplastic removal using a membrane bioreactor (MBR). Reprinted from *Separation and Purification Technology* [53].

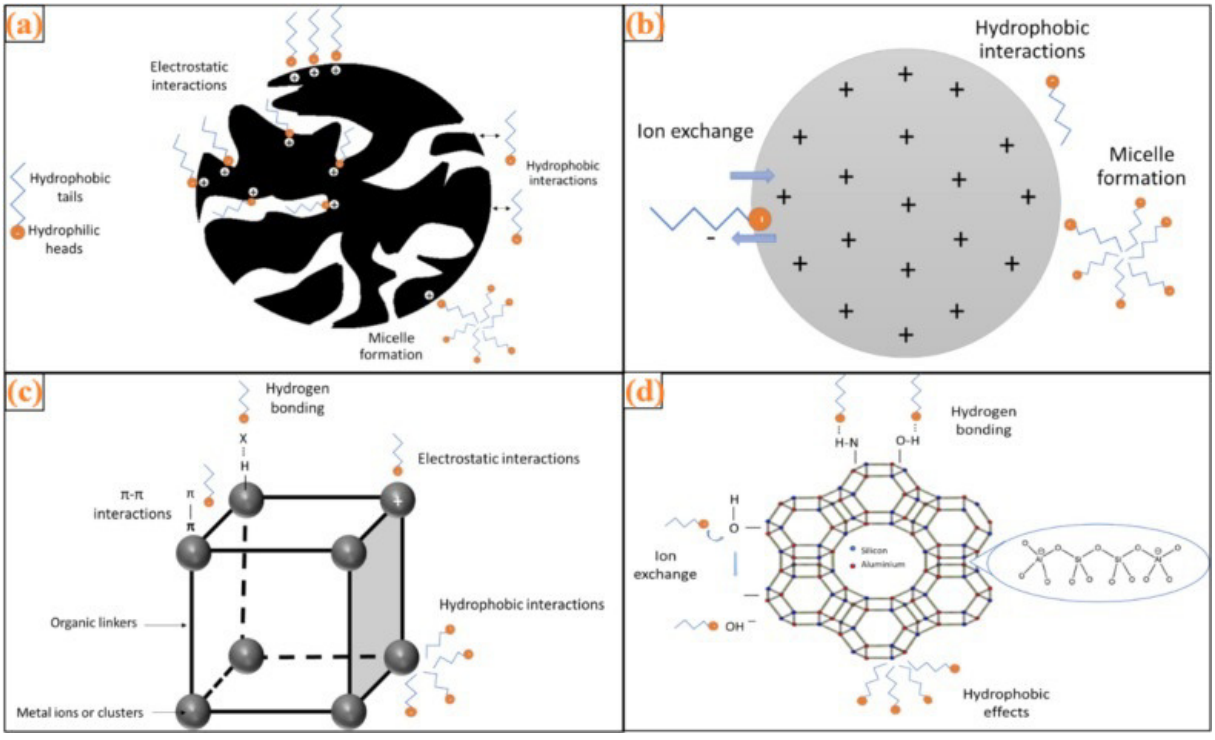

Fig. 6. Mechanisms of PFAS uptake on adsorbents: (a) Activated carbon (AC), (b) Anion exchange resins (AER), (c) Metal-organic frameworks (MOFs), and (d) Zeolite. Reprinted from *Journal of Water Process Engineering* [74].

multiple mechanisms. Specifically, adsorption onto granular activated carbon (GAC) predominantly results from hydrophobic interactions between PFAS molecules and the internal pore surfaces of the carbon. In addition to hydrophobic interactions, secondary electrostatic forces can affect PFAS adsorption, with the net surface charge of the GAC determining whether these forces are attractive or repulsive [74, 101]. Additionally, Chang, et al. [102] demonstrated that MOF-808, a zirconium-based metal–organic framework, exhibits a high specific surface area of 1610 m^2/g, along with a remarkable perfluorooctane sulfonate (PFOS) adsorption capacity of 939 mg/g, optimized at pH levels between 4.1 and 5.4. Engineered photocatalysts, such as heterostructures, metal-doped semiconductors, and metal-organic frameworks, have recently demonstrated mineralization efficiencies exceeding 85% PFASs when exposed to optimized UV light conditions [25]. These engineered materials promote degradation by optimizing light absorption, facilitating charge separation, and generating reactive oxygen species, thereby enabling selective cleavage of C–F bonds with minimal formation of toxic by-products.

For the effective mitigation of pesticide pollution, it is recommended to employ a synergistic approach that combines various advanced treatment methods, thereby enhancing overall contaminant removal efficiency [55]. From a broader perspective, electrochemical technologies, such as electrochemical oxidation, anodic oxidation, electrocoagulation, and electro-Fenton processes, are extensively employed for the degradation of pesticides [103-105]. In electro-Fenton processes, H_2O_2 is first produced in situ from O_2 via the electrochemical oxygen reduction reaction, followed by its activation to generate highly reactive •OH and $•O_2^-$ radicals. These reactive species effectively decompose organic contaminants and pesticide residues in aqueous systems [55, 106]. Nevertheless, these approaches demand significant electrical input to sustain electrochemical reactions, resulting in high energy consumption. Thus, it needs to be further investigated, as they provide a greener and more cost-effective alternative by generating electricity within the system itself, which can then be utilized for contaminant degradation.

It can be seen that advanced treatment technologies, including adsorption, advanced oxidation processes, and membrane filtration, have been increasingly applied to remove persistent pollutants such as PFASs, micro/nanoplastics, and PPCPs (pesticides). These technologies target the degradation or separation of resistant contaminants that conventional treatments fail to eliminate. However, challenges remain regarding energy consumption, cost, and the formation of transformation by-products.

5. Research gaps and future directions

Despite growing attention to CECs in environmental systems, significant knowledge gaps remain regarding their sources, environmental behavior, ecological impacts, and effective mitigation strategies.

1. The presence of CECs in ecosystems such as aquatic systems or agriculture is an escalating worldwide challenge for food safety and public health protection. For instance, these contaminants —including pharmaceuticals, micro/nanoplastics, engineered nanomaterials, pesticides, and PFASs—enter agricultural soils through diverse pathways linked to various pollution sources, from wastewater discharge to waste-derived inputs. Evidence indicates that CECs pose multifaceted risks, including the emergence of antimicrobial resistance and sublethal impacts on plant and soil ecosystems, while critical knowledge gaps persist [107]. These findings emphasize the urgent need for coordinated regulatory strategies and sustainable practices to mitigate contamination at its source.

2. Despite increasing detection of CECs in natural systems, their long-term environmental fate, transformation pathways, and transport mechanisms in soil–plant–water systems remain poorly understood [108]. Future studies should focus on integrated monitoring and modeling approaches to better elucidate the persistence, mobility, and accumulation of CECs across different ecosystems.

3. The analytical detection and quantification of CECs in environmental matrices remain challenging due to their low concentrations, diverse chemical properties, and complex environmental matrices [12, 109]. Further work should prioritize the development of standardized, sensitive, and cost-effective analytical techniques to improve environmental monitoring and risk assessment.

4. Most existing studies assess the individual toxicity of CECs, whereas real-world conditions often involve complex mixtures of pharmaceuticals, microplastics, PFASs, and nanomaterials across aquatic and terrestrial environments. Future research should investigate their synergistic, antagonistic, and chronic sublethal effects on soil and aquatic microorganisms, plant physiology, ecosystem functioning, biodiversity, and potential implications for food safety and human health.

5. Recent advances in nanomaterial development have increasingly considered the possibility of material reuse and regeneration as an approach to improve sustainability and reduce operational costs. However, the associated technologies remain relatively immature and are still largely confined to laboratory or pilot-scale studies. Issues, including high manufacturing costs, scale-up challenges, and regulatory limitations, hinder broader application [110]. In addition, the long-term environmental implications of reused nanomaterials require further investigation. Therefore, it is needed to develop more reliable and scalable strategies for the effective reuse of nanomaterials in practical applications.

6. CECs frequently exhibit high mobility in aquatic and soil environments, facilitating their widespread distribution across environmental compartments [108, 111]. This mobility increases the risk of contaminant transport through water systems and soil–plant pathways. Therefore, effective countermeasures addressing this challenge should be incorporated into the remediation strategies section. Also, although various remediation technologies have been proposed (e.g., adsorption materials, advanced oxidation, and nature-based systems), their effectiveness, scalability, and long-term sustainability in environments are still uncertain. Emerging investigations should emphasize integrated remediation approaches, including bio-based materials, phytoremediation, and nature-based solutions, to reduce CEC contamination at its source and within ecosystems.

6. Conclusions

CECs are predominantly anthropogenic compounds that occur in aquatic environments at trace levels and are often over-

looked. These substances originate from various human and industrial activities, posing significant risks to human health and ecological integrity. Addressing the transport and removal of CECs within ecosystems remains a complex and persistent challenge for both developed and developing nations, underscoring the global nature of this issue.

While advanced oxidation, membrane filtration, and activated carbon adsorption effectively remove many pollutants, NbS are gaining increasing attention. Constructed wetlands, in particular, show high efficiency and cost-effectiveness in eliminating CECs. Yet, research gaps remain in evaluating the cost, scalability, and long-term performance of methods for removing CECs. Future studies should integrate cost and scalability analyses to help policymakers choose between NbS and advanced technologies, enabling more sustainable and practical large-scale CEC mitigation strategies. Implementing appropriate regulations, providing adequate training, and enhancing public education can help mitigate the adverse impacts of CECs while promoting safer and more sustainable agricultural practices. In addition, to achieve high performance, it is essential to explore green, eco-friendly chemicals that are low-persistent, minimally bioaccumulative, non-toxic, and environmentally compatible.

Acknowledgements

This work was partly funded by the Vietnam National Foundation for Science and Technology Development (NAFOSTED) under Grant No. 105.08-2025.29 and by Nong Lam University of Ho Chi Minh City (Code: CS-CB25-PHGL-01).

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Hernandez-Maldonado, A., and Blaney, L. (2019). Contaminants of emerging concern in water and wastewater: advanced treatment processes, (Butterworth-Heinemann).

[2] Krzeminski, P.; Tomei, M. C., Karaolia, P.; Langenhoff, A.; Almeida, C. M. R., Felis, E.; Gritten, F.; Andersen, H. R., Fernandes, T.; Manaia, C. M., et al. Performance of secondary wastewater treatment methods for the removal of contaminants of emerging concern implicated in crop uptake and antibiotic resistance spread: A review. *Sci. Total Environ.*, 2019, 648: 1052–1081.

[3] AL Falahi, O. A., Abdullah, S. R. S., Abu Hasan, H.; Othman, A. R., Ewadh, H. M., Kurniawan, S. B., Imron, M. F. Occurrence of pharmaceuticals and personal care products in domestic wastewater, available treatment technologies, and potential treatment using constructed wetland: A review. *Process. Saf. Environ. Prot.*, 2022, 168: 1067–1088.

[4] Neculita, C. M.; Coudert, L.; Rosa, E.; Mulligan, C. N. Future prospects for treating contaminants of emerging concern in water and soils/sediments. *Advanced Nano-Bio Technologies for Water and Soil Treatment*. Cham: Springer International Publishing, 2020, 589–605.

[5] Zhang, S. Y.; Gitungo, S.; Dyksen, J. E., Raczko, R. F., Axe, L. Indicator compounds representative of contaminants of emerging concern (CECs) found in the water cycle in the United States. *Int. J. Environ. Res. Public Health*, 2021, 18: 1288.

[6] Hayouni, W.; Pistre, S.; Chkir, N.; Zouari, K. Contaminants of emerging concern (CECs) as indicators of pollution and hydrological processes in an anthropized Mediterranean water basin: Case of the Kasserine Basin (Central Tunisia). *Sci. Total Environ.*, 2025, 984: 179744.

[7] Golovko, O.; Örn, S.; Sörengård, M.; Frieberg, K.; Nassazzi, W.; Lai, F. Y.; Ahrens, L. Occurrence and removal of chemicals of emerging concern in wastewater treatment plants and their impact on receiving water systems. *Sci. Total Environ.*, 2021, 754: 142122.

[8] Ahmad, A.; Kurniawan, S. B., Abdullah, S. R. S., Othman, A. R., Abu Hasan, H. Contaminants of emerging concern (CECs) in aquaculture effluent: Insight into breeding and rearing activities, alarming impacts, regulations, performance of wastewater treatment unit and future approaches. *Chemosphere*, 2022, 290: 133319.

[9] Nguyen, M. K.; Lin, C.; Nguyen, D. D. Microplastic pollution associated with probabilistic human health risks: Potential hazards, critical factors, challenges, and limitations. *Mar. Pollut. Bull.*, 2025, 221: 118528.

[10] Nguyen, M. K.; Lin, C.; Nguyen, H. L.; Hung, N. T. Q., La, D. D., Nguyen, X. H., Chang, S. W., Chung, W. J., Nguyen, D. D. Occurrence, fate, and potential risk of pharmaceutical pollutants in agriculture: Challenges and environmentally friendly solutions. *Sci. Total Environ.*, 2023, 899: 165323.

[11] Koumaki, E.; Konomi, A.; Gkotsis, G.; Nika, M. C.; Seintos, T.; Stati-ris, E.; Maragou, N.; Thomaidis, N. S.; Kouris, N.; Mamais, D. et al. Circular water management in agriculture: Screening of contaminants of emerging concern in a real-world water-soil-crop system and human health risk assessment. *J. Hazard. Mater.*, 2025, 492: 138167.

[12] Li, X. Y.; Shen, X. J.; Jiang, W. W.; Xi, Y. K.; Li, S. Comprehensive review of emerging contaminants: Detection technologies, environmental impact, and management strategies. *Ecotoxicol. Environ. Saf.*, 2024, 278: 116420.

[13] Harish, H.; Jegatheesan, V. A review of sources, worldwide legislative measures and the factors influencing the treatment technologies for contaminants of emerging concern (CECs). *Curr. Pollut. Rep.*, 2025, 11: 44.

[14] Feng, W. Y.; Deng, Y. X.; Yang, F.; Miao, Q. F.; Ngien, S. K. Systematic review of contaminants of emerging concern (CECs): Distribution, risks, and implications for water quality and health. *Water*, 2023, 15: 3922.

[15] Keerthanan, S.; Jayasinghe, C.; Biswas, J. K., Vithanage, M. Pharmaceutical and Personal Care Products (PPCPs) in the environment: Plant uptake, translocation, bioaccumulation, and human health risks. *Crit. Rev. Environ. Sci. Technol.*, 2021, 51: 1221–1258.

[16] Evgenidou, E. N., Konstantinou, I. K., Lambropoulou, D. A. Occurrence and removal of transformation products of PPCPs and illicit drugs in wastewaters: A review. *Sci. Total Environ.*, 2015, 505: 905–926.

[17] Escapa, C.; Coimbra, R. N., Paniagua, S.; García, A. I., Otero, M. Paracetamol and salicylic acid removal from contaminated water by microalgae. *J. Environ. Manage.*, 2017, 203: 799–806.

[18] Nguyen, M. K.; Lin, C.; Bui, X. T.; Rakib, M. R. J., Nguyen, H. L.; Truong, Q. M.; Hoang, H. G.; Tran, H. T.; Malafaia, G.; Idris, A. M. Occurrence and fate of pharmaceutical pollutants in wastewater: Insights on ecotoxicity, health risk, and state–of–the-art removal. *Chemosphere*, 2024, 354: 141678.

[19] Bai, X. L.; Lutz, A.; Carroll, R.; Keteles, K.; Dahlin, K.; Murphy, M.; Nguyen, D. Occurrence, distribution, and seasonality of emerging contaminants in urban watersheds. *Chemosphere*, 2018, 200: 133–142.

[20] Adeoye, J. B., Tan, Y. H., Lau, S. Y., Tan, Y. Y., Chiong, T.; Mubarak, N. M., Khalid, M. Advanced oxidation and biological integrated

processes for pharmaceutical wastewater treatment: A review. *J. Environ. Manag.*, 2024, 353: 120170.

[21] Tudi, M.; Daniel Ruan, H.; Wang, L.; Lyu, J.; Sadler, R.; Connell, D.; Chu, C.; Phung, D. T. Agriculture development, pesticide application and its impact on the environment. *Int. J. Environ. Res. Public Health*, 2021, 18: 1112.

[22] FAO (2025). Pesticides use and trade – 1990–2023. In No. 109, Volume 109, F.A. Briefs, ed. (Rome: FAOSTAT Analytical Briefs).

[23] Ahamad, A.; Kumar, J. Pyrethroid pesticides: An overview on classification, toxicological assessment and monitoring. *J. Hazard. Mater. Adv.*, 2023, 10: 100284.

[24] Carter, A. How pesticides get into water - and proposed reduction measures. *Pest. Outlook*, 2000, 11: 149–156.

[25] Le, V. G.; Nguyen, M. K., Luu, T. A.; Nguyen, P. H., Dang, V. D., Pham, M. T.; Kim, S. S., Um, M. J.; Nguyen, D. D. Advanced functional materials for photocatalytic removal of PFASs from water and wastewater: Progress toward sustainable development goals (SDGs). *J. Water Process. Eng.*, 2025, 77: 108403.

[26] Ackerman Grunfeld, D.; Gilbert, D.; Hou, J.; Jones, A. M., Lee, M. J., Kibbey, T. C. G., O'Carroll, D. M. Underestimated burden of per- and polyfluoroalkyl substances in global surface waters and groundwaters. *Nat. Geosci.*, 2024, 17: 340–346.

[27] Ehsan, M. N., Riza, M.; Pervez, M. N., Khyum, M. M. O., Liang, Y. N.; Naddeo, V. Environmental and health impacts of PFAS: Sources, distribution and sustainable management in North Carolina (USA). *Sci. Total Environ.*, 2023, 878: 163123.

[28] Glüge, J.; Scheringer, M.; Cousins, I. T., DeWitt, J. C., Goldenman, G.; Herzke, D.; Lohmann, R.; Ng, C. A., Trier, X.; Wang, Z. Y. An overview of the uses of per- and polyfluoroalkyl substances (PFAS). *Environ. Sci.: Processes Impacts*, 2020, 22: 2345–2373.

[29] Dasu, K.; Xia, X. Y.; Siriwardena, D.; Klupinski, T. P., Seay, B. Concentration profiles of per- and polyfluoroalkyl substances in major sources to the environment. *J. Environ. Manag.*, 2022, 301: 113879.

[30] Kochanek, A.; Grąz, K.; Potok, H.; Gronba-Chyła, A.; Kwaśny, J.; Wiewiórska, I.; Ciuła, J.; Basta, E.; Łapiński, J. Micro- and nanoplastics in the environment: Current state of research, sources of origin, health risks, and regulations—a comprehensive review. *Toxics*, 2025, 13: 564.

[31] Nguyen, M. K.; Lin, C.; Nguyen, H. L.; Le, V. G.; Haddout, S.; Um, M. J.; Chang, S. W., Nguyen, D. D. Ecotoxicity of micro- and nanoplastics on aquatic algae: Facts, challenges, and future opportunities. *J. Environ. Manag.*, 2023, 346: 118982.

[32] Allen, S.; Allen, D.; Karbalaei, S.; Maselli, V.; Walker, T. R. Micro(nano)plastics sources, fate, and effects: What we know after ten years of research. *J. Hazard. Mater. Adv.*, 2022, 6: 100057.

[33] Kiran, B. R., Kopperi, H.; Venkata Mohan, S. Micro/nano-plastics occurrence, identification, risk analysisandmitigation: Challenges and perspectives. *Rev. Environ. Sci. Bio/Technol.*, 2022, 21: 169–203.

[34] Cárdenas-Alcaide, M. F., Godínez-Alemán, J. A., González-González, R. B., Iqbal, H. M. N., Parra-Saldívar, R. Environmental impact and mitigation of micro(nano)plastics pollution using green catalytic tools and green analytical methods. *Green Anal. Chem.*, 2022, 3: 100031.

[35] Kan, M. Q.; Miller, S. A. Environmental impacts of plastic packaging of food products. *Resour. Conserv. Recycl.*, 2022, 180: 106156.

[36] Tran, T. K.; Nguyen, M. K.; Lin, C.; Hoang, T. D.; Nguyen, T. C.; Lone, A. M., Khedulkar, A. P., Gaballah, M. S., Singh, J.; Chung, W. J., et al. Review on fate, transport, toxicity and health risk of nanoparticles in natural ecosystems: Emerging challenges in the modern age and solutions toward a sustainable environment. *Sci. Total Environ.*, 2024, 912: 169331.

[37] Mahbub, T.; Hoque, M. E. Introduction to nanomaterials and nanomanufacturing for nanosensors. *Nanofabrication for Smart Nanosensor Applications*. Amsterdam: Elsevier, 2020, 1–20.

[38] Gupta, P.K. (2025). Chapter 2 - Sources, synthesis, and classification of nanomaterials. In Nanotechnology of Veterinary Medicine and Livestock Production, P.K. Gupta, ed. (Academic Press), pp. 25-55.

[39] Khedulkar, A. P., Bobade, R. G., Doong, R. A.; Pandit, B.; Ky, N. M., Ambare, R. C., Hoang, T. D.; Kumar, K. J. Bio-based nanomaterials as effective, friendly solutions and their applications for protecting water, soil, and air. *Mater. Today Chem.*, 2025, 46: 102688.

[40] Previšić, A.; Rožman, M.; Mor, J. R.; Acuña, V.; Serra-Compte, A.; Petrović, M.; Sabater, S. Aquatic macroinvertebrates under stress: Bioaccumulation of emerging contaminants and metabolomics implications. *Sci. Total Environ.*, 2020, 704: 135333.

[41] Pastorino, P.; Ginebreda, A. Contaminants of emerging concern (CECs): Occurrence and fate in aquatic ecosystems. *Int. J. Environ. Res. Public Health*, 2021, 18: 13401.

[42] Naseem, A.; Alneghery, L. M., Al-Zharani, M.; Nasr, F. A., Jawad, S. S., Umer, M.; Sayyed, R.; Ilyas, N. An insight into the impacts of pharmaceutical pollutants on the ecosystem and the potential role of bioremediation in mitigating pharmaceutical pollutants. *Int. J. Pharm.*, 2025, 680: 125791.

[43] Belle, G.; Moodley, B.; Moodley, R.; Omotola, E. O., Truter, C.; Olatunji, O.; Oberholster, P. Occurrence and detection of selected pharmaceuticals of emerging concern: Potential risks for aquatic ecosystems and human health. *Discov. Appl. Sci.*, 2025, 7: 1078.

[44] Kalaji, H.M., and Rastogi, A. (2017). Pharmaceutical compounds: an emerging pollutant (a review on plant-pharmaceuticals interaction). Chiang Mai J Sci *44*, 287-297.

[45] Santos, L. H. M. L. M., Araújo, A. N., Fachini, A.; Pena, A.; Delerue-Matos, C.; Montenegro, M. C. B. S. M. Ecotoxicological aspects related to the presence of pharmaceuticals in the aquatic environment. *J. Hazard. Mater.*, 2010, 175: 45–95.

[46] Srain, H. S.; Beazley, K. F.; Walker, T. R. Pharmaceuticals and personal care products and their sublethal and lethal effects in aquatic organisms. *Environ. Rev.*, 2021, 29: 142–181.

[47] Overturf, M. D., Anderson, J. C., Pandelides, Z.; Beyger, L.; Holdway, D. A. Pharmaceuticals and personal care products: A critical review of the impacts on fish reproduction. *Crit. Rev. Toxicol.*, 2015, 45: 469–491.

[48] Macherius, A.; Eggen, T.; Lorenz, W. G., Reemtsma, T.; Winkler, U.; Moeder, M. Uptake of galaxolide, tonalide, and triclosan by carrot, barley, and meadow fescue plants. *J. Agric. Food Chem.*, 2012, 60(32): 7785–7791.

[49] Ribeiro, A. R., Sures, B.; Schmidt, T. C. Ecotoxicity of the two veterinarian antibiotics ceftiofur and cefapirin before and after photo-transformation. *Sci. Total Environ.*, 2018, 619: 866–873.

[50] Christou, A.; Antoniou, C.; Christodoulou, C.; Hapeshi, E.; Stavrou, I.; Michael, C.; Fatta-Kassinos, D.; Fotopoulos, V. Stress-related phenomena and detoxification mechanisms induced by common pharmaceuticals in alfalfa (Medicago sativa L. *) plants. Sci. Total Environ.*, 2016, 557: 652–664.

[51] Sun, C. L.; Dudley, S.; Trumble, J.; Gan, J. Pharmaceutical and personal care products-induced stress symptoms and detoxification mechanisms in cucumber plants. *Environ. Pollut.*, 2018, 234: 39–47.

[52] Khan, H.K., Rehman, M.Y.A., and Malik, R.N. (2020). Fate and toxicity of pharmaceuticals in water environment: An insight on their occurrence in South Asia. Journal of Environmental Management *271*, 111030.

[53] Nguyen, D.; Nguyen, M. K.; Truong, Q. M.; Thai, V. A.; Pham, M. T.; Woong Chang, S.; Nguyen, D. D. Microplastics and pharmaceut-

icals from water and wastewater: Occurrence, impacts, and membrane bioreactor-based removal. *Sep. Purif. Technol.*, 2025, 361: 131489.

[54] Kumar, V.; Sharma, N.; Sharma, P.; Pasrija, R.; Kaur, K.; Umesh, M.; Thazeem, B. Toxicity analysis of endocrine disrupting pesticides on non-target organisms: A critical analysis on toxicity mechanisms. *Toxicol. Appl. Pharmacol.*, 2023, 474, 116623.

[55] AbuQamar, S. F., El-Saadony, M. T., Alkafaas, S. S., Elsalahaty, M. I., Elkafas, S. S., Mathew, B. T., Aljasmi, A. N., Alhammadi, H. S., Salem, H. M., Abd El-Mageed, T. A., et al. Ecological impacts and management strategies of pesticide pollution on aquatic life and human beings. *Mar. Pollut. Bull.*, 2024, 206: 116613.

[56] Pathak, V. M.; Verma, V. K.; Rawat, B. S.; Kaur, B.; Babu, N.; Sharma, A.; Dewali, S.; Yadav, M.; Kumari, R.; Singh, S. et al. Current status of pesticide effects on environment, human health and it's eco-friendly management as bioremediation: A comprehensive review. *Front. Microbiol.*, 2022, 13: 962619.

[57] Bhandari, G.; Atreya, K.; Scheepers, P. T. J.; Geissen, V. Concentration and distribution of pesticide residues in soil: Non-dietary human health risk assessment. *Chemosphere*, 2020, 253: 126594.

[58] Lebelo, K.; Malebo, N.; Mochane, M. J.; Masinde, M. Chemical contamination pathways and the food safety implications along the various stages of food production: A review. *Int. J. Environ. Res. Public Health*, 2021, 18: 5795.

[59] Fang, L.; Liao, X. F.; Jia, B. Y.; Shi, L. C.; Kang, L. Z.; Zhou, L. D.; Kong, W. J. Recent progress in immunosensors for pesticides. *Biosens. Bioelectron.*, 2020, 164: 112255.

[60] Ahrens, L.; Bundschuh, M. Fate and effects of poly- and perfluoroalkyl substances in the aquatic environment: A review. *Environ. Toxicol. Chem.*, 2014, 33: 1921–1929.

[61] Hogue, C. (2005). PFOA called likely human carcinogen. Chem. Eng. News *83*, 5.

[62] Nguyen, M. K.; Walker, T. R., Lin, C.; Nguyen, D.; Kim, S. S., Chung, W.; Nguyen, D. D. Emerging challenges of microplastic impacts to ecological health and climate change. *Mar. Pollut. Bull.*, 2026, 222: 118778.

[63] Nguyen, M. K.; Lin, C.; Nguyen, H. L.; Le, V. R.; Kl, P.; Singh, J.; Chang, S. W., Um, M. J.; Nguyen, D. D. Emergence of microplastics in the aquatic ecosystem and their potential effects on health risks: The insights into Vietnam. *J. Environ. Manag.*, 2023, 344: 118499.

[64] Gupta, C.; Kaushik, S.; Himanshu, Jain, S.; Dhanwani, I.; Mansi, Garg, S.; Paul, A.; Pant, P.; Gupta, N. Bioaccumulation and toxicity of polystyrene nanoplastics on marine and terrestrial organisms with possible remediation strategies: A review. *Environ. Adv.*, 2022, 8: 100227.

[65] Le, V. G.; Nguyen, M. K.; Nguyen, H. L.; Lin, C.; Hadi, M.; Hung, N. T. Q., Hoang, H. G.; Nguyen, K. N., Tran, H. T.; Hou, D. Y. et al. A comprehensive review of micro- and nano-plastics in the atmosphere: Occurrence, fate, toxicity, and strategies for risk reduction. *Sci. Total Environ.*, 2023, 904: 166649.

[66] Shukla, S.; Khanna, S.; Khanna, K. Unveiling the toxicity of micro-nanoplastics: A systematic exploration of understanding environmental and health implications. *Toxicol. Rep.*, 2025, 14: 101844.

[67] Winiarska, E.; Jutel, M.; Zemelka-Wiacek, M. The potential impact of nano- and microplastics on human health: Understanding human health risks. *Environ. Res.*, 2024, 251: 118535.

[68] Nouri, M.; Massahi, T.; Hossini, H. Microplastics in human body: A narrative on routes of exposure to contamination and potential health effects. *Environ. Pollut. Bioavailab.*, 2025, 37: 2538535.

[69] Qaiser, N.; Sidra, S.; Javid, A.; Iqbal, A.; Amjad, M.; Azmat, H.; Arooj, F.; Farooq, K.; Nimra, A.; Ali, Z. Microplastics abundance in abiotic and biotic components along aquatic food chain in two freshwater ecosystems of Pakistan. *Chemosphere*, 2023, 313: 137177.

[70] Singh, S. Adverse effects of nanoparticles on human health and the environment. *Antiviral and Antimicrobial Coatings Based on Functionalized Nanomaterials*. Amsterdam: Elsevier, 2023, 305–330.

[71] Maharramov, A. M., Hasanova, U. A., Suleymanova, I. A., Osmanova, G. E., Hajiyeva, N. E. The engineered nanoparticles in food chain: Potential toxicity and effects. *SN Appl. Sci.*, 2019, 1: 1362.

[72] Sharma, S.; Shree, B.; Aditika, Sharma, A.; Irfan, M.; Kumar, P. Nanoparticle-based toxicity in perishable vegetable crops: Molecular insights, impact on human health and mitigation strategies for sustainable cultivation. *Environ. Res.*, 2022, 212: 113168.

[73] Overton, O. C., Olson, L. H., Das Majumder, S.; Shwiyyat, H.; Foltz, M. E., Nairn, R. W. Wetland removal mechanisms for emerging contaminants. *Land*, 2023, 12: 472.

[74] Sanzana, S.; Fenti, A.; Iovino, P.; Panico, A. A review of PFAS remediation: Separation and degradation technologies for water and wastewater treatment. *J. Water Process. Eng.*, 2025, 74: 107793.

[75] Mahmoud, M. E., Amira, M. F., Daniele, S.; Abouelanwar, M. E., Morcos, B. M. Synthesis of ferrofluid DAA-Glu COF@Aminated alginate/Psyllium hydrogel nanocomposite for effective removal of polymethyl methacrylate nanoparticles and silver quantum dots pollutants. *J. Taiwa Inst. Chem. Eng.*, 2023, 146: 104793.

[76] Hoang, V. H.; Nguyen, M. K.; Hoang, T. D.; Nguyen, H. L.; Lin, C.; Yousaf, B.; Ha, M. C., Bui, V. K. H., Pham, M. T.; Chang, S. W., et al. Global occurrence and environmental fate of microplastics in stormwater runoff: Unlock the in-depth knowledge on nature-based removal strategies. *Rev. Environ. Contam. Toxicol.*, 2025, 263: 5.

[77] Sforza, E. B.; Valsecchi, S.; Mariani, C.; Platini, S.; Collina, E.; Mezzanotte, V.; Mantovani, M. Microalgal-based carbon encapsulated iron nanoparticles as novel adsorbents for PFAS removal: From dye proxies to target compounds. *J. Environ. Chem. Eng.*, 2026, 14: 122508.

[78] Shaker, O. A.; Berhe, R. N.; Li, Y. N.; Suehring, R.; Dagnew, M. Electrocoagulation of landfill leachate: Unravelling the fate and mechanisms of PFAS removal under various operating conditions. *J. Water Process. Eng.*, 2026, 86: 109763.

[79] Carnesi, M.; Mineo, A.; Amata, S.; Piccionello, A. P.; Rizzo, C.; Mannina, G. Emerging contaminants in wastewater treatment: The effect of microplastics in an Integrated Fixed-film Activated Sludge (IFAS) Membrane BioReactor (MBR). *Bioresour. Technol. Rep.*, 2025, 32: 102374.

[80] Muniz Sacco, F. C.; Venditti, S.; Carvalho, P. N.; Kisielius, V.; Wilmes, P.; Steinmetz, H.; Hansen, J. Removal pathways of pharmaceuticals and personal care products within vertical flow constructed wetlands as a decentralized greywater treatment. *Bioresour. Technol.*, 2026, 448: 134326.

[81] Mukarunyana, B.; Sundberg, C.; Boman, C.; Kabera, T.; Fick, J. Coffee pulp and husk-derived hydrochars and biochars adsorb polyphenols and pesticides from wastewater. *Environ. Technol. Innov.*, 2026, 41: 104739.

[82] Rana, V.; Maiti, S. K. Municipal and industrial wastewater treatment using constructed wetlands. *Phytoremediation*. Cham: Springer International Publishing, 2020, 329–367.

[83] Nguyen, M. K.; Hung, N. T. Q.; Nguyen, C. M.; Lin, C.; Nguyen, T. A.; Nguyen, H. L. Application of vetiver grass (Vetiveria Zizanioides L.) for organic matter removal from contaminated surface water. *Bioresour. Technol. Rep.*, 2023, 22: 101431.

[84] Daverey, A.; Pandey, D.; Verma, P.; Verma, S.; Shah, V.; Dutta, K.; Arunachalam, K. Recent advances in energy efficient biological treatment of municipal wastewater. *Bioresour. Technol. Rep.*,

2019, 7: 100252.
[85] Nguyen Minh, K. Y.; Hung, N. T. Q.; Manh, N. C.; Lap, B. Q.; Dang, H. T. T.; Ozaki, A. Assessment of nutrients removal by constructed wetlands using reed grass (phragmites australis L.) and vetiver grass (vetiveria zizanioides L.). *J. Fac. Agric. Kyushu Univ.*, 2020, 65: 149–156.
[86] Kataki, S.; Chatterjee, S.; Vairale, M. G., Dwivedi, S. K., Gupta, D. K. Constructed wetland, an eco-technology for wastewater treatment: A review on types of wastewater treated and components of the technology (macrophyte, biolfilm and substrate). *J. Environ. Manag.*, 2021, 283: 111986.
[87] Wu, H. M.; Wang, R. G.; Yan, P. H.; Wu, S. B.; Chen, Z. B.; Zhao, Y. Q.; Cheng, C.; Hu, Z.; Zhuang, L. L.; Guo, Z. Z. et al. Constructed wetlands for pollution control. *Nat. Rev. Earth Environ.*, 2023, 4: 218–234.
[88] Yan, C. N.; Li, X.; Huang, J.; Cao, C.; Ji, X. Y.; Qian, X. W.; Wei, Z. H. Long-term synergic removal performance of N, P, and CuO nanoparticles in constructed wetlands along with temporal record of Cu pollution in substrate-biofilm. *Environ. Pollut.*, 2023, 322: 121231.
[89] Wang, Y. H.; Liu, J. Z.; Kang, D.; Wu, C. X.; Wu, Y. H. Removal of pharmaceuticals and personal care products from wastewater using algae-based technologies: A review. *Rev. Environ. Sci. Bio/Technol.*, 2017, 16: 717–735.
[90] Ge, L. Y.; Deng, H. H.; Wu, F.; Deng, N. S. Microalgae-promoted photodegradation of two endocrine disrupters in aqueous solutions. *J. Chem. Technol. Biotechnol.*, 2009, 84: 331–336.
[91] Oussadou, S. E., Backer, S. N., Almanassra, I. W., Shabib, A.; Ali Atieh, M.; Shanableh, A. Nanofiltration membranes for efficient removal of pharmaceuticals from wastewater: A state-of-the-art review. *Clean. Water*, 2025, 4: 100100.
[92] García-Ávila, F.; Zambrano-Jaramillo, A.; Velecela-Garay, C.; Coronel-Sánchez, K.; Valdiviezo-Gonzales, L. Effectiveness of membrane technologies in removing emerging contaminants from wastewater: Reverse Osmosis and Nanofiltration. *Water Cycle*, 2025, 6: 357–373.
[93] Le-Clech, P. Membrane bioreactors and their uses in wastewater treatments. *Appl. Microbiol. Biotechnol.*, 2010, 88: 1253–1260.
[94] Tran, H. T.; Lesage, G.; Lin, C.; Nguyen, T. B.; Bui, X. T.; Nguyen, M. K.; Nguyen, D. H.; Hoang, H. G.; Nguyen, D. D. Activated sludge processes and recent advances. *Current Developments in Biotechnology and Bioengineering*. Amsterdam: Elsevier, 2022, 49–79.
[95] Reif, R.; Besancon, A.; Le Corre, K.; Jefferson, B.; Lema, J. M.; Omil, F. Comparison of PPCPs removal on a parallel-operated MBR and AS system and evaluation of effluent post-treatment on vertical flow reed beds. *Water Sci. Technol.*, 2011, 63: 2411–2417.
[96] Chtourou, M.; Mallek, M.; Dalmau, M.; Mamo, J.; Santos-Clotas, E.; Ben Salah, A.; Walha, K.; Salvadó, V.; Monclús, H. Triclosan, carbamazepine and caffeine removal by activated sludge system focusing on membrane bioreactor. *Process. Saf. Environ. Prot.*, 2018, 118: 1–9.
[97] Ba, S.; Haroune, L.; Soumano, L.; Bellenger, J. P.; Jones, J. P., Cabana, H. A hybrid bioreactor based on insolubilized tyrosinase and laccase catalysis and microfiltration membrane remove pharmaceuticals from wastewater. *Chemosphere*, 2018, 201: 749–755.
[98] Obotey Ezugbe, E.; Rathilal, S. Membrane technologies in wastewater treatment: A review. *Membranes*, 2020, 10: 89.
[99] Das, S.; O'Connell, M. G., Xu, H.; Bernstein, R.; Kim, J. H.; Sankhala, K.; Segal-Peretz, T.; Shevate, R.; Zhang, W.; Zhou, X. C. et al. Assessing advances in anti-fouling membranes to improve process economics and sustainability of water treatment. *ACS ES&T Engg.*, 2022, 2(11): 2159–2173.
[100] Sheng, C. G.; Agwu Nnanna, A. G., Liu, Y. H.; Vargo, J. D. Removal of Trace Pharmaceuticals from Water using coagulation and powdered activated carbon as pretreatment to ultrafiltration membrane system. *Sci. Total Environ.*, 2016, 550: 1075–1083.
[101] Chow, S. J.; Croll, H. C.; Ojeda, N.; Klamerus, J.; Capelle, R.; Oppenheimer, J.; Jacangelo, J. G.; Schwab, K. J.; Prasse, C. Comparative investigation of PFAS adsorption onto activated carbon and anion exchange resins during long-term operation of a pilot treatment plant. *Water Res.*, 2022, 226: 119198.
[102] Chang, P. H.; Chen, C. Y.; Mukhopadhyay, R.; Chen, W. H.; Tzou, Y. M.; Sarkar, B. Novel MOF-808 metal–organic framework as highly efficient adsorbent of perfluorooctane sulfonate in water. *J. Colloid Interface Sci.*, 2022, 623: 627–636.
[103] Martínez-Sánchez, C.; Robles, I.; Godínez, L. A. Review of recent developments in electrochemical advanced oxidation processes: Application to remove dyes, pharmaceuticals, and pesticides. *Int. J. Environ. Sci. Technol.*, 2022, 19: 12611–12678.
[104] Das, S.; Raj, R.; Das, S.; Ghangrekar, M. M. A sustainable approach for the production of green energy with the holistic treatment of wastewater through microbial electrochemical technologies: A review. *Front. Sustain.*, 2021, 2: 792028.
[105] Wang, J. Z.; Ha, T. H.; Chiemchaisri, C.; Lu, M. C. Application of electro-Fenton technology for the degradation of imidacloprid from pesticide wastewater. *J. Water Process. Eng.*, 2024, 63: 105504.
[106] Pham, T. L., Boujelbane, F.; Bui, H. N., Nguyen, H. T., Bui, X. T.; Nguyen, D. N., Nguyen, H. T. T., Phan, H. A., Duong, H. T. G., Bui, H. M. Pesticide production wastewater treatment by Electro-Fenton using Taguchi experimental design. *Water Sci. Technol.*, 2021, 84: 3155–3171.
[107] Carter, L. J., Ben Mordechay, E.; Chefetz, B.; Chen, Z. Y.; Cui, X. Y.; Gan, J.; Li, H.; Moores, A.; Gao, X. Y. Contaminants of emerging concern in agricultural soils: Current understanding, overlooked issues, and future priorities. *PLANTS PEOPLE PLANET*, 2026, 8: 792–810.
[108] Nishmitha, P. S., Akhilghosh, K. A., Aiswriya, V. P., Ramesh, A.; Muthuchamy, M.; Muthukumar, A. Understanding emerging contaminants in water and wastewater: A comprehensive review on detection, impacts, and solutions. *J. Hazard. Mater. Adv.*, 2025, 18: 100755.
[109] Elbitar, F. S., Algethami, F. K., Bedair, A.; Mansour, F. R. Analytical challenges and future directions for the holistic assessment of emerging contaminants in soils. *Trac Trends Anal. Chem.*, 2026, 194: 118506.
[110] Hashmi, Z.; Idriss, I. M., Gapsari, F.; Samsuddin, N.; Bilad, M. R. The role of nanomaterials in enhancing membrane-based treatment for emerging contaminants: A review. *Sustain. Chem. Clim. Action*, 2025, 7: 100092.
[111] Li, Y.; Li, Y. H.; Zhang, S. Y.; Gao, T. Y.; Gao, Z. Y.; Lai, C. W., Xiang, P.; Yang, F. Q. Global distribution, ecotoxicity, and treatment technologies of emerging contaminants in aquatic environments: A recent five-year review. *Toxics*, 2025, 13: 616.