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EMERGING POLLUTANTS IN THE ENVIRONMENT. II. RISKS AND MITIGATION TECHNOLOGIES FOR SUSTAINABLE ENVIRONMENTAL MANAGEMENT

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Rezumat. *Emerging pollutants (EPs), including pharmaceuticals, personal care products, endocrine-disrupting chemicals, pesticides, industrial compounds, and microplastics, have raised growing concerns due to their persistence, bioaccumulation potential, and insufficient regulation. Although often present at trace levels, these substances pose significant risks to ecosystems and human health, particularly due to their chronic toxicity, endocrine-disrupting properties, and contribution to antimicrobial resistance. This review provides an in-depth assessment of the ecological and human health implications of EPs, highlighting their disruptive effects on biodiversity, microbial communities, reproductive systems, neurological health, and the development of antibiotic resistance. Special emphasis is placed on the synergistic interactions between EPs and climate change, which can amplify their dispersion and toxicity. The study further explores major exposure pathways, including contaminated drinking water and food chains, underscoring the urgent need for integrated monitoring and risk mitigation frameworks. Current removal technologies, such as advanced oxidation processes, membrane filtration, adsorption, and biological treatments are critically examined for their efficiency, scalability, and limitations. Nature-based solutions, including constructed wetlands, biofiltration, and phytoremediation, are discussed as sustainable alternatives offering multiple co-benefits. Finally, the paper advocates for coordinated regulatory action, innovation in green chemistry, and investment in advanced and nature-based treatment systems to address the complex challenges posed by EPs and to ensure long-term environmental and public health protection.*

Abstract. *Poluanții emergenți (EP), incluzând produse farmaceutice, produse de îngrijire personală, compuși perturbatori endocrini, pesticide, substanțe chimice industriale și microplastice, generează îngrijorări tot mai mari din cauza persistenței lor, potențialului de bioacumulare și reglementărilor insuficiente. Deși prezenți adesea în concentrații foarte mici, acești compuși reprezintă riscuri semnificative pentru ecosisteme și sănătatea umană, în special prin toxicitatea lor cronică, efectele endocrine și contribuția la apariția*

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rezistenței antimicrobiene. Această lucrare oferă o analiză aprofundată a impactului ecologic și asupra sănătății umane al EP-urilor, evidențiind efectele lor perturbatoare asupra biodiversității, comunităților microbiene, sistemelor reproductive, sănătății neurologice și dezvoltării rezistenței la antibiotice. Se acordă o atenție deosebită interacțiunilor sinergice dintre EP-uri și schimbările climatice, care pot amplifica dispersia și toxicitatea acestora. Studiul analizează, de asemenea, principalele căi de expunere, inclusiv apa potabilă contaminată și lanțurile trofice, subliniind necesitatea urgentă a unor cadre integrate de monitorizare și atenuare a riscurilor. Tehnologiile actuale de îndepărtare, cum ar fi procesele avansate de oxidare, filtrarea prin membrane, adsorbția și tratamentele biologice sunt evaluate critic în funcție de eficiență, scalabilitate și limitări. Soluțiile bazate pe natură, precum zonele umede construite, biofiltrarea și fitoremedierea, sunt discutate ca alternative sustenabile care oferă beneficii multiple. În final, lucrarea pledează pentru o acțiune coordonată în materie de reglementare, inovație în chimia verde și investiții în sisteme de tratare avansate și ecologice, pentru a face față provocărilor complexe generate de EP-uri și pentru a asigura protecția pe termen lung a mediului și a sănătății publice.

Keywords: adsorption, antimicrobial resistance, biodiversity, emerging pollutants, phytoremediation, risk

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1. Introduction

Emerging pollutants (EPs) are a diverse group of synthetic or naturally occurring substances that have been detected in various environmental compartments but are not yet fully regulated. These include pharmaceuticals, personal care products, pesticides, plasticizers, industrial chemicals, per- and polyfluoroalkyl substances (PFAS), and microplastics. Due to their widespread use and persistence, EPs pose significant risks to ecosystems and human health. Unlike conventional pollutants, they often occur at trace levels, making detection and regulation challenging. However, even at low concentrations, EPs can induce chronic and sub-lethal effects that compromise environmental and public health [1, 2].

The increasing concern over EPs stems from their ability to persist in natural ecosystems, bioaccumulate in organisms, and disrupt key biological and ecological functions. Many EPs exhibit chemical stability and resistance to biodegradation, allowing them to accumulate in water bodies, sediments, and soil. Once released into the environment, they undergo transformation processes such as photodegradation, microbial metabolism, and chemical oxidation, sometimes leading to the formation of more toxic byproducts [3, 4]. Their continuous release into aquatic and terrestrial ecosystems through municipal wastewater, industrial discharge, and agricultural runoff exacerbates their impact, particularly because conventional wastewater treatment plants (WWTPs) are often inefficient in their removal [5].

1.1. Environmental and ecological risks of emerging pollutants

One of the primary concerns associated with EPs is their ecological impact, particularly in aquatic ecosystems where many of these pollutants accumulate. Pharmaceuticals, for instance, can interfere with the endocrine systems of aquatic species, leading to reproductive disorders, altered behavior, and developmental abnormalities. Endocrine-disrupting chemicals (EDCs) such as bisphenol A (BPA), phthalates, and synthetic hormones mimic natural hormones, affecting the growth and reproduction of fish, amphibians, and invertebrates. The presence of antibiotics in surface waters promotes the development of antibiotic-resistant bacteria, creating serious public health risks as these bacteria proliferate and spread through water systems [6, 7]. Moreover, bioaccumulation and biomagnification amplify the risks of EPs across trophic levels. Many persistent organic pollutants (POPs) and heavy metals accumulate in the tissues of organisms, with higher concentrations found in predatory species. For example, mercury and certain PFAS compounds have been shown to biomagnify in aquatic food chains, leading to elevated toxicity in top predators such as fish, birds, and marine mammals. This not only disrupts ecosystem balance but also raises concerns for human populations relying on contaminated food sources [8, 9].

In terrestrial environments, EPs can alter microbial communities in soil, affecting nutrient cycling and plant growth. The infiltration of pharmaceuticals and pesticides into groundwater poses additional risks, as these substances persist in drinking water sources, affecting both human health and agricultural productivity. Additionally, microplastics, which serve as carriers for other pollutants, have been detected in soils and sediments, impacting soil fertility and contaminating food supplies [10].

1.2. Human health risks associated with emerging pollutants

The presence of EPs in drinking water, food, and air exposes humans to a range of health hazards. Endocrine disruptors have been linked to hormonal imbalances, reproductive disorders, metabolic diseases, and developmental defects. Prenatal exposure to certain EDCs, such as phthalates and flame retardants, has been associated with birth defects, neurological impairments, and immune dysfunction in infants. Long-term exposure to PFAS compounds has been correlated with immune suppression, thyroid disease, and increased risks of certain cancers [11, 12]. Neurotoxic pollutants, including specific pesticides, have been implicated in cognitive impairments, neurodevelopmental disorders, and neurodegenerative diseases such as Parkinson’s and Alzheimer’s.

Additionally, the widespread use of antibiotics in agriculture and human medicine has contributed to the emergence of antimicrobial resistance (AMR), which threatens the efficacy of modern medical treatments. As resistant bacteria proliferate, infections become harder to treat, increasing mortality rates and healthcare costs globally [13].

1.3. The need for improved monitoring and regulatory measures

Despite growing awareness of the risks posed by EPs, existing regulatory frameworks remain insufficient to address their complexity. Many EPs lack standardized environmental quality thresholds, and current risk assessment models fail to capture their long-term and combined effects. The dynamic nature of EPs, coupled with their low-dose chronic toxicity, necessitates the development of more comprehensive monitoring programs, improved analytical techniques, and stricter regulations to mitigate their impact [14, 15].

Advancements in analytical chemistry, such as high-resolution mass spectrometry and non-target screening methods, have enhanced the detection of EPs and their transformation products. However, more efforts are needed to integrate these findings into policy decisions and risk management strategies. Strengthening wastewater treatment infrastructure, promoting the development of biodegradable alternatives, and implementing stricter industrial discharge controls are essential steps toward reducing environmental contamination [16].

Emerging pollutants represent a growing environmental challenge with complex implications for ecosystems and human health. Their persistence, bioaccumulative potential, and resistance to conventional treatment methods necessitate urgent action to mitigate their risks. A comprehensive approach integrating scientific research, technological innovations, and regulatory interventions is crucial for addressing the environmental and health threats posed by EPs. By improving pollutant detection, enforcing stringent policies, and investing in green chemistry solutions, society can work toward minimizing the long-term consequences of these contaminants and ensuring a sustainable future.

In this context, this study explores the environmental and human health risks associated with EPs, highlighting the mechanisms through which they affect ecosystems and human exposure. It also examines key factors influencing the persistence of these pollutants, their interactions with natural processes, and the strategies available for their management. By identifying current challenges and priority research directions, this analysis contributes to the development of sustainable solutions for reducing pollution caused by EPs and ensuring long-term environmental protection.

2. Environmental and human health risks

Emerging pollutants (EPs) represent a significant environmental and public health concern due to their persistence, bioactivity, and increasing prevalence in various environmental compartments. These contaminants, which include pharmaceuticals, personal care products, industrial chemicals, pesticides, and microplastics, have been detected in water, soil, air, and biota at varying concentrations. The risks posed by EPs are not only linked to their direct toxicity but also to their long-term effects on ecosystems, biodiversity, and human well-being [17].

The complexity of these risks arises from their diverse chemical nature, their ability to act in synergy with other pollutants, and their potential to induce sub-lethal yet cumulative biological disruptions.

2.1. Ecological and environmental risks

2.1.1 Biodiversity loss and species vulnerability

Emerging pollutants (EPs) significantly contribute to biodiversity decline by undermining species survival, impairing reproductive success, and degrading habitat quality. These pollutants disrupt vital physiological and ecological processes across multiple trophic levels, threatening the integrity of both aquatic and terrestrial ecosystems [7, 18].

In aquatic environments, contaminants such as endocrine-disrupting compounds (EDCs), synthetic hormones, and pharmaceuticals interfere with hormonal regulation in fish, amphibians, and other aquatic organisms. Such disruptions lead to reproductive anomalies, including skewed sex ratios, reduced fertility, and feminization of male individuals [19]. For example, continuous exposure to synthetic estrogens in wastewater effluents has been linked to the collapse of fish populations due to severely impaired reproductive capacity. These physiological effects are often accompanied by behavioral alterations, such as diminished courtship displays or impaired mate recognition, which further hinder species propagation (Figure 1) [20].

The effects of EPs extend beyond individual organisms to entire communities, altering interspecific interactions and ecological roles. Pharmaceuticals like antidepressants can modify behavioral responses, such as risk assessment and foraging behavior, disrupting predator-prey relationships and increasing species' vulnerability. These behavioral changes weaken ecological networks and reduce the resilience of affected populations to environmental stressors [21]. Terrestrial biodiversity is similarly at risk. Pollutants deposited in soil, including pesticides, persistent organic compounds, accumulate in vegetation and enter food webs.

These substances adversely affect soil microbial diversity, suppressing functions critical to nutrient cycling, organic matter decomposition, and plant-microbe symbiosis. Such disruptions compromise plant health and productivity, ultimately influencing the abundance and diversity of herbivores, pollinators, and higher trophic organisms dependent on these habitats [22, 23].

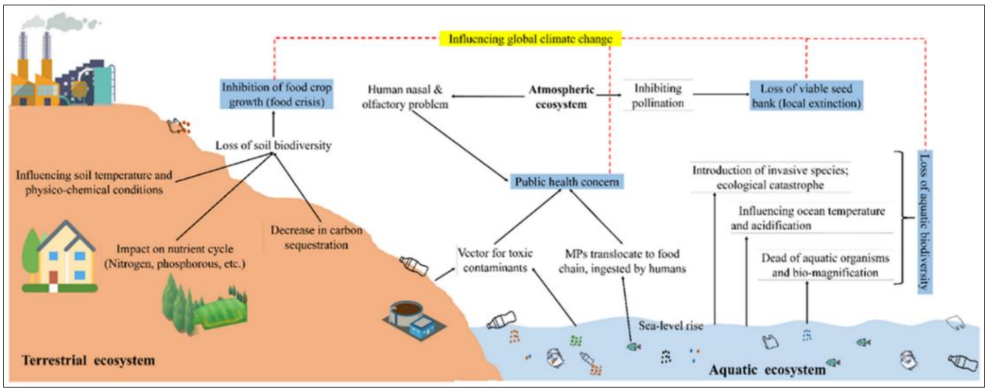

Figure 1. Illustration of emerging pollutants (microplastics and nanoplastics) affecting various ecosystem services and climate change on terrestrial, aquatic, and atmospheric ecosystems (reused from Kumar et al., 2021 [20], under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Species that feed on contaminated vegetation or prey, such as birds, small mammals, and reptiles, are exposed to bioaccumulated toxins, which may lead to neurotoxicity, hormonal imbalances, immune suppression, and decreased reproductive performance. Long-lived or top-predator species are particularly vulnerable due to biomagnification of pollutants through the food chain, resulting in chronic toxicity and population decline over time [24].

Moreover, microbial communities in both soil and aquatic environments are essential for maintaining ecological balance. EPs such as antibiotics and disinfectants disrupt microbial diversity and functionality, leading to altered decomposition rates, nutrient cycling, and primary productivity. These changes can cascade through ecosystems, affecting services like soil fertility, water purification, and climate regulation. The loss of microbial functionality also hinders the resilience of ecosystems to environmental fluctuations and anthropogenic pressures [25, 26].

Overall, the widespread presence of emerging pollutants disrupts the interconnected processes that sustain biodiversity. By impairing reproduction, behavior, and ecological interactions across species and habitats, EPs accelerate the erosion of biological diversity and compromise the long-term viability of ecosystems and the services they provide.

2.1.2 Alteration of aquatic and terrestrial ecosystems

Emerging pollutants (EPs) exert wide-ranging toxic effects on both aquatic and terrestrial ecosystems, disrupting essential biological functions such as reproduction, development, metabolism, immunity, and behavior in a broad spectrum of organisms. Their persistent presence in the environment poses a multifaceted threat to biodiversity, ecosystem services, and overall ecological balance.

In aquatic environments, EPs such as pharmaceuticals, antibiotics, pesticides, industrial solvents, plastic additives, microplastics have been frequently detected in rivers, lakes, and coastal waters. Pharmaceuticals, including hormones, antidepressants, and beta-blockers have been shown to interfere with the endocrine systems of fish and amphibians, leading to reproductive disorders, developmental abnormalities, and behavioral changes that impair survival and disrupt natural population dynamics [27, 28].

Such behavioral alterations, including reduced predator avoidance or impaired migratory instincts, can destabilize food webs and diminish ecosystem resilience (Figure 1) [20, 28]. Antibiotics released into water bodies not only disturb microbial community structures but also promote the emergence and proliferation of antibiotic-resistant bacteria. This not only threatens aquatic biodiversity but also poses indirect risks to human health through waterborne exposure and bioaccumulation in the food chain. The ecological implications are further amplified by the persistence of these compounds and their potential to interact with other contaminants, creating synergistic or cumulative toxic effects [29].

Industrial chemicals and synthetic compounds, such as plasticizers (e.g., phthalates) and solvents, further compromise the physiological integrity of aquatic organisms. These substances can impair metabolic processes, suppress immune function, and increase susceptibility to infections, thereby reducing the overall fitness of aquatic populations. Additionally, persistent organic pollutants (POPs), including polychlorinated biphenyls (PCBs) and dioxins, accumulate in fatty tissues and magnify through trophic levels, resulting in chronic toxicity across generations of aquatic and semi-aquatic species [30].

Terrestrial ecosystems are similarly vulnerable. Airborne contaminants and the deposition of EPs in soils and groundwater extend the range of ecological impact beyond aquatic zones. Agricultural areas are particularly susceptible due to the application of biosolids, irrigation with contaminated water, and atmospheric fallout. Leaching of pharmaceutical residues and microplastic-associated additives alters soil chemistry, suppresses beneficial microbial activity, and impairs nutrient cycling. These disruptions affect plant growth, reduce crop productivity, and jeopardize long-term soil fertility. Moreover, pesticides such as neonicotinoids have raised significant concern due to their adverse effects on non-target terrestrial species, especially pollinators like bees and butterflies. Exposure to sublethal doses impairs foraging behavior, navigation, and colony health, contributing to population declines that compromise pollination services essential for food production and ecological stability [29, 31].

The cumulative impact of emerging pollutants, through direct toxicity and indirect ecological disturbances, underscores the urgent need for comprehensive monitoring and mitigation strategies. Without intervention, the continued alteration of aquatic and terrestrial ecosystems may lead to irreversible changes in biodiversity and the collapse of critical ecosystem functions.

2.1.3 Climate change interactions and synergistic effects

The environmental impact of emerging pollutants (EPs) is increasingly influenced by their interactions with climate change-related stressors. Rising global temperatures, altered precipitation patterns, and the increased frequency of extreme weather events not only exacerbate the dispersion and persistence of EPs but also amplify their ecological effects in unpredictable ways (Figure 2) [32].

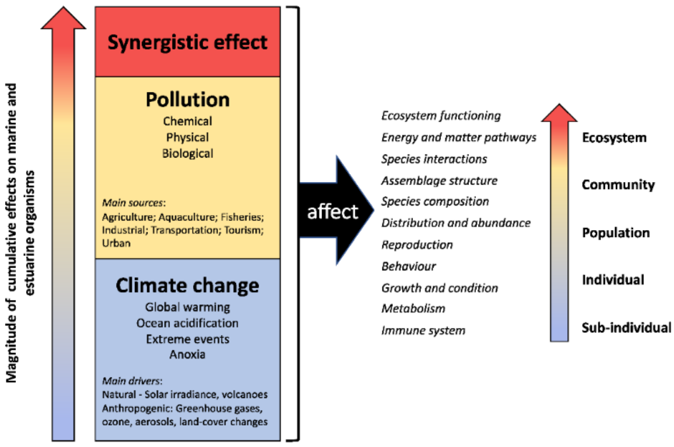

Figure 2. Conceptual model diagram of the cumulative and synergistic effects of climate change and pollution on marine coastal and estuarine (reused from Cabral et al., 2019 [32], under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Temperature plays a pivotal role in modulating the physicochemical behavior of pollutants. Warmer conditions can enhance the volatility and diffusion rates of semi-volatile organic compounds, facilitating their transport across wider geographical regions and promoting their infiltration into previously unaffected ecosystems. In aquatic systems, elevated temperatures can accelerate the metabolic rates of organisms, potentially increasing their uptake of pollutants and exacerbating toxic responses [33].

Changes in precipitation patterns, including more intense rainfall and prolonged droughts, influence the mobility and concentration of EPs in the environment. Heavy rainfall and flooding events can remobilize contaminants from sediments, soils, and landfills, leading to pulses of pollution in water bodies and wetlands. Conversely, drought conditions can concentrate pollutants in shrinking water volumes, increasing exposure levels for aquatic organisms and intensifying toxicological effects [34, 35].

Moreover, the degradation and transformation rates of many EPs are temperature- and moisture-dependent. Warmer and drier conditions may reduce microbial degradation capacity in soils and water, allowing pollutants to persist longer in the environment. This can lead to the buildup of toxic compounds in both biotic and abiotic components of ecosystems. Beyond the direct influence of climate variables, the interaction between EPs and other anthropogenic stressors, such as habitat fragmentation, overexploitation of species, and the introduction of non-native organisms, creates cumulative and often synergistic effects. These combined pressures can push ecosystems beyond critical thresholds, reducing their capacity to recover from disturbances. For instance, pollutants may weaken the immune systems or reproductive success of species already stressed by habitat loss, while invasive species may be more tolerant to contaminated environments, outcompeting native fauna and flora [36].

The complexity of these interactions makes it increasingly difficult to isolate the effects of individual pollutants or to predict long-term ecological outcomes. As climate change reshapes environmental baselines, the behavior, fate, and impact of EPs are becoming more variable and context-dependent. This underscores the need for integrated risk assessment frameworks that account for multiple stressors and their dynamic interactions under evolving climate scenarios.

2.2. Human health risks

Emerging pollutants (EPs) pose a growing threat to human health due to their persistence, bioaccumulation potential, and ability to disrupt biological systems even at low concentrations. These substances, which include pharmaceuticals, endocrine disruptors, heavy metals, and antimicrobial agents, enter the human body through contaminated water, food, air, and direct contact. Unlike traditional pollutants, many EPs act subtly over long periods, contributing to a range of chronic health conditions (Figure 3) [37]

2.2.1. Chronic exposure and low-dose toxicity

Emerging pollutants (EPs) pose a unique and often underestimated threat to human health due to their ability to induce chronic toxicity at low, sub-lethal concentrations. Unlike traditional toxicants that elicit immediate or acute effects, many EPs persist in the environment and bioaccumulate in human tissues, resulting in long-term health consequences through continuous, low-level exposure.

Exposure to EPs occurs through a variety of pathways, including ingestion of contaminated drinking water and food, inhalation of airborne particles or volatile compounds, and dermal absorption through contact with polluted soil, dust, or consumer products. Persistent compounds such as per- and polyfluoroalkyl substances (PFAS), phthalates, bisphenol A (BPA), and pharmaceutical residues are particularly concerning due to their environmental persistence, bioaccumulative potential, and widespread presence in human populations [17, 38].

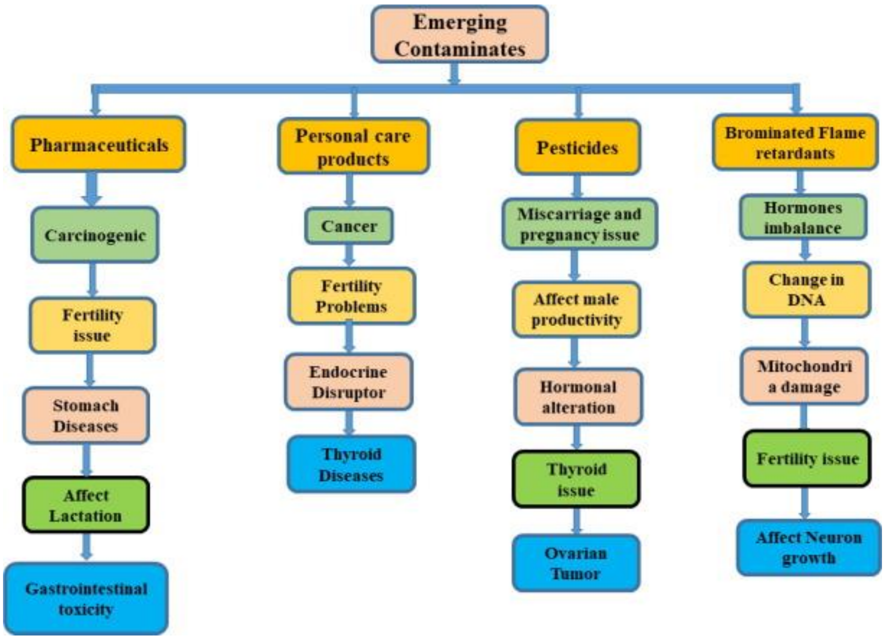

Figure 3. A variety of diseases originated due to emerging contaminates (reused from Mishra et al., 2023 [37], under the terms and conditions of the Creative Commons At-tribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/)

One of the major challenges associated with low-dose exposure is the subtle and cumulative nature of the effects. These pollutants can interfere with cellular signaling, hormone regulation, and gene expression, often without producing immediate or overt symptoms. Over time, however, chronic exposure has been linked to a wide range of adverse health outcomes, including immune system dysregulation, metabolic disorders such as obesity and diabetes, cardiovascular diseases, and increased risks of certain cancers [39, 40].

Two separate conceptual models were formulated to support the assessment of both acute and chronic risks. These models are adaptations of established risk assessment approaches, modified to incorporate the likelihood of public exposure to pollution sources and to enable evaluation of long-term (chronic) risk (Figure 4) [41]. Traditional risk assessment methodologies typically follow four key stages: identifying hazards, assessing exposure, evaluating dose-response relationships, and performing risk characterization [41, 42].

In scenarios involving cyanobacterial blooms, the primary hazard often stems from the presence of harmful cyanotoxins, such as microcystins. The exposure assessment phase focuses on identifying the routes of exposure, as well as determining how long and to what extent individuals may be exposed. The subsequent dose-response assessment examines how varying levels of exposure correlate with the severity of health effects. These effects can vary widely among individuals, depending on factors like physical condition and body weight, making it challenging to quantify them precisely. To address this variability, the models include a classification of risk severity, which supports a more objective approach to managing pollution-related hazards (Figure 4a, step 1) [41]. The final component, risk characterization, involves synthesizing information to assign risk levels. This helps authorities prioritize interventions and establish appropriate safety measures aimed at reducing exposure and safeguarding public health [41].

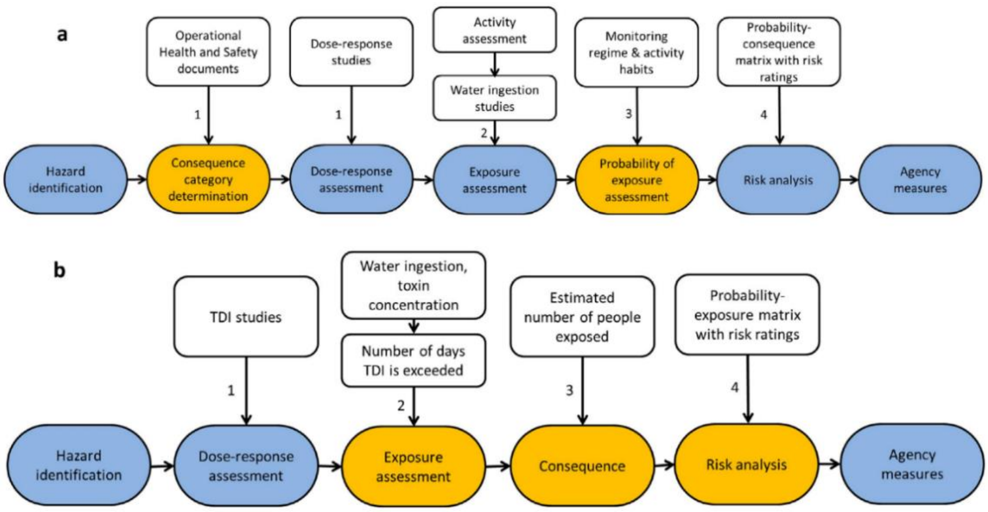

Figure 4. Conceptual framework for (**a**) acute and (**b**) chronic risk assessment models. Blue boxes present steps from previous risk assessment frameworks. Orange boxes represent steps that are newly incorporated or adapted within this newly proposed framework to allow an accurate estimation of the risk by assessing the probabilities that humans come into contact with undetected pollution (acute framework) or the probability that chronic illnesses are developed (chronic framework) (reused from Reichwaldt et al., 2016 [41], under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/)

Endocrine-disrupting chemicals (EDCs) among EPs are especially problematic, as they can mimic or block natural hormones even at extremely low concentrations. Continuous exposure during sensitive developmental windows, such as fetal growth, infancy, and puberty can result in permanent changes to the endocrine system, leading to neurodevelopmental impairments, delayed puberty, altered reproductive function, and reduced fertility. These effects may also extend across generations through epigenetic mechanisms, contributing to heritable changes in gene expression.

Moreover, chronic low-dose exposure may produce non-linear dose-response relationships, meaning that even trace amounts of certain EPs can have significant biological effects, especially when exposure occurs in combination with other environmental stressors or during critical stages of development (Figure 5) [43]. This complexity complicates traditional toxicological risk assessments and regulatory frameworks, which often rely on threshold-based models that may underestimate the real-world impact of chronic exposure.

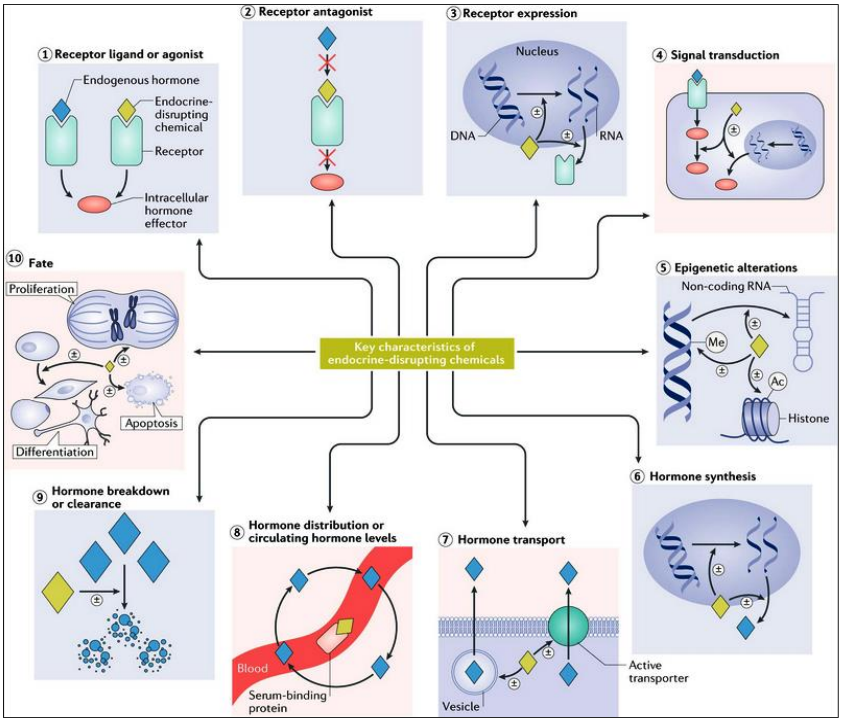

Figure 5. The key characteristics of endocrine-disrupting chemicals (reused from La Merrill et al., 2020 [43], under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/)

Recent biomonitoring studies have revealed the ubiquity of EP residues in human blood, urine, and tissues, highlighting the need for ongoing surveillance and more comprehensive health evaluations. The cumulative burden of these substances over time emphasizes the importance of precautionary approaches, particularly in vulnerable populations such as children, pregnant women, and individuals with pre-existing health conditions [44].

In summary, the health risks posed by EPs are amplified by their chronic, low-dose nature and their capacity to disrupt physiological systems gradually. Addressing these risks requires a paradigm shift in how chemical safety is evaluated, emphasizing long-term exposure scenarios and subtle biological effects that may not be captured by traditional toxicology.

2.2.2. Neurological and developmental effects

Emerging pollutants (EPs) present a growing concern for neurological health due to their ability to interfere with the structure and function of the nervous system. Many of these substances, including heavy metals, pharmaceutical residues, and industrial chemicals, disrupt neurochemical signaling and neural development, resulting in cognitive, behavioral, and emotional impairments that may manifest across the lifespan.

Pharmaceutical contaminants that target neurotransmitter systems have raised new concerns regarding subtle yet pervasive effects on human neurobiology. Selective serotonin reuptake inhibitors (SSRIs), anxiolytics, and antiepileptics have been increasingly detected in surface waters and, in some cases, in treated drinking water [45]. These substances are designed to modulate brain chemistry, and when present in the environment, they may impact non-target organisms and potentially influence human mental health. Chronic exposure to such compounds, even at trace levels, has been associated with altered mood regulation, anxiety, and sleep disturbances (Figure 6) [46].

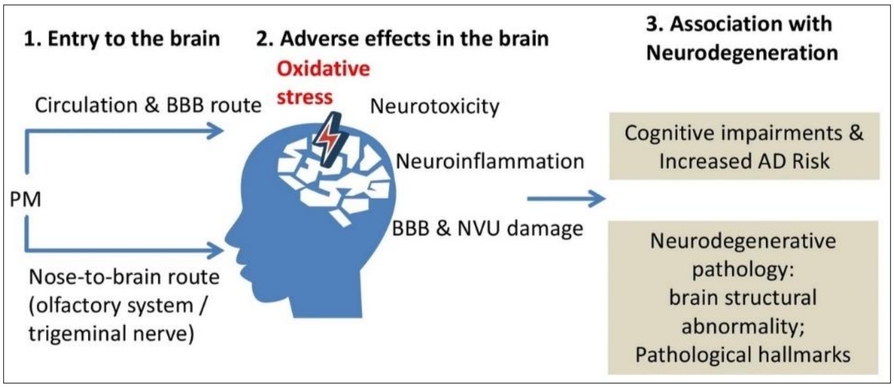

Figure 6. Mechanisms of pollutant-induced neurotoxicity: oxidative stress and neuroinflammation contributing to neuronal damage and cognitive decline (reused from You et al., 2022 [46], under the terms of the Creative Commons CC BY license, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited, according to the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/)

Emerging research suggests that long-term exposure to certain EPs may also play a role in the etiology of neurodegenerative diseases. Chemicals that induce oxidative stress, disrupt mitochondrial function, or provoke chronic inflammation in neural tissue are being investigated for their potential contribution to conditions such as

Parkinson's and Alzheimer's disease. While direct causal links are still under investigation, the biological plausibility is supported by mechanistic studies demonstrating neuroinflammatory responses and protein misfolding pathways triggered by specific environmental toxicants [47].

Moreover, the combined or cumulative effects of multiple EPs on neurological health are not yet fully understood. Many pollutants act on similar molecular targets or pathways, raising the possibility of additive or synergistic effects that amplify neurotoxicity. This is particularly concerning in urban and industrial regions where individuals are often exposed to complex mixtures of contaminants over extended periods [27, 29].

EPs pose a significant and multifaceted risk to neurological development and cognitive health. Their ability to cross physiological barriers, persist in the environment, and interfere with critical neurobiological processes underscores the need for more comprehensive risk assessments and public health strategies focused on early-life exposures and long-term neurotoxic outcomes.

2.2.3. Antimicrobial resistance and public health threats

Among the most urgent human health concerns linked to emerging pollutants (EPs) is the acceleration of antimicrobial resistance (AMR), a phenomenon that undermines the effectiveness of antibiotics and threatens global disease control efforts. The widespread release of antibiotic residues into the environment, originating from municipal wastewater, agricultural runoff, aquaculture, and hospital effluents, creates sustained selective pressure on microbial communities, promoting the evolution and proliferation of resistant bacterial strains [27, 28].

Environmental contamination with antibiotics, particularly in aquatic and soil ecosystems, facilitates the survival of bacteria harboring resistance traits. These conditions not only favor the enrichment of resistant populations but also stimulate the expression and dissemination of antibiotic resistance genes (ARGs). Through mechanisms such as horizontal gene transfer, resistance traits can rapidly spread across diverse bacterial species, including pathogenic strains, significantly expanding the scope and scale of the threat [48, 49].

The spread of antimicrobial resistance (AMR) primarily takes place in environments characterized by intense microbial activity and risk accumulation, such as hospitals, agricultural facilities, or interconnected healthcare systems spanning from primary to tertiary care. These settings concentrate various interacting risk factors, including overcrowding, high antimicrobial usage, susceptible individuals, environmental reservoirs of multidrug-resistant organisms, and transmission agents like long-term patients or healthcare personnel with frequent cross-institutional contact. Moreover, wastewater treatment plants are increasingly identified as significant hotspots for AMR dissemination (Figure 7) [50].

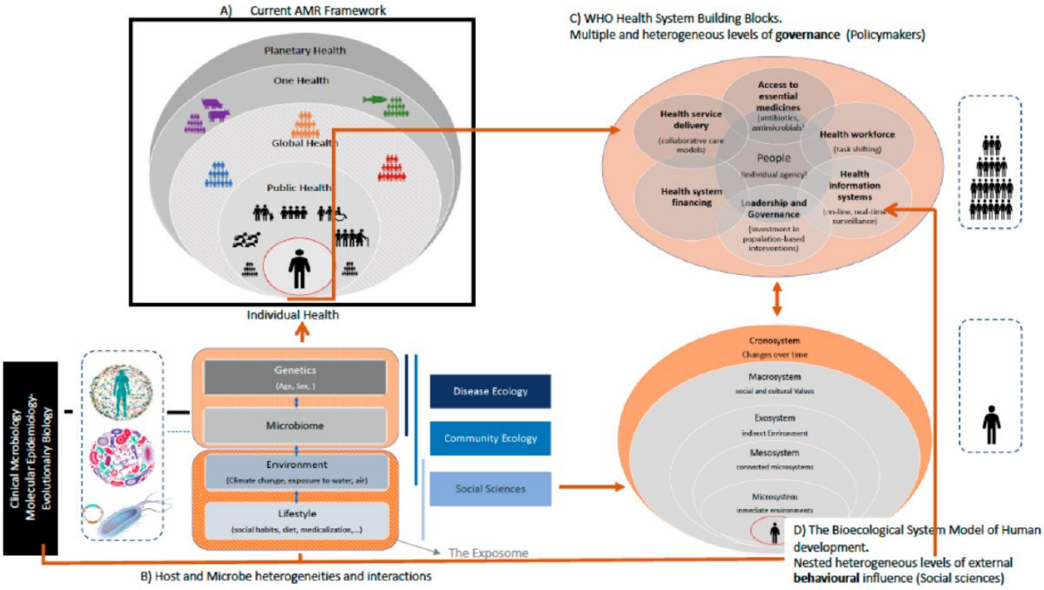

Figure 7. A framework for antimicrobial resistance in the healthcare network of the 21st century. A multidisciplinary approach for the analysis of AMR in a host metasystem landscape. (**A**) The current framework to approach health and global health challenges, which includes antimicrobial resistance (AMR) and pandemics. (**B**) Multidisciplinary approaches to analyzing host and microbe heterogeneity and their interactions in the context of individual human health, which is influenced by intrinsic individual traits (e.g., genetics and physiology) and the exposome (exposure to environment/s, social habits, and contact with abiotic and non-abiotic entities). Individual microbial heterogeneity at sub-specific (gene, plasmid, clone) and supra-specific (microbiome) hierarchical levels is the focus of clinical microbiology and molecular epidemiology; host-microbe interactions and dynamics are analyzed by disease ecology and community ecology. (**C**) The WHO Health System Building Blocks framework, which was developed to promote a common understanding of the health system. This is relevant for public health investments and results to feed global decision-making. (**D**) The Bioecological System Model of Human development. It establishes different levels (systems) of exposure to social groups. These levels overlap those of microbial exposure. Orange-colored areas represent the influence of time in all systems (human, microbial, individual species, and institutions). Brown arrows represent connections between the various levels. Dotted boxes reflect the central targeted unit, namely humans, in (**A**,**D**); human groups in (**C**); and microbes and hosts in (**B**) (reused from Coque et al., 2023 [50], under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/)

Wastewater treatment plants, healthcare facilities, and livestock operations serve as critical hotspots where high concentrations of antibiotic residues and resistant bacteria converge. Conventional treatment technologies are often ineffective at fully removing pharmaceutical compounds or resistance genes, enabling their release into natural water bodies. Once in the environment, these pollutants persist and interact with native microbial communities, contributing to the formation of environmental reservoirs of resistance [2, 37].

This environmental dimension of AMR extends its implications beyond healthcare settings, posing risks through contaminated water used in agriculture, irrigation, or drinking supplies. Resistant bacteria can enter the human food chain via consumption of produce irrigated with polluted water or through animal products derived from livestock exposed to antibiotics. The resulting infections may be untreatable with conventional antibiotics, leading to prolonged illness, higher treatment costs, and increased mortality. The global spread of AMR represents a critical public health threat, with projections indicating that resistant infections could surpass cancer as a leading cause of death in the coming decades if left unaddressed. Environmental EPs, especially antibiotic residues, act as silent enablers of this crisis by maintaining selective environments that drive resistance evolution outside the clinical sphere [13, 48, 51].

Moreover, emerging evidence suggests that other EPs, including disinfectants, biocides, can co-select for resistance by promoting cross-resistance or co-resistance mechanisms. This further complicates containment efforts and highlights the interconnectedness of environmental pollution, microbial ecology, and human health outcomes. The contribution of EPs to the rise and spread of antimicrobial resistance exemplifies the complex intersection between environmental contamination and public health. Addressing this challenge requires integrated strategies that combine environmental monitoring, improved waste management, responsible antibiotic use, and interdisciplinary research focused on mitigating the environmental drivers of AMR.

2.2.4. Endocrine disruption and reproductive health concerns

A significant number of emerging pollutants (EPs) function as endocrine-disrupting chemicals (EDCs), mimicking or interfering with the body’s natural hormones and disrupting key physiological processes related to growth, development, reproduction, and metabolism. These substances, including bisphenol A (BPA), phthalates, alkylphenols, certain pesticides, and flame retardants are widely used in industrial processes and consumer products, and their persistence in the environment makes them a major concern for both human and ecological health [52, 53].

In humans, exposure to EDCs has been associated with a spectrum of reproductive and hormonal health problems. These include decreased sperm quality, reduced fertility, altered timing of puberty, menstrual irregularities, and an increased incidence of hormone-related cancers such as breast, prostate, and testicular cancer. EDCs can disrupt hormone receptor binding, interfere with hormone synthesis and metabolism, and alter the feedback mechanisms of the endocrine system, even at very low concentrations. The non-monotonic dose-response behavior of many of these compounds further complicates risk assessment, as low-dose effects may be significant and difficult to predict [54].

Certain endocrine-disrupting chemicals (EDCs) can alter the availability of hormones by affecting their release, transport, or by interfering with the enzymatic processes responsible for hormone production and breakdown. Gaining insight into how EDCs, particularly those with obesogenic properties contribute to male infertility is crucial. This includes understanding their role in disrupting the regulatory mechanisms that control the reproductive axis, spermatogenesis, and sperm function (Figure 8) [55].

Particularly vulnerable are fetuses, infants, and children, whose endocrine systems are still developing. Prenatal and early-life exposure to EDCs has been linked to irreversible developmental effects, including congenital malformations of the reproductive tract, neuroendocrine disorders, immune dysfunction, and long-term metabolic disturbances such as obesity and insulin resistance. These developmental disruptions may not manifest immediately but can lead to increased disease susceptibility later in life, reinforcing the need for precautionary measures during critical exposure windows [56].

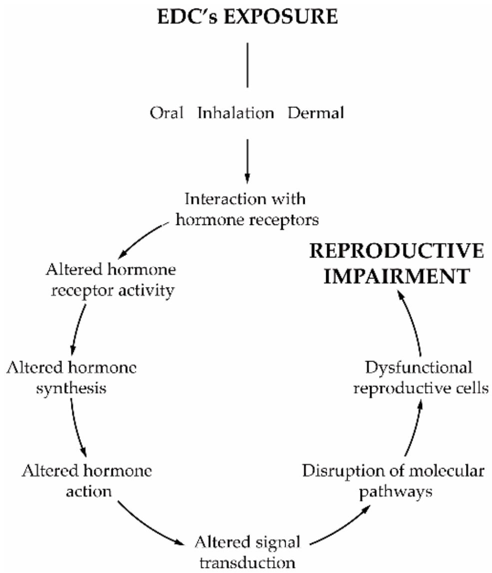

Figure 8. Schematic representation of the most important characteristics of obesogens' effects (reused from Rato and Sousa, 2021 [55] under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/)

The effects of endocrine-disrupting EPs are also evident in wildlife, where hormonal interference has been linked to population declines and reproductive anomalies across diverse species. In aquatic ecosystems, exposure to estrogenic compounds from pharmaceuticals, personal care products, and agricultural runoff has resulted in the feminization of male fish, reduced reproductive capacity, and altered sex ratios. Amphibians, sensitive to both aquatic and terrestrial pollutants, have exhibited intersex characteristics and developmental delays in contaminated habitats. Similar impacts have been observed in birds and reptiles, particularly in areas near agricultural or industrial discharge points [57, 58].

A substantial body of experimental and epidemiological evidence has established associations between exposure to endocrine-disrupting chemicals (EDCs) and impairments in male reproductive health. The proper development of the male reproductive system relies on androgen activity; therefore, compounds with anti-androgenic properties can interfere with this process and potentially lead to reproductive abnormalities (Figure 9) [59]. These anti-androgenic agents may act through various mechanisms, such as blocking androgen receptors or inhibiting androgen synthesis, and their effects can be cumulative. As a result, even low-dose mixtures of such chemicals may pose significant health risks. Additionally, EDCs often exhibit non-monotonic dose-response relationships, complicating risk assessment.

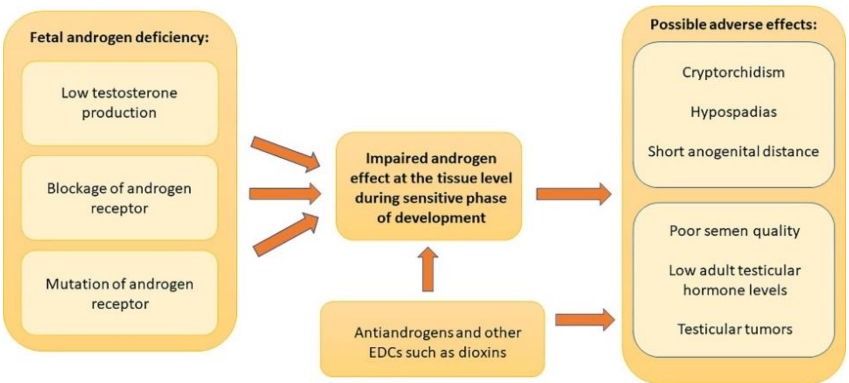

Figure 9. Role of androgen effects in male reproductive disorders (reused from Rodprasert et al., 2021 [59], under the terms of the Creative Commons Attribution License (CC BY)

These disruptions not only threaten individual species but can also lead to broader ecological imbalances by altering predator-prey dynamics, mating behaviors, and reproductive success. The long-term consequences of these shifts include population instability and potential local extinctions, particularly in ecosystems already stressed by habitat loss or climate change.

The pervasive nature of endocrine-disrupting EPs and their ability to affect both humans and wildlife across generations underscores the importance of monitoring and regulating these substances. Their capacity to cause significant biological effects at low doses, especially during sensitive life stages, makes them a priority for environmental and public health protection efforts [60, 61].

2.2.5. Contaminated drinking water and food chain exposure

The presence of emerging pollutants (EPs) in drinking water and food supplies represents a critical pathway for human exposure, with growing evidence linking these contaminants to a range of chronic health issues. As the use of pharmaceuticals, personal care products, industrial compounds, and agricultural chemicals increases, so too does their infiltration into natural and engineered water systems, ultimately reaching household taps and food products consumed daily [62].

Conventional water treatment facilities are not specifically designed to eliminate trace concentrations of EPs. Many pharmaceuticals, synthetic fragrances, plasticizers, and per- and polyfluoroalkyl substances (PFAS) are resistant to degradation and pass through filtration, chlorination, and sedimentation processes largely intact. As a result, low levels of these contaminants have been consistently detected in municipal drinking water supplies across the globe [63, 64]. Though individual concentrations may fall below regulatory thresholds, the potential for cumulative health effects from lifelong, multi-contaminant exposure remains a pressing concern, particularly for vulnerable populations such as children, pregnant individuals, and the immunocompromised. Figure 10 illustrate the exposure routes of antibiotics from water, transfer of resistance genes to humans, and the fate of veterinary antibiotics [65].

In parallel, EPs infiltrate the food chain through multiple routes, including the use of reclaimed water for irrigation, bioaccumulation in aquatic organisms, and uptake by crops grown in contaminated soils. Seafood, especially fish and shellfish from polluted waters, is a significant vector of exposure due to the accumulation of persistent pollutants such as heavy metals, PFAS, and pharmaceutical residues in muscle and fatty tissues. Similarly, meat and dairy products derived from livestock exposed to contaminated feed or water may contain residual antibiotics, hormones, or industrial chemicals [66, 67].

The ingestion of such contaminated food products contributes to the slow but continuous accumulation of toxic substances in human tissues. Bioaccumulative compounds can persist in organs such as the liver, kidneys, and adipose tissue, interfering with endocrine function, immune response, and metabolic regulation. Long-term exposure has been associated with increased risks of liver and kidney dysfunction, hormonal imbalances, reproductive disorders, and certain types of cancer [68].

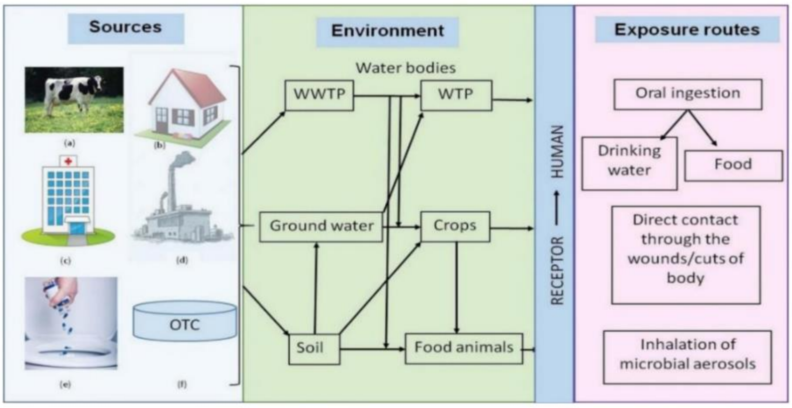

Figure 10. Sources of antibiotic usage, its spread, and transfer of resistance genes to humans. The excessive usage of antibiotics as growth stimulants in livestock and other food animals can contaminate water sources when animal excreta is washed off with water into the environment (a). The contamination of sewage treatment plants can be a result of excessive human usage of antibiotics (b). Hospitals and pharmaceutical industries contribute significantly to wastewater treatment plants' pollution by antibiotics when they are illegally let into sewage systems (c,d). Improper disposal of antibiotic pills and unprescribed over-the-counter antibiotics can contaminate wastewater treatment plants (e,f) (reused from Lebelo et al., 2021 [65], under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/)

Furthermore, the simultaneous presence of multiple EPs in both food and water sources raises concerns about combined or synergistic toxic effects. These mixtures may interact in ways that amplify biological responses, complicating risk assessments and public health interventions. The lack of comprehensive data on the health impacts of chronic, low-level exposure to such complex mixtures underscores the need for improved monitoring, stricter regulation, and the development of more advanced purification technologies [69].
Therefore, contaminated drinking water and food chain exposure constitute a significant and insidious route of human contact with emerging pollutants. The persistence, bioaccumulative nature, and potential toxicity of these substances call for an integrated approach to environmental management, food safety, and public health policy.

3. The need for integrated risk management and mitigation strategies

3.1. Toward prevention and control: Strategic responses to emerging pollutants

Given the widespread occurrence and long-term consequences of emerging pollutants (EPs), immediate and coordinated efforts are essential to minimize their risks. A holistic strategy must integrate regulatory, technological, societal, and scientific dimensions. The following key priorities outline a comprehensive approach to addressing the challenges posed by EPs.

Strengthening monitoring and regulatory frameworks

Effective management of EPs begins with robust, science-based monitoring and regulatory systems. Current frameworks often lag behind scientific evidence, leaving many pollutants unregulated or insufficiently controlled. To address this gap, regulatory agencies must [70-73]. Expand pollutant watch lists based on up-to-date toxicological data and environmental occurrence.

- Develop standardized methods for detection and quantification of EPs across different matrices (water, soil, air, biota).
- Establish health-based guideline values that account for chronic, low-dose, and mixture effects.
- Implement early warning systems for emerging contaminants with high persistence or bioaccumulation potential.
- Encourage international harmonization of regulations to address transboundary pollution and ensure consistent protection.

Proactive regulation not only protects public and environmental health but also guides industry toward safer product design and chemical use.

Advancing wastewater treatment technologies

Conventional wastewater treatment systems are not designed to remove most EPs, allowing them to enter surface waters and re-enter the human and ecological food chains. Upgrading treatment infrastructure is crucial and should involve [16, 74-76]:

- Integrating advanced treatment techniques such as ozonation, advanced oxidation processes (AOPs), nanofiltration, and activated carbon adsorption.
- Exploring innovative bio-based approaches, including enzymatic degradation and microbial consortia tailored to degrade pharmaceuticals and synthetic compounds.
- Developing modular and decentralized treatment systems for rural or industrial settings with specific EP profiles.
- Encouraging the recovery and reuse of water and resources from treated effluents to reduce environmental discharge.

Investments in modern wastewater treatment not only enhance pollution control but also support water reuse, aligning with circular economy principles.

Promoting sustainable production and consumption patterns

Preventing EPs at the source is one of the most cost-effective and environmentally sound strategies. This requires a transformation in how chemicals are produced, used, and disposed [39, 77-79]:

- Encouraging green chemistry approaches in product design to minimize hazardous substances.
- Promoting eco-labeling and transparency in consumer goods to support informed choices.
- Implementing take-back programs for unused pharmaceuticals, personal care products, and household chemicals.
- Fostering behavioral change through education campaigns that raise awareness about EP sources and environmentally responsible practices.
- Supporting sustainable agricultural practices that reduce reliance on chemical inputs and improve soil and water management.

These actions not only limit pollutant release but also cultivate a culture of sustainability and environmental responsibility across society.

Investing in research, innovation, and nature-based solutions

Scientific research and technological innovation are essential to understand, anticipate, and mitigate the effects of EPs. Priority areas for investment include [27, 80-83]:

- Expanding toxicological studies on EPs, including mixture effects and long-term exposure risks in humans and wildlife.
- Developing predictive models to assess pollutant fate, transport, and transformation in complex environments.
- Designing novel, environmentally friendly alternatives to conventional pollutants, such as biodegradable materials and low-toxicity chemical substitutes.
- Scaling up nature-based solutions, such as constructed wetlands, riparian buffer zones, and phytoremediation systems, which provide cost-effective and ecologically integrated remediation.
- Supporting interdisciplinary research collaborations that link environmental science, public health, policy, and social sciences to develop holistic mitigation strategies.

Such investments drive the transition toward innovative and resilient systems capable of addressing both current and emerging environmental challenges.

3.2. Socio-economic implications

The socio-economic consequences of emerging pollutant (EP) contamination extend far beyond their direct toxicological effects, impacting healthcare systems, food production, industry, and environmental governance. As the presence of EPs in air, water, soil, and food continues to grow, the economic burden of managing their impacts escalates. Mitigation strategies, ranging from upgrading infrastructure to developing safer alternatives, require substantial public and private investments. Moreover, the uncertainty surrounding the long-term effects of EP exposure adds complexity to risk assessment, policymaking, and cost forecasting [37, 62, 84].

Industries reliant on clean water and uncontaminated natural resources, such as agriculture, aquaculture, and tourism, are particularly vulnerable. The agricultural sector, for example, must contend with soil degradation, reduced fertility, and food safety concerns, while fisheries face declining stocks and international trade restrictions due to contamination. Simultaneously, healthcare systems are being strained by a rising prevalence of chronic conditions linked to EP exposure, such as endocrine disorders, neurological impairments, and antimicrobial-resistant infections [29, 85].

There is also a social dimension to consider: the disproportionate impact of EPs on marginalized communities, who often live near polluted environments or lack access to clean water and safe food. These inequities highlight the need for environmental justice approaches in future regulatory frameworks.

3.2.1. Economic costs of healthcare and disease burden

The chronic health effects associated with long-term EP exposure translate into escalating healthcare costs and productivity losses. Conditions such as hormone-related cancers, infertility, neurodevelopmental disorders, metabolic syndromes, and antibiotic-resistant infections often require prolonged medical care, specialized treatments, and continuous monitoring, all of which place pressure on national healthcare budgets [86].

The societal burden extends to reduced labor force participation and diminished cognitive performance in populations exposed during developmental stages, leading to long-term economic productivity losses. Endocrine-disrupting pollutants may increase the incidence of reproductive issues that affect family planning and demographic trends [87].

As scientific understanding of EP-induced disease mechanisms improves, health systems will face mounting pressure to address not only treatment but also prevention, demanding integration of environmental monitoring into public health strategies [29, 88].

3.2.2. Agricultural and food security concerns

The contamination of agricultural land and water with EPs poses direct threats to food safety, productivity, and security. Polluted irrigation water introduces pharmaceuticals, pesticides, plastic additives, and heavy metals into crop systems, where they can accumulate in edible tissues or disrupt plant growth. These residues may pose consumption risks to humans and animals, triggering trade restrictions and lowering market value [27, 35].

In livestock production, exposure to EPs through contaminated feed or water can lead to the accumulation of harmful compounds in meat, milk, and eggs. This not only jeopardizes consumer safety but may also affect animal health and productivity, with economic repercussions for farmers and supply chains [89, 90].

The decline of pollinator species, especially bees and butterflies, due to pesticide exposure further threatens agricultural output. Pollination is vital for the reproduction of many food crops, and its disruption can result in lower yields, reduced crop quality, and increased dependency on artificial pollination or imported goods, driving up food prices and intensifying food insecurity, particularly in vulnerable regions [1, 89].

3.2.3. Costs of environmental remediation

Remediating EP-contaminated environments requires substantial financial and technological resources. Most conventional wastewater treatment plants are not equipped to remove trace levels of complex pollutants such as pharmaceuticals, microplastics, and synthetic organic compounds. Retrofitting these facilities with advanced treatment technologies, such as activated carbon adsorption, membrane filtration, advanced oxidation processes (AOPs), or biofiltration, can be capital- and energy-intensive [78, 91, 92].

Soil and sediment remediation, especially at industrial or agricultural sites, often involves excavation, stabilization, or phytoremediation methods, each with significant cost and logistical implications. Furthermore, continuous pollution from non-point sources, such as agricultural runoff or household waste, makes remediation a long-term endeavor requiring sustained investment and maintenance [93, 94]. The economic cost of inaction is equally high, as degraded ecosystems lead to loss of ecosystem services such as clean water, fertile soil, and biodiversity, resources that are essential to economic resilience and human well-being.

3.2.4. Regulatory and governance challenges

Effective management of EPs is hindered by fragmented regulatory frameworks, data gaps, and the absence of global standards for many pollutants. The diversity and complexity of EPs, ranging from pharmaceuticals and industrial chemicals to microplastics and personal care products, complicate risk assessment and make prioritization difficult for regulators [95].

Many EPs are still unregulated or fall under outdated chemical safety laws that do not account for chronic low-dose exposure or mixture effects. Furthermore, the transboundary nature of pollution demands international coordination, yet regulatory capacity varies widely between countries, leading to enforcement gaps and inconsistencies in monitoring and reporting [93, 96].

Developing robust governance strategies will require collaboration between scientists, industry, policymakers, and civil society. This includes the creation of harmonized monitoring protocols, investment in green chemistry innovations, and the establishment of clear guidelines for pollution prevention and response. Public awareness and stakeholder engagement will also be essential to drive policy reform and ensure equitable implementation of environmental health protections [16, 97].

The socio-economic implications of emerging pollutants are broad and multifaceted, affecting not only human health and the environment but also the stability of key economic sectors and the effectiveness of governance systems. Tackling these challenges will require integrated, interdisciplinary solutions that bridge science, policy, and societal needs, ensuring a sustainable and equitable future.

4. Strategies to mitigate risks and reduce persistence

The persistence of emerging pollutants (EPs) in the environment poses significant challenges to ecosystems, human health, and socio-economic systems. Addressing these challenges requires robust strategies to mitigate the risks and reduce the persistence of these pollutants. One key approach is the development and implementation of advanced technological solutions for detecting, treating, and ultimately removing EPs from environmental matrices such as water, soil, and air.

4.1. Technological solutions

Technological solutions represent the frontline defense in mitigating the risks associated with emerging pollutants. These approaches often focus on advanced treatment technologies capable of targeting specific pollutants or broad categories of EPs. While promising, the efficiency and feasibility of these technologies vary depending on factors such as pollutant properties, environmental conditions, and economic constraints (Table 1) [39].

4.1.1. Advanced treatment technologies

4.1.1.1. Advanced Oxidation Processes (AOPs):

AOPs are a class of chemical treatment methods that generate highly reactive species, such as hydroxyl radicals, to oxidize and degrade pollutants. These processes are particularly effective in breaking down complex, persistent compounds into less harmful or completely mineralized forms (e.g. water, carbon dioxide).

Table 1. Treatment processes for removing emerging pollutants (reused from Arman et al., 2021 [39], under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/)

Types of EPs compounds	*Removal treatment*	*Result*
Pharmaceuticals, suncreen compounds, fragrances, antiseptics, flame retardants, surfactants, pesticides and plasticizers	An extended aeration system (AS) and a rotating biological contactor (RBC), a constructed wetland (CW) and a waste stabilization pond (WSP)	The efficiency of removal was 42%, 62%, 63%, 82% for the CW, AS, RBC and WSP, respectively
4,4'-(Propane-2,2-diyl) diphenol, Nonylphenol, and 5-chloro-2-(2,4-dichlorophenoxy) phenol	Electrooxidation	Removal efficiency for selected emerging pollutants reached 73-89%
Pharmaceutical (carbamazepine, flumequine, ibuprofen, ofloxacin and sulfamethoxazole)	NF/Solar photo-Fenton	Removal by NF produced a permeate containing less than 1,5% of the initial concentration of pharmaceuticals and application of solar photo-Fenton to this stream led to a reduction of 88% and 89%
Pharmaceutical (β-blockers)	Fe^{2+}/O_3	β-blockers were completely degraded, when the remocal rate of organic matter reached 30,6% and 49,1% for O_3, respectevely
Pharmaceutical (Antibiotics)	NF and UV/ O_3	High rejection of antibiotics (>98%) were obtained in all sets of NF experiments and UV/ O_3 process achieved excellent removal efficiencies of antibiotics (>87%)
PFC_s	MBR and PAC	Removal efficiencies of 77,4% for PFOS and 67,7% for PFOA were observed in PAC-MBR with PAC dosage of 30 mg/L. The increase of PAC dosage from 30 mg/L to 100 mg/L in PAC-MBR had increase the removal efficiency for PFOS or PFOA both to more than 90%.
Pharmaceutical (ketoprofen)	O_3/UV	O_3 highly contributed to the mineralization of small carboxylic acids. High (~90%) mineralization degree was achieved using the O_3/UV method.

Pharmaceutical (diclorofenac)	UF and photocatalytic (TiO_2/UV-A catalysis-)	Optimum diclorofenac removal at UV-A radiant power per unit volume 6,57 W/L, pH ~ 6 and TiO_2 loading near 0,5 g/L with maximum of diclorofenac molecular degradation and mineralization ~ 69%, respectively.
Disinfection by-products (THMs)	UV/H_2O_2	The degradation rates of 6 iodinated THMs in UV/ H_2O_2 system were rather comparable and significantly higher than those achieved in the UV system without H_2O_2
Pharmaceutical active compounds (PhACs)	NF	The overall rejection was approximately 31-39% and 55-61% for neutral carbamazepine (CBZ), and ionic diclofenac (DIC) and ibuprofen (IBU) respectively.
Pharmaceuticals	UV/H_2O_2	Most of the compounds are degraded by 90% at UV doses between 500 (MP) and 1000 (LP) mJ/cm^2 and 10 mg/L hydrogen peroxide
Perfluoroalkyl acids (PFAAs)	NF and GAC	Both virgin and fouled NF270 membranes demonstrated >93% removal for all PFAAs under all conditions tested. The F300 GAC had <20% breakthrough of all PFAAs in DI water for up to 125,000 bed volumes (BVs)
Pesticides	UV photolysis and NF	The combination of UV photolysis and NF allows the production of water with higher quality than the individual processes with global removals higher than 95% for all the spiked compounds throughout the treatment.
Pesticides (diazinon)	NH_4Cl-induced activated carbon (NAC)	Maximum adsorption rate was 97,5% of 20 mg/L diazinon adsorbed onto NAC at a low solution concentration of 0,3 g/L and short contact time of 30 min sat neutral pH
Industrial chemical (1,4-dioxane)	Coagulation –floculation and photocatalysis	The addition of TiO_2 ohotocatalysis to a coagulation-floculation water treatment process significatly increased 1,4-dioxane removal up to 100% within 1 h in a bath reactor and >60% of 1,4-dioxane was removed in a continuous flow reactor with a residence time of 39 min at a UV dose of 0,35 WL^{-1}
Hormone (17a-Ethynyestradiol)	UV/H_2O_2	The UV/H_2O_2 treatment was able to remove 90% of the 17a-Ethynyestradiol content within 30 min.

Pharmaceutical (Bezafibrate)	UV/H_2O_2	The removal of bezafibrate is >99,8% in 16 min under UV intensity of 61.4 µm cm^{-2}, at the H_2O_2 concentration of 0,1 mgL^{-1}, and neutral pH condition
Hormones and pesticides	NF	High percent rejections (67.4-99.9%) were obtained for the pesticides and hormones, often indepently of the water composition.
Hormones	NF and UV Photolysis	The use of NF in the treatment gives rejection at levels higher than 71% for all target hormones except estriol. Low pressure indirect photolysis with 100 mg/L of hydrogen peroxide was abso efficient to degrade the selected hormones with percent degradation higher than 74% achieved for all the hormones,except nonylphenol (55%).
Pharmaceutical and drug abuse	UV and RO	Lopromide (up to 17.2 ng/L), nicotine (13.7ng/L), benzoylecgonine (1,9 ng/L), cotinine (3,6 ng/L), acetaminophen (15,6 ng/L), erythromicyn (2.0 ng/L) and caffeine (6.0 ng/L) with elimination efficiencies >94%.
Pharmaceuticals, hormones and BPA	GAC and UV	The remobal effciency 1. Carbamazepine = 71 to 93 using GAC and 75% using GAC followed by UV.\ 2. Gemfibrozil = 44 and 55% using GAC and increased to 82% when GAC was followed by UV. 3. BPA = 80 to 99% using GAC or GAC followed by UV.
Pesticides	NF	The highest removal of diuron was achieved in the presence of intermediate ionic strength where in increase in diuron removal of 36.47% was obtained after the addition of 0,02 M of NaCl.
Pesticides	UF	The rejection coefficients for the phenyl-urea herbicides were also determined, with values ranged from 50-90% for linuron to 10-50% for isoproturon, depending on the selected membrane and the operating conditions.
DBPs (Duichloroacetic Acid)	UV/H_2O_2/Micro-Aeration	Removal efficiency greater than 95.1% of DCAA in 180 min. Under UV intensity of 1048.7 µW/cm^2, H_2O_2 dosage of 30 mg/L and micro-aeration flow rate of 2 L/min.

Caffeine, PPCPs and ESCs	Ozonation	Ozonation removed over 80% of caffeine, pharmaceuticals and endocrine disruptiors.
BPA	UF	75% removal using polysulfone-made UF membrane.
EE2	UF	85% removal using polyvinylidene fluoride UF membranes.

Advanced oxidation processes (AOPs) have gained significant attention for their effectiveness in eliminating a wide range of contaminants, including emerging pollutants found in wastewater. These processes rely on the production of highly reactive oxidizing species capable of breaking down complex organic compounds [98, 99]. Among the most notable of these is the hydroxyl radical (HO•), which possesses a high oxidation potential of 2.80 V.
Comparable in reactivity to traditional oxidants like chlorine, oxygen, and ozone, hydroxyl radicals stand out due to their ability to interact with a broad spectrum of organic and inorganic substances. This broad reactivity makes AOPs particularly suitable for degrading pollutants that are otherwise resistant to conventional treatments. An overview of the main categories of AOPs effective against emerging contaminants is presented in Figure 11 [100].

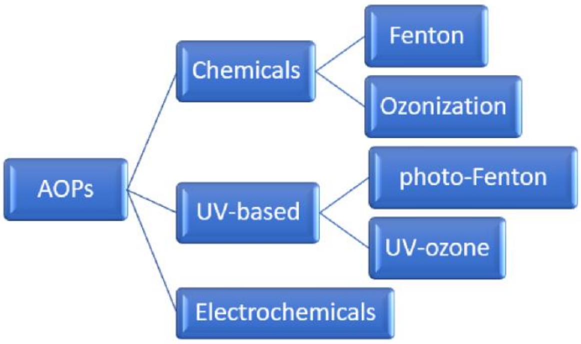

Figure 11. Most common advanced oxidation processes (AOPs) (reused from Bracamontes-Ruelas et al., 2022 [100], under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Photocatalysis
This process employs light-activated catalysts, such as titanium dioxide (TiO_2), to degrade pollutants. When exposed to ultraviolet (UV) light, the catalyst generates reactive species that attack and decompose pollutants. Figure 12 illustrates a basic representation of the photocatalytic reaction process involving hydroxyl radicals and environmental pollutants [101]. The degradation process begins when a photocatalyst, typically a semiconductor material is exposed to light energy equal

to or greater than its bandgap. This exposure excites electrons, causing them to move from the valence band to the conduction band. As a result, positively charged holes remain in the valence band, which then react with water molecules to produce hydroxyl radicals. These radicals, known for their strong oxidative capacity, break down organic contaminants commonly found in wastewater. Meanwhile, the excited electrons in the conduction band interact with dissolved oxygen species, contributing further to the breakdown of substances attached to the catalyst's surface. As with other environmentally focused catalytic systems, the efficiency of the process largely depends on the performance of the catalyst itself [102, 103].
Photocatalysis is highly effective for removing pharmaceuticals, pesticides, and industrial chemicals from water. However, its efficiency depends on the availability of UV light, and its widespread adoption is limited by the need for cost-effective light sources.

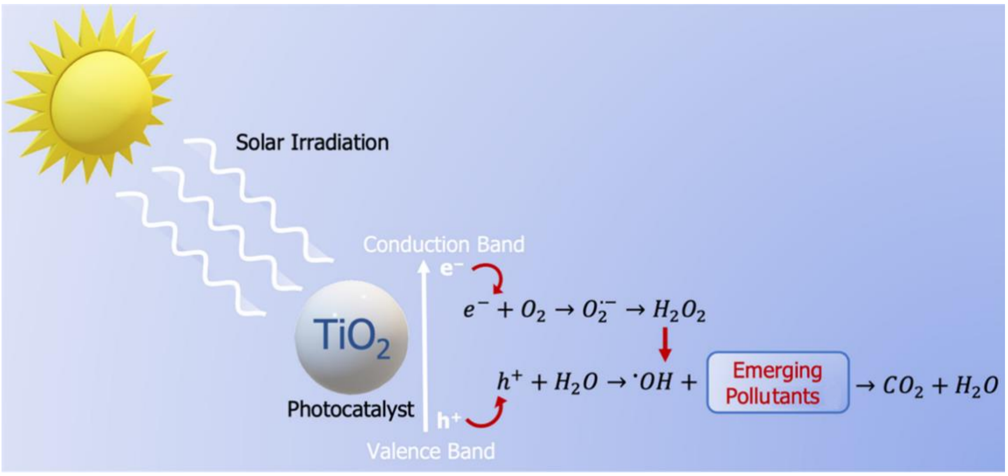

Figure 12. Mechanism schema of photocatalytic degradation of organic pollutants into CO_2 and H_2O in a TiO_2 catalyst (reused from Borges et al., 2023 [101], under the terms and conditions of the Creative Commons Attribution (CC BY) license https://creativecommons.org/licenses/by/4.0/).

Ozone-based treatments

Ozone-based treatments are advanced oxidation processes used to remove emerging pollutants from water. Ozonation involves injecting ozone gas into water to oxidize organic and inorganic pollutants (Figure 13) [104]. This process is effective against a broad range of EPs, including pharmaceuticals and endocrine-disrupting chemicals (EDCs). Ozone (O_3), a strong oxidant, reacts directly with contaminants or generates hydroxyl radicals (•OH) in water, enhancing degradation efficiency [105, 106].
These treatments are effective against a wide range of organic micropollutants, including pharmaceuticals, personal care products, and endocrine-disrupting

compounds. Ozone-based processes can be applied alone or combined with hydrogen peroxide (peroxone) or UV light to boost oxidation. Their main advantages include fast reaction rates and high oxidation potential.

Ozone treatment is relatively fast and scalable, but it requires careful control to avoid the formation of harmful byproducts, such as bromates, in water [74].

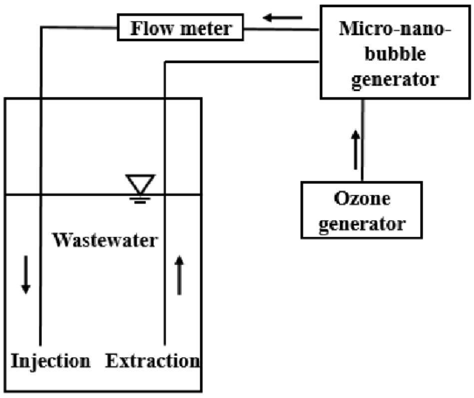

Figure 13. Schematic wastewater treatment by ozone (reused from Xia and Hu, 2019 [104], under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Fenton and photo-Fenton processes

These processes use hydrogen peroxide and iron salts to generate hydroxyl radicals. They are particularly effective for degrading recalcitrant organic pollutants in wastewater. Photo-Fenton processes, which combine this reaction with UV light, offer enhanced efficiency but are limited by the need for acidic conditions and proper waste management of iron residues [107, 108].

The Fenton process is an advanced oxidation technique that combines hydrogen peroxide (H_2O_2) with ferrous iron (Fe^{2+}) to produce hydroxyl radicals (•OH), which are highly reactive species capable of breaking down a wide range of organic pollutants. This reaction is most effective under acidic conditions (optimal pH around 3) and is commonly used in wastewater treatment for its simplicity and efficiency in degrading persistent contaminants (Figure 14) [109].

The photo-Fenton process is a modified version that incorporates light, typically UV or solar radiation to enhance the reaction. The light promotes the regeneration of Fe^{2+} from Fe^{3+}, sustaining radical production and improving degradation rates. This process is particularly effective for treating emerging pollutants, offering higher efficiency and faster reaction times compared to the conventional Fenton method [110, 111].

4.1.1.2. Membrane filtration technologies

Membrane filtration technologies are advanced separation methods that employ semi-permeable barriers to remove a broad spectrum of contaminants from water, including emerging pollutants (EPs) such as microplastics, pharmaceuticals, and industrial chemicals. These systems are widely applied in water treatment due to their ability to achieve high purification efficiency without the use of chemical reagents [112, 113].

The movement of substances through membranes is governed by various driving forces, which influence both the mechanism and effectiveness of the separation. Based on these forces, membrane processes can be categorized into equilibrium-based and non-equilibrium-based systems, as well as pressure-driven and non-pressure-driven methods. Figure 15 presents a schematic overview of selected membrane techniques classified according to their respective driving forces. A more detailed description of each process is provided in the following sections [114].

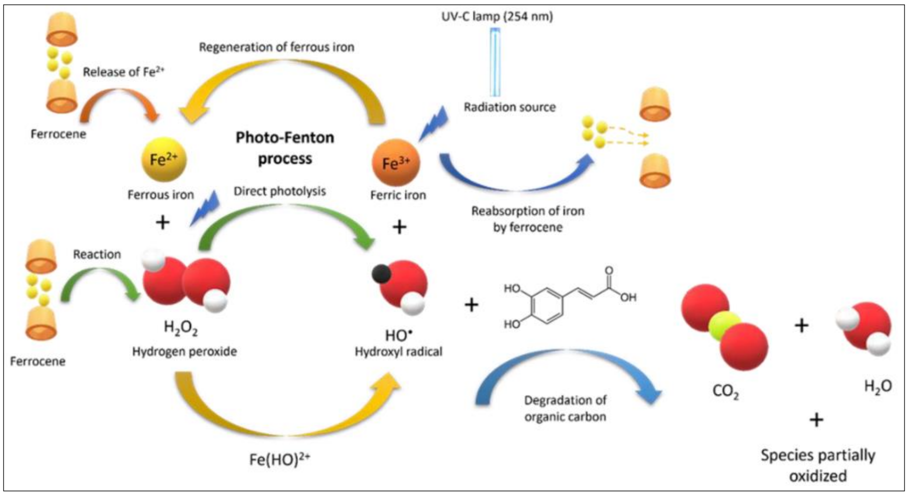

Figure 14. Schematic mechanism suggested for ferrocene releasing/absorption of ferrous iron in the photo-Fenton process (reused from Jorge et al., 2023 [109], under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Membrane separation operates by selectively allowing certain particles or molecules to pass through while retaining others, depending on factors such as size, charge, and hydrophobicity. This is primarily achieved through size exclusion, although electrostatic interactions can also play a role in the separation process. There are four principal types of membrane filtration, each offering distinct selectivity.

Microfiltration targets larger particles, such as suspended solids and bacteria, but is less effective for smaller organic contaminants. Ultrafiltration provides finer separation and is capable of removing viruses, proteins, and other macromolecules. Nanofiltration is suitable for eliminating low-molecular-weight organic compounds, divalent ions, and some pharmaceutical residues Among these, reverse osmosis offers the highest level of filtration, capable of removing a wide range of micropollutants, including endocrine-disrupting chemicals and personal care products [115-117].

These technologies are valued for their ability to produce clean effluent with minimal chemical input. Nevertheless, practical challenges such as membrane fouling, energy demands, and concentrate (brine) disposal must be addressed, particularly in large-scale applications. Despite these issues, membrane filtration remains a key component in advanced water treatment systems, thanks to its proven efficiency in removing a wide array of emerging contaminants from both municipal and industrial wastewater sources.

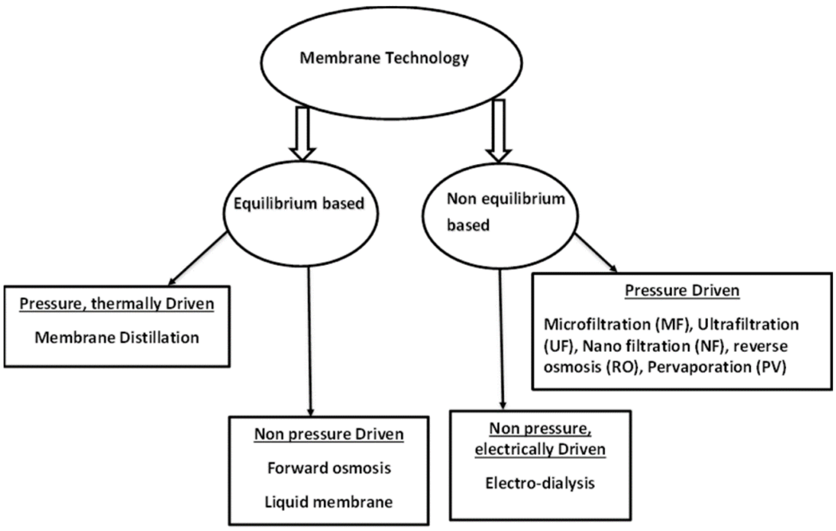

Figure 15. Schematic representation of some membrane processes (reused from Ezugbe and Rathilal, 2020 [114], under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Reverse osmosis (RO)

Reverse osmosis (RO) is a highly efficient membrane-based technology widely used for removing a broad range of contaminants, including emerging pollutants such as pharmaceuticals, endocrine-disrupting compounds, personal care products, pesticides, and industrial chemicals. The process involves applying high pressure to force water through a semi-permeable membrane that permits only small water molecules to pass while retaining most dissolved substances.

The effectiveness of reverse osmosis in removing emerging pollutants is largely due to its ability to reject both large and small organic molecules through size exclusion. Additionally, the membrane can block many ionic and polar substances through charge repulsion, while certain uncharged micropollutants are retained due to hydrophobic interactions with the membrane surface. The process uses a semipermeable membrane to filter out contaminants (Figure 16) [88]. While highly effective, RO systems are energy-intensive, require frequent maintenance, and produce significant volumes of brine as a byproduct.

Reverse osmosis is commonly used in advanced water purification and wastewater reuse systems, ensuring the production of high-quality treated water. However, the process also generates a concentrated waste stream, or brine, containing the removed pollutants, which must be properly managed. Operational challenges such as membrane fouling and relatively high energy consumption must also be addressed. Despite these issues, reverse osmosis remains one of the most reliable and effective technologies for the removal of emerging contaminants from water sources [118, 119].

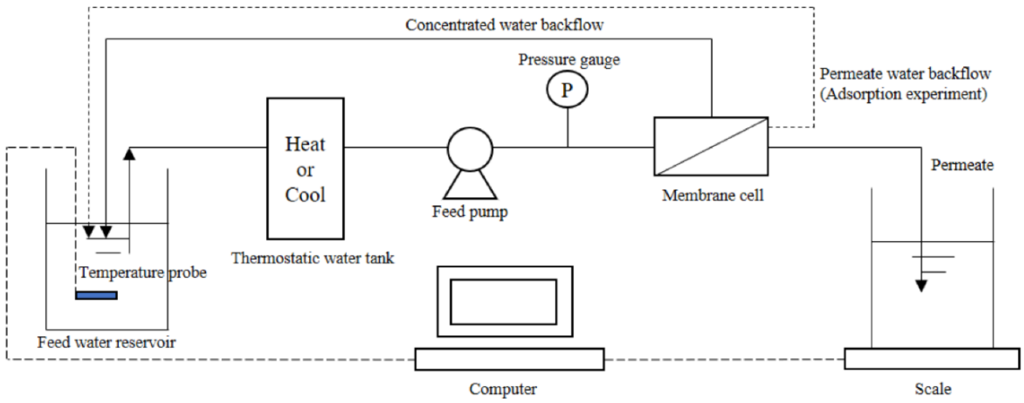

Figure 16. Flow diagram of the reverse osmosis device system (reused from Liu et al., 2023 [88], under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Nanofiltration (NF)

Nanofiltration (NF) membranes are designed to selectively remove smaller organic molecules and multivalent ions, positioning them as an effective option for the treatment of water contaminated with various emerging pollutants (EPs)**.** These pollutants may include pharmaceuticals, endocrine-disrupting compounds, personal care products, and pesticide residues, many of which fall within the molecular weight range and charge characteristics that NF membranes can effectively retain.

Figure 17 illustrates the working principle of nanofiltration membranes and demonstrates its suitability for targeted EP removal, particularly in the treatment of surface water, groundwater, and industrial effluents [120, 121]. Compared to reverse osmosis (RO), nanofiltration operates at moderate pressures**,** typically between 4–30 bar, which significantly reduces energy consumption and operational costs.

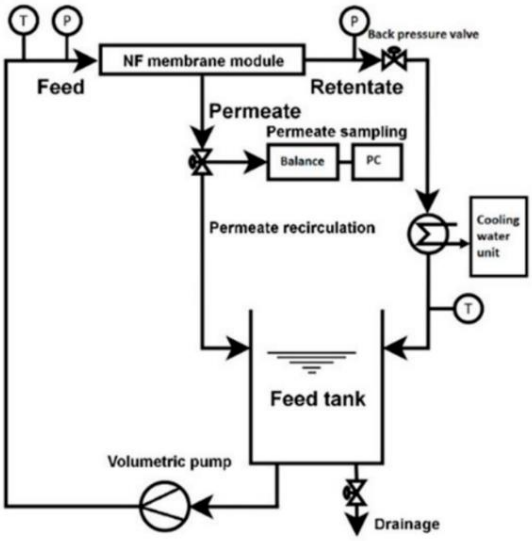

Figure 17. Setup of the nanofiltration unit (reused from Nayak et al., 2022 [120], under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/)

While RO provides a broader contaminant rejection spectrum due to its tighter pore structure, NF offers a balanced compromise between selectivity and energy efficiency. NF membranes can retain compounds based on molecular size, charge, and hydrophobicity, effectively removing multivalent ions and larger polar organic molecules, while allowing smaller monovalent salts (e.g., Na^+, Cl^-) to pass through. This selectivity makes NF particularly suitable in applications where partial desalination or the selective removal of specific pollutants is desired. However, due to their relatively larger pore size compared to RO membranes, nanofiltration systems are less effective at eliminating very small or uncharged micropollutants**.** For this reason, NF is often used as part of a multi-barrier treatment strategy**,** complementing other processes such as activated carbon adsorption or advanced oxidation [117, 121-123].

Overall, nanofiltration represents an energy-efficient and effective technology for emerging contaminant removal when tailored to the specific characteristics of the pollutants and integrated into a well-designed water treatment system.

Microfiltration and ultrafiltration

Microfiltration (MF) and ultrafiltration (UF) are membrane-based technologies primarily used to remove suspended solids, turbidity, and microorganisms such as bacteria and protozoa from water. Their membranes have relatively large pore sizes compared to nanofiltration and reverse osmosis, making them less effective at retaining low-molecular-weight organic compounds or dissolved pollutants. However, they can play a supportive role in the removal of emerging pollutants (EPs), especially when integrated into multi-barrier treatment systems [124, 125].

While MF and UF alone are generally insufficient to eliminate most EPs, such as pharmaceuticals, personal care products, and endocrine-disrupting compounds, they can contribute indirectly to their reduction. These processes effectively remove particulate-bound pollutants and reduce the overall load of natural organic matter and colloidal substances in water, which can interfere with downstream treatment technologies. By acting as a pretreatment step, MF and UF improve the efficiency and longevity of more advanced processes like activated carbon adsorption, ozonation, or advanced oxidation processes (AOPs), which are specifically designed to degrade or adsorb EPs [18, 116]. In particular, UF membranes, with their tighter pore structures compared to MF, can also retain some larger macromolecules and viruses, and have demonstrated partial removal of high-molecular-weight EPs or those associated with organic matter or suspended particles. The integration of MF or UF with other technologies, such as granular activated carbon, ozone, UV-based AOPs, or biological filtration creates a synergistic effect, significantly enhancing the overall removal efficiency of emerging contaminants [126, 127].

Therefore, although microfiltration and ultrafiltration are not standalone solutions for emerging pollutant removal, they are essential components in comprehensive water treatment schemes. Their role in pretreatment, membrane fouling control, and pathogen removal supports the overall performance and stability of integrated systems targeting a broader spectrum of contaminants.

4.1.1.3. Adsorption techniques

Adsorption techniques are widely employed in the removal of emerging pollutants (EPs) from water and air due to their simplicity, efficiency, and adaptability. These processes rely on the ability of certain materials to bind contaminants onto their surface through physical or chemical interactions. Commonly used adsorbents include activated carbon, which is highly porous and offers a large surface area, as well as biochar, zeolites, and more recently developed materials such as metal-organic frameworks (MOFs) and carbon-based nanomaterials [128].

Adsorption is particularly effective for removing a broad range of EPs, including pharmaceuticals, endocrine-disrupting compounds, personal care products, and industrial chemicals, many of which are difficult to degrade by conventional biological or chemical treatment processes. The effectiveness of adsorption depends on several factors, including the physicochemical properties of both the pollutant and the adsorbent, such as surface area, pore size distribution, surface chemistry, and the presence of functional groups [27, 79].

Among the adsorbents, activated carbon**,** in its powdered or granular form, remains the most widely used due to its high affinity for organic micropollutants and its proven performance in both drinking water and wastewater treatment applications. Biochar**,** derived from biomass pyrolysis, has gained attention as a low-cost, sustainable alternative, although its adsorption capacity can vary depending on the feedstock and production conditions. Novel materials like MOFs offer tunable pore structures and high selectivity, making them promising candidates for targeted removal of specific EPs, though their large-scale application is still under investigation [129-132].

Adsorption processes are often used as polishing steps following primary and secondary treatment stages or combined with other technologies such as membrane filtration or advanced oxidation processes. This integration enhances overall removal efficiency, particularly for persistent and low-concentration contaminants [64, 133].

Although adsorption is a non-destructive process, meaning pollutants are transferred rather than degraded the technique remains essential in water treatment due to its reliability, scalability, and compatibility with various treatment trains. The regeneration or disposal of saturated adsorbents remains a consideration for long-term sustainability and cost-effectiveness in large-scale applications.

Activated carbon

Activated carbon is one of the most extensively used adsorbents in water treatment due to its high surface area, porous structure, and strong affinity for a wide variety of organic micropollutants, including pharmaceuticals, pesticides, endocrine-disrupting compounds, and industrial chemicals. It is available in two main forms: powdered activated carbon (PAC) and granular activated carbon (GAC)**,** both of which are effective in removing emerging pollutants through physical adsorption and, in some cases, chemisorption [39, 134].

Its effectiveness lies in its ability to trap pollutants within its pore network, making it highly suitable for the removal of low-concentration contaminants that are difficult to eliminate through conventional treatment methods. Activated carbon can be used as a stand-alone treatment or as a polishing step after biological or physicochemical processes, particularly in advanced wastewater and drinking water treatment plants [128, 129].

Despite its proven efficiency, the adsorption capacity of activated carbon is finite and gradually decreases as the pores become saturated with contaminants. Once saturation is reached, the adsorbent loses its effectiveness and must be regenerated or replaced, which can be costly and energy-intensive. Thermal regeneration is the most common method, though it may lead to carbon loss and decreased adsorption performance over repeated cycles. Chemical regeneration methods are also being explored but may not be effective for all types of pollutants [135].

The performance of activated carbon also depends on the physicochemical characteristics of both the adsorbent and the targeted pollutants, including molecular size, polarity, solubility, and the presence of competing substances in the water matrix. Additionally, operational parameters such as contact time, dosage, and temperature influence its removal efficiency [136, 137].

Nevertheless, activated carbon remains a key component in water treatment systems due to its versatility, wide applicability, and well-established role in improving water quality, especially in the context of emerging contaminant removal. Its use continues to evolve alongside the development of novel carbon-based materials and hybrid systems designed to enhance performance and reduce costs.

Biochar

Biochar is an emerging and more sustainable alternative to conventional adsorbents like activated carbon, produced through the pyrolysis of biomass under limited oxygen conditions. Derived from a variety of organic materials such as agricultural waste, forestry residues, or other biomass sources, biochar offers a porous structure and functional surface chemistry that enable it to adsorb a wide range of pollutants, including pharmaceuticals, pesticides, dyes. Although its adsorption capacity is generally lower than that of activated carbon, biochar’s lower production cost, renewability, and potential for carbon sequestration make it an increasingly attractive option for large-scale environmental applications. Its environmental footprint is significantly smaller, particularly when sourced from waste biomass, contributing to circular economy strategies and sustainable water treatment solutions [138, 139].

The effectiveness of biochar as an adsorbent largely depends on the feedstock type and pyrolysis conditions, which influence its surface area, pore distribution, and surface functional groups. High-temperature pyrolysis typically results in biochars with greater surface areas and enhanced adsorption capacity. Biochar can interact with contaminants through multiple mechanisms, including hydrophobic interactions, electrostatic attraction, ion exchange, and surface complexation, allowing it to target a range of emerging pollutants in both water and wastewater treatment [139, 140].

In addition to its cost-effectiveness and environmental benefits, biochar can be modified or functionalized, physically or chemically to improve its performance for specific pollutants, further increasing its potential as a competitive alternative to synthetic adsorbents. However, similar to other adsorption processes, biochar eventually reaches saturation and may require regeneration or disposal, which needs to be managed carefully to avoid secondary pollution [138, 141].

Overall, biochar represents a promising, low-cost, and eco-friendly solution for the adsorption of emerging pollutants, especially in decentralized or resource-limited settings. As research advances, optimized production methods and targeted modifications are expected to further improve its adsorption capacity and broaden its applicability in sustainable water treatment systems.

4.1.1.4. Biological treatments

Biological treatments rely on the metabolic activity of microorganisms or the catalytic action of enzymes to break down pollutants into less harmful or non-toxic compounds. These methods have long been used in conventional wastewater treatment processes, primarily for the removal of biodegradable organic matter and nutrients. However, many emerging pollutants (EPs), such as pharmaceuticals, personal care products, hormones, and synthetic chemicals, are structurally complex, poorly biodegradable, or present at trace concentrations, making them challenging to eliminate through traditional biological systems [77, 131].

Conventional activated sludge processes and standard bioreactors often exhibit limited efficiency in degrading such recalcitrant compounds due to factors such as low bioavailability, resistance to microbial attack, or inhibitory effects on microbial communities. As a result, a significant fraction of EPs may pass through these systems untreated, leading to their accumulation in aquatic environments. In recent years, advances in environmental biotechnology have led to the development of enhanced biological treatment strategies designed specifically to improve the removal of emerging contaminants [133]. These include the use of specialized microbial consortia, genetically engineered microorganisms, and the integration of biofilm-based systems, membrane bioreactors (MBRs), and moving bed biofilm reactors (MBBRs), which offer greater surface area and retention time for microbial degradation. The application of enzymatic treatments, such as the use of laccases and peroxidases, has also shown promise in catalyzing the breakdown of complex organic micropollutants under milder conditions, often with higher specificity and fewer by-products [142-144].

The effectiveness of biological treatments for EP removal can be further improved through process optimization, including the adjustment of operational parameters (e.g., pH, temperature, retention time, oxygen levels), the addition of co-substrates to stimulate microbial activity, or the combination with other technologies such as adsorption or advanced oxidation processes. Moreover, anaerobic and aerobic hybrid systems have been explored to expand the range of degradable compounds and enhance overall system resilience [74, 145]. Despite their potential, biological treatments still face challenges related to the incomplete mineralization of certain EPs, the formation of transformation products with unknown toxicity, and the long adaptation time required for microbial communities to effectively degrade new contaminants. Nevertheless, they remain a key component of sustainable and cost-effective treatment systems and continue to evolve as research uncovers new microbial pathways and enzymes capable of tackling a broader spectrum of emerging pollutants.

Enhanced biodegradation

Enhanced biodegradation refers to the optimization and intensification of biological processes to improve the removal of emerging pollutants (EPs), particularly those that are resistant to conventional treatment methods. While standard biological treatment systems may struggle with the degradation of structurally complex or low-biodegradability compounds, enhanced biodegradation techniques aim to overcome these limitations by stimulating microbial activity or introducing specialized organisms capable of breaking down persistent contaminants [77, 146].

One approach involves the enrichment or bioaugmentation of microbial communities with strains that possess specific metabolic pathways for degrading targeted pollutants, such as pharmaceuticals, endocrine-disrupting compounds, or industrial chemicals. These specialized microorganisms can be naturally occurring, selectively cultivated, or genetically engineered to improve degradation rates and efficiency. In parallel, co-metabolism strategies, where a non-target pollutant is degraded incidentally in the presence of a primary substrat used to facilitate the transformation of otherwise recalcitrant compounds [147, 148].

The optimization of environmental conditions within the treatment system is another key strategy in enhanced biodegradation. Factors such as temperature, pH, oxygen availability, nutrient levels, and hydraulic retention time can significantly influence microbial activity and pollutant removal efficiency. By carefully adjusting these parameters, treatment systems can be fine-tuned to create favorable conditions for the microbial breakdown of specific emerging contaminants [149, 150].

Biofilm-based systems, such as moving bed biofilm reactors (MBBRs) and membrane bioreactors (MBRs), are also widely used in enhanced biodegradation due to their high microbial density, improved biomass retention, and greater resistance to toxic shocks. These systems provide a stable environment for slow-growing or pollutant-specific microbes to thrive, thus increasing the likelihood of successful contaminant degradation [84, 151].

Overall, enhanced biodegradation represents a promising strategy for improving the removal of emerging pollutants from wastewater. Although challenges remain in terms of process scalability, variability in pollutant mixtures, and potential formation of toxic by-products, ongoing advancements in microbiology, enzymology, and reactor design continue to expand the applicability and reliability of these biologically driven solutions in environmental protection.

Enzyme-based treatments

Enzyme-based treatments represent a specialized and increasingly explored approach for the removal of emerging pollutants (EPs) from water and wastewater. These methods utilize isolated enzymes, rather than whole microbial cells, to catalyze the breakdown of specific organic contaminants into less harmful or more biodegradable compounds. Enzymes offer several advantages over conventional biological treatments, including faster reaction rates, operation under a wide range of environmental conditions, and the ability to act on pollutants that are otherwise recalcitrant to microbial degradation [152, 153].

Enzymes such as laccases**,** peroxidases, and monooxygenases have been widely studied for their ability to degrade a variety of emerging contaminants, including pharmaceuticals, hormones, pesticides, synthetic dyes, and phenolic compounds. These enzymes work by oxidizing or transforming target molecules, often resulting in the cleavage of complex chemical structures or the reduction of toxicity. Because enzyme activity is highly specific, enzyme-based treatments can be tailored to focus on particular classes of pollutants, reducing the formation of undesirable by-products and improving overall treatment selectivity [154, 155]. One of the major benefits of enzyme-based systems is their independence from microbial viability. This allows treatment to occur even in environments that may be toxic or inhibitory to microbial life, such as wastewater streams containing high concentrations of antibiotics or industrial solvents. Enzymes can be applied in free form or immobilized on various carriers, such as activated carbon, polymers, or nanoparticles, to enhance their stability, reusability, and resistance to environmental degradation. Immobilization also facilitates their integration into continuous treatment systems and helps reduce operational costs [152].

Despite their potential, enzyme-based treatments face several challenges that need to be addressed for broader application. These include the high cost of enzyme production and purification, sensitivity to operational conditions (e.g., temperature, pH, and the presence of inhibitors), and potential deactivation over time. Moreover, scaling up enzyme applications for real-world wastewater treatment remains complex, particularly when dealing with mixtures of contaminants or fluctuating pollutant loads [156, 157].

Nevertheless, ongoing research in enzyme engineering, immobilization techniques, and reactor design continues to enhance the feasibility and efficiency of enzyme-based treatments. As part of integrated water treatment strategies, enzymes offer a promising tool for the selective and environmentally friendly degradation of emerging pollutants, complementing other advanced oxidation, adsorption, or membrane-based technologies.

4.1.2. Efficiency and feasibility of current solutions for the removal of emerging pollutants

4.1.2.1. Efficiency

The removal of emerging pollutants (EPs), such as pharmaceuticals, personal care products, endocrine disruptors, microplastics, and industrial chemicals, poses a major challenge for modern water and wastewater treatment. Present at low concentrations (ng/L to µg/L), these compounds are often chemically stable, biologically persistent, and not effectively removed by conventional treatment systems. Traditional wastewater treatment plants, primarily based on biological processes like activated sludge, are generally ineffective at eliminating EPs, many of which resist microbial degradation. Consequently, these pollutants often enter aquatic environments, posing ecological and health risks. To address these shortcomings, advanced treatment technologies have been introduced in tertiary treatment stages, including membrane filtration, advanced oxidation processes (AOPs), adsorption, and biological or enzyme-based methods [158, 159].

Membrane technologies like reverse osmosis (RO) and nanofiltration (NF) are highly effective due to size and charge-based separation, with RO achieving over 90% removal for many EPs. However, they are energy-intensive and produce brine that requires further treatment. AOPs, such as ozonation, UV/H_2O_2, and Fenton reactions use reactive radicals to break down pollutants but may form toxic by-products and involve high operational costs [114, 117, 125].

Adsorption, especially using activated carbon, offers a simple, low-energy option compatible with existing infrastructure, though its capacity can be limited. New adsorbents like biochar, MOFs, and carbon nanomaterials are being explored for improved performance. Biological and enzyme-based treatments are gaining interest as greener alternatives. While conventional biological methods have limited efficacy, enhanced biodegradation and enzyme-based systems show promise, especially for complex or recalcitrant compounds [135, 138, 139].

Hybrid systems combining technologies, such as membranes with AOPs or adsorption with biodegradation can enhance removal efficiency, lower costs, and reduce by-products. However, effectiveness depends on factors like influent composition, pollutant types, concentrations, and operational conditions [146].

Moreover, many emerging pollutants remain poorly understood or unmonitored. No single method can fully eliminate all EPs, but integrated approaches, combined with advances in materials science, biotechnology, and process engineering, continue to improve treatment outcomes. Ongoing monitoring, toxicity assessment of by-products, and holistic system design are key to meeting the growing challenges posed by emerging pollutants.

4.1.2.2. Feasibility

The feasibility of technologies for removing emerging pollutants (EPs) from water is shaped by technical, economic, environmental, and operational factors. While many advanced methods perform well in controlled settings, large-scale use is limited by high costs, system complexity, and evolving regulations [27, 74].
Technologies like reverse osmosis, AOPs, and advanced adsorption are effective but often energy-intensive, costly, and sensitive to water quality. Simpler, lower-cost options such as biochar, natural adsorbents, and hybrid systems offer more practical solutions, especially in resource-limited settings. Environmental concerns, such as toxic by-products, energy use, and waste generation, also impact feasibility and must be assessed holistically. Operational challenges include integration into existing plants and the need for specialized expertise, with modular and scalable systems offering better adaptability [74, 133].
Regulatory gaps reduce incentives for investment, though increasing awareness is prompting policy shifts. Persistent knowledge gaps, including pollutant behavior and by-product toxicity, further complicate technology selection [160]. While no single solution fits all, multi-barrier systems tailored to local needs offer the most feasible path forward. Progress depends on innovation, supportive policies, and real-world testing.

4.1.2.3. Integrated approaches

Due to the limitations of standalone technologies in removing diverse emerging pollutants (EPs), integrated treatment approaches are gaining attention as more effective and sustainable solutions. EPs are chemically varied, persistent, and present in low concentrations, making single-process removal inefficient [161].
Combining biological treatment with advanced oxidation processes (AOPs) is a common strategy. Biological methods are cost-effective but limited for persistent pollutants, while AOPs degrade residuals, boosting overall efficiency and reducing energy use and by-product formation. Adsorption, using materials like activated carbon or biochar, can also complement biological processes by capturing hard-to-degrade pollutants. In some cases, adsorbed compounds are later biodegraded, enhancing performance and reducing regeneration needs. Membrane technologies benefit from integration too. Coupling with adsorption or AOPs improves removal, reduces fouling, and manages concentrate streams. Pre- and post-treatment steps help optimize efficiency and longevity [39, 126, 133].

Hybrid biological systems, such as combining anaerobic and aerobic processes or incorporating enzymes, further expand treatment capabilities by exploiting diverse microbial pathways.

Effective integration requires thoughtful design, considering pollutant types, retention times, energy demands, and treatment interactions. Though more complex, integrated systems are often more robust, adaptable, and cost-effective. Integrated treatment approaches offer a promising path for the efficient removal of emerging pollutants, combining the strengths of multiple technologies to meet evolving environmental and regulatory demands [134].

4.2. Nature-based solutions

Nature-based solutions (NBS) represent an innovative and sustainable approach to addressing the challenges posed by emerging pollutants (EPs) in the environment. By leveraging natural processes and ecosystems, NBS provide effective ways to mitigate the persistence and impact of these pollutants while promoting ecological balance and biodiversity.

These solutions focus on harnessing biological, chemical, and physical interactions within natural systems to remove or degrade EPs in water, soil, and air [162, 163]. Among the most widely implemented strategies are phytoremediation, biofiltration, and constructed wetlands.

4.2.1. Phytoremediation, biofiltration, and constructed wetlands

Phytoremediation, biofiltration, and constructed wetlands represent nature-based treatment strategies that offer sustainable and cost-effective solutions for the removal of emerging pollutants from water and wastewater. These systems rely on the synergistic action of plants, microorganisms, and natural substrates to degrade, transform, or retain a variety of micropollutants, including pharmaceuticals, personal care products, and endocrine-disrupting compounds [164, 165].

While their removal efficiencies may vary depending on pollutant type, environmental conditions, and system design, they are increasingly recognized for their low energy requirements, minimal chemical use, and potential for integration into decentralized or rural wastewater treatment systems. These approaches contribute to ecological restoration and water quality improvement, supporting long-term environmental sustainability.

4.2.1.1. Phytoremediation

Phytoremediation is an environmentally friendly and cost-effective strategy that uses plants, often in combination with their root-associated microbial communities, to remove, degrade, or stabilize a wide range of environmental contaminants. This method harnesses the natural physiological and biochemical processes of plants to treat polluted soils and water, including sources contaminated with emerging pollutants (EPs) such as pharmaceuticals, endocrine-disrupting compounds, and personal care products [77, 166].

Plants function as biological filters by absorbing contaminants through their root systems and either metabolizing them into less harmful substances or storing them within their tissues. The efficiency of phytoremediation depends on the plant species used, the nature of the pollutants, environmental conditions, and the presence of synergistic microbial communities in the rhizosphere. The primary mechanisms involved in phytoremediation include phytoextraction, phytodegradation, and phytostabilization (Figure 18) [167].

In phytoextraction, pollutants are absorbed from the surrounding soil or water and accumulated in the plant biomass. This approach is especially effective for the removal of heavy metals and certain persistent organic pollutants. In the case of phytodegradation, plants, often in collaboration with rhizospheric microorganisms produce enzymes that break down complex organic molecules into simpler, less toxic forms [168, 169]. This mechanism has shown promising results in the degradation of pharmaceutical residues such as ibuprofen, diclofenac, and other micropollutants. Phytostabilization, on the other hand, focuses on limiting the mobility and bioavailability of contaminants by immobilizing them in the root zone, thus reducing their risk of spreading to groundwater or adjacent ecosystems [170, 171].

Phytoremediation has found diverse applications in environmental management, particularly in the rehabilitation of soils contaminated with agrochemicals, hydrocarbons, and industrial effluents. In recent years, it has also been increasingly adopted for the treatment of wastewater and effluents containing emerging pollutants, where aquatic plants such as *Typha*, *Phragmites*, and *Eichhornia* species have demonstrated the ability to absorb and transform a wide range of pharmaceutical and chemical contaminants [167].

Although phytoremediation generally requires more time than physicochemical methods and is sensitive to climatic and ecological variables, its low operational cost, minimal energy input, and potential for landscape integration make it an attractive option, especially in decentralized or low-resource settings. Moreover, ongoing research in plant biotechnology and microbiome engineering continues to enhance the capacity of phytoremediation systems to address the growing challenge of emerging pollutants in the environment.

4.2.1.2. Biofiltration

Biofiltration is a natural and sustainable treatment approach that employs biological materials, such as microbial biofilms, plant roots, and organic substrates to capture, retain, and degrade environmental pollutants. Widely applied in both water and air treatment systems, biofiltration integrates physical filtration with biological activity, making it a versatile and effective method for addressing a broad range of contaminants, including emerging pollutants (EPs) [39, 150, 171].

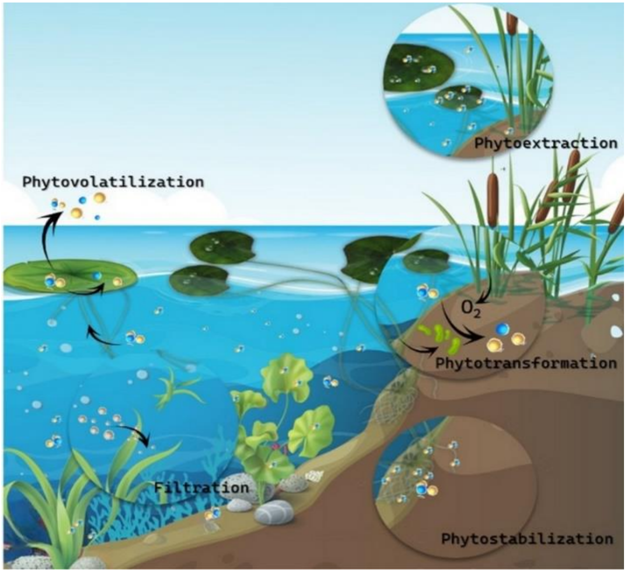

Figure 18. Phytoremediation strategies employed by aquatic macrophytes in wetland-based sewage treatment systems. Phytovolatilization occurs as plants absorb contaminants and release them as gases through transpiration. Phytoextraction involves plants absorbing pollutants from the water and/or sediment, accumulating them in their tissues. Phytotransformation highlights the chemical transformation of contaminants through plant or microorganism metabolism. Phytostabilization is depicted in the root zone of emergent plants, where contaminants are immobilized in the sediment, reducing their mobility and environmental impact. Additionally, macrophytes capture particles and enhance sediment stability, decreasing turbidity and clearing the water. They also improve microbial activity within the treatment system, with some microorganisms collaborating in contaminant metabolism (reused from Maranho and Gomes, 2024 [167], under the terms and conditions of the Creative Commons At-tribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/)

In water treatment applications, biofilters are typically constructed with multiple layers of porous media such as sand, gravel, compost, or other organic materials. These media serve as support structures for dense microbial communities that colonize the surfaces and form biofilms. As polluted water flows through the filter, suspended solids and organic micropollutants are first physically retained within the porous matrix. Simultaneously, microorganisms within the biofilm degrade or transform the contaminants through metabolic processes. This combination of filtration and biodegradation enables the removal of a variety of emerging contaminants, including pharmaceuticals, pesticides, and endocrine-disrupting compounds (EDCs), which are often resistant to conventional treatment (Figure 19) [172].

The efficiency of biofiltration depends on several factors, including the type of filter media, pollutant characteristics, microbial community composition, moisture content, temperature, and residence time. Properly managed systems can achieve high removal rates for a variety of EPs, particularly when designed to optimize conditions for microbial activity and biofilm stability. One of the key advantages of biofiltration is its low energy consumption and minimal chemical use, making it suitable for sustainable water and air treatment. It is also relatively easy to operate and maintain, and its modularity allows for easy scaling depending on treatment needs. Furthermore, biofiltration can be integrated with other treatment technologies, such as constructed wetlands or adsorption systems, to enhance overall contaminant removal and system resilience [150, 173, 174].

Although biofiltration may face limitations related to clogging, media aging, or sensitivity to environmental fluctuations, ongoing research is focused on improving media composition, microbial performance, and system design. This makes biofiltration a promising, eco-friendly solution for mitigating the risks posed by emerging pollutants in various environmental contexts.

Figure 19. Alternatives and mechanisms to remove ECs in batch and filtration technologies (reused from Almeida-Naranjo et al., 2023 [173], under the terms and conditions of the Creative Commons At-tribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/)

4.2.1.3. Constructed wetlands

Constructed wetlands are engineered treatment systems designed to replicate the natural purification processes found in natural wetlands. By integrating physical, chemical, and biological mechanisms, these systems offer an efficient and sustainable approach to treating a wide range of waterborne contaminants, including emerging pollutants (EPs) such as pharmaceuticals, pesticides, endocrine-disrupting compounds, and various industrial chemicals [145, 175].

Constructed wetlands typically consist of shallow basins filled with substrates like gravel, sand, or soil and planted with wetland vegetation. As contaminated water flows through the system, it undergoes a series of treatment processes driven by the interaction between plants, substrates, and microbial communities. These systems can be classified into different types based on water flow patterns and structural design. Surface flow wetlands allow water to move slowly over a vegetated surface, facilitating direct interaction with plants and sunlight. In contrast, subsurface flow wetlands direct water through a porous medium beneath the surface, where it comes into contact with plant roots and dense microbial biofilms that support pollutant degradation. Hybrid systems combine surface and subsurface flows to enhance removal performance by exploiting the complementary strengths of both configurations [27, 100, 145].

The effectiveness of constructed wetlands in removing pollutants stems from several interconnected mechanisms. Wetland vegetation plays a vital role by taking up nutrients and certain organic pollutants through their root systems and by providing oxygen and organic matter to support microbial activity in the rhizosphere. Microbial degradation, particularly under aerobic and anaerobic conditions, is essential for breaking down complex organic compounds, including many persistent micropollutants found in wastewater. Additionally, physical processes such as sedimentation help remove suspended solids and associated pollutants, while adsorption onto substrate materials contributes to the retention of heavy metals and hydrophobic contaminants (Figure 20) [176].

Constructed wetlands have been successfully applied in the treatment of municipal and industrial wastewater, agricultural runoff, landfill leachate, and stormwater, often in decentralized or rural settings. Their ability to remove nutrients such as nitrates and phosphates, in addition to organic micropollutants, makes them particularly valuable for integrated water resource management. Moreover, they offer multiple co-benefits, including habitat creation, landscape enhancement, and carbon sequestration [151, 177].

While constructed wetlands may require a relatively large land area and are influenced by seasonal variations in temperature and vegetation growth, they remain one of the most cost-effective and environmentally sustainable options for the long-term removal of emerging contaminants. Advances in design, substrate selection, and plant species optimization continue to improve their performance and expand their applicability to a wider range of pollutants and climatic conditions.

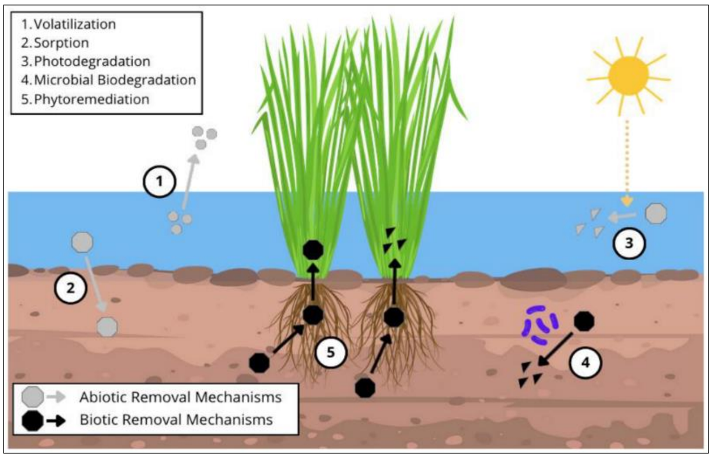

Figure 20. Wetland removal mechanisms of emerging contaminants. Octagons represent parent compounds, triangles represent transformation products. Abiotic removal mechanisms in grey, biotic removal mechanisms in black. Purple rods represent bacteria involved in biodegradation (reused from Overton et al., 2020 [176], under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

4.2.2. Advantages of integrating nature-based approaches

4.2.2.1. Sustainability and eco-friendliness

One of the most significant advantages of integrating nature-based approaches, such as constructed wetlands, biofiltration, and phytoremediation into water and wastewater treatment systems is their inherent sustainability and low environmental footprint. These systems are designed to work in harmony with natural processes, utilizing biological, physical, and chemical mechanisms driven by plants, microorganisms, and natural substrates. Unlike conventional technologies that often rely on high energy input and chemical additives, nature-based solutions operate with minimal external resources, significantly reducing greenhouse gas emissions, chemical use, and energy consumption (Figure 21) [178].

Because they mimic or enhance natural ecological functions, these approaches promote biodiversity, restore degraded environments, and improve the resilience of ecosystems. They often integrate seamlessly into the landscape, contributing to green infrastructure, enhancing aesthetic value, and supporting ecological corridors. In addition, many of these systems, such as constructed wetlands, provide multiple co-benefits beyond pollutant removal, including flood control, carbon sequestration, habitat provision, and climate regulation [112, 179].

Nature-based approaches are also highly adaptable to local environmental conditions and are particularly suited for decentralized and rural applications where access to advanced infrastructure is limited. Their ability to operate effectively with variable loads and without intensive management makes them ideal for long-term, low-maintenance pollution control. Furthermore, the materials used, such as gravel, soil, and plants are often locally available and renewable, making these systems both cost-effective and environmentally responsible [180, 181].

In a broader context, the integration of nature-based treatment methods supports the transition toward circular and regenerative water management, aligning with global sustainability goals and environmental policy frameworks such as the EU Green Deal and the UN Sustainable Development Goals (SDGs) [181, 182]. By combining pollutant removal with ecosystem services, these approaches represent a holistic and future-oriented solution for addressing the complex challenges posed by emerging pollutants in a changing world.

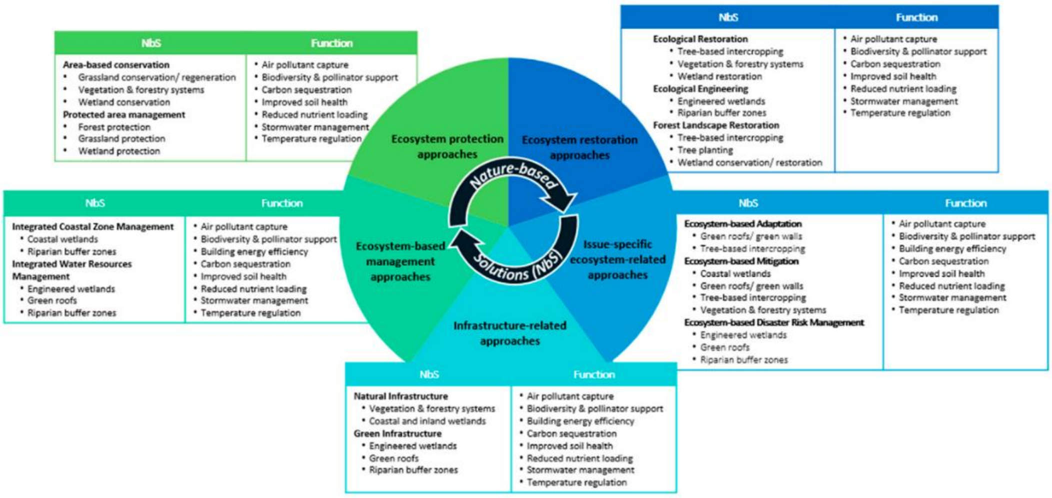

Figure 21. International Union for the Conservation of Nature (IUCN) categories of NbS, with examples of specific applications and functions (reused from Anderson et al., 2023 [178], under under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

4.2.2.2. Cost-effectiveness

Nature-based solutions (NBS) are cost-effective alternatives to conventional water treatment systems, which often require high capital investment, energy use, and specialized infrastructure. In contrast, NBS, such as constructed wetlands, biofilters, and phytoremediation, use low-cost, locally sourced materials and operate with minimal energy and maintenance [183].

These benefits are especially valuable in low-resource or rural areas, where technical capacity and funding are limited. NBS are typically simple to build, adaptable to local conditions, and easy to maintain, requiring only basic skills and low ongoing costs. Beyond direct savings, NBS offer economic co-benefits such as supporting ecotourism, biomass production, irrigation, and land restoration. By

improving water quality and ecosystem health, they can also reduce healthcare and environmental costs [184, 185].
NBS add resilience to systems by reducing dependence on energy and supply chains, key advantages in times of financial or environmental stress. As climate adaptation and sustainability priorities grow, NBS are increasingly seen as efficient, multi-benefit investments [186-188]. Nature-based solutions provide affordable, low-impact options for managing emerging pollutants and broader environmental challenges, appealing to both resource-limited communities and forward-looking institutions.
Nature-based solutions, including phytoremediation, biofiltration, and constructed wetlands, provide effective, sustainable, and multifaceted approaches to mitigating the risks and reducing the persistence of emerging pollutants [189, 190]. Their ability to integrate seamlessly with natural ecosystems while offering co-benefits such as biodiversity enhancement and community engagement makes them an essential component of modern environmental management strategies. By combining these solutions with advanced technological methods, it is possible to create comprehensive and adaptive frameworks to address the growing challenges of pollution in a rapidly changing world.

5. Conclusions

Emerging pollutants (EPs) are increasingly recognized as a major environmental and public health challenge due to their chemical diversity, persistence, potential for bioaccumulation, and the subtle yet significant effects they exert even at trace concentrations. As this review has shown, EPs encompass a wide range of substances, including pharmaceuticals, personal care products, endocrine-disrupting chemicals, pesticides, industrial compounds, and microplastics, which are frequently detected in surface waters, groundwater, soils, and even in drinking water systems. Their presence is often linked to anthropogenic activities, inadequate treatment infrastructure, and insufficient regulatory frameworks.
The impacts of EPs are both broad and complex. Ecologically, these substances can disrupt aquatic and terrestrial food webs, alter microbial community structure, and impair reproductive and neurological functions in wildlife. From a human health perspective, chronic exposure, often through contaminated water or food has been associated with endocrine disruption, reproductive toxicity, carcinogenicity, neurodevelopmental disorders, and the proliferation of antimicrobial resistance. These effects are further compounded by global environmental pressures, such as climate change, which can influence the distribution, transformation, and toxicity of emerging contaminants, thereby amplifying their risks.
In response to these concerns, considerable research and technological innovation have focused on developing efficient strategies for the removal of EPs from

contaminated environments. Conventional methods such as adsorption, membrane filtration, and advanced oxidation processes offer valuable removal efficiencies but are often limited by high operational costs, energy demand, and the potential generation of toxic transformation products. Biological treatments, while more sustainable, may be less effective for recalcitrant compounds. As this review has emphasized, integrated approaches that combine physical, chemical, and biological processes are gaining traction as more effective and adaptable solutions.

In particular, nature-based solutions (NBS), such as constructed wetlands, phytoremediation systems, and biofiltration units have emerged as promising alternatives due to their low cost, minimal energy requirements, scalability, and multifunctionality. These systems not only facilitate the degradation or sequestration of pollutants through natural processes but also provide additional ecosystem services, such as biodiversity support, carbon capture, and water retention. Their adaptability to diverse environmental contexts and long-term viability further underline their potential in future pollution control strategies.

However, despite notable progress, several challenges remain. There is a need for improved monitoring technologies and standardized analytical methods to detect and quantify EPs, especially at low concentrations and in complex mixtures. Regulatory gaps must also be addressed to establish permissible limits and safety thresholds for a broader range of contaminants. Moreover, knowledge gaps regarding the environmental fate, transformation products, and combined effects of EPs require urgent attention. Continued research should aim to enhance the selectivity, efficiency, and sustainability of existing treatment technologies while fostering innovation in green chemistry and eco-engineering.

Ultimately, addressing the growing threat of emerging pollutants demands a systemic and interdisciplinary approach, integrating scientific research, technological development, regulatory reform, and public engagement. Cross-sector collaboration, among academia, industry, government bodies, and communities will be crucial in implementing effective solutions, promoting responsible chemical management, and ensuring the long-term protection of ecosystems and human health in the face of evolving environmental pressures.

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