Annals of the Academy of Romanian Scientists
Series on Physics and Chemistry
Online ISSN **2559 – 1061** Volume **9**, Number 2/**2024**

EMERGING POLLUTANTS IN THE ENVIRONMENT. I. SOURCES, ACCUMULATION, AND ECOLOGICAL IMPLICATIONS

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Rezumat. *Persistența poluanților emergenți (EPs) în mediu reprezintă o provocare globală semnificativă, deoarece acești contaminanți, incluzând produse farmaceutice, produse de îngrijire personală, substanțe chimice industriale, pesticide, nanomateriale și microplastice, se acumulează în apă, sol, aer și biotă, având adesea consecințe pe termen lung necunoscute. Stabilitatea lor chimică, rezistența la degradare și utilizarea pe scară largă contribuie la prezența lor continuă în mediu, ridicând îngrijorări privind perturbările ecologice și riscurile pentru sănătatea umană. Mulți EP acționează ca perturbatori endocrini, neurotoxine sau agenți cancerigeni, afectând sănătatea reproductivă, funcțiile metabolice, biodiversitatea și comunitățile microbiene. Bioacumularea și biomagnificarea acestora în lanțurile trofice amplifică și mai mult riscurile, în timp ce mobilitatea lor transfrontalieră complică eforturile de atenuare. Cadrul de reglementare actual rămâne insuficient pentru a aborda persistența EP, fiind necesare acțiuni globale coordonate, strategii avansate de monitorizare și dezvoltarea unor tehnologii de tratare îmbunătățite. Această lucrare analizează sursele, comportamentul în mediu și impacturile EP, subliniind necesitatea unor abordări integrate de management pentru a minimiza consecințele lor ecologice și asupra sănătății umane pe termen lung.*

Abstract. *The persistence of emerging pollutants (EPs) in the environment presents a significant global challenge, as these contaminants, including pharmaceuticals, personal care products, industrial chemicals, pesticides, nanomaterials, and microplastics, accumulate in water, soil, air, and biota with often unknown long-term consequences. Their chemical stability, resistance to degradation, and widespread use contribute to their continuous environmental presence, raising concerns about ecological disruptions. Many EPs induce impacts on reproductive health, metabolic functions, biodiversity, and microbial communities. Their bioaccumulation and biomagnification through food chains*

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further amplify risks, while their transboundary mobility complicates mitigation efforts. Current regulatory frameworks remain insufficient in addressing EP persistence, necessitating coordinated global actions, enhanced monitoring strategies, and the development of advanced treatment technologies. This review explores the sources, environmental behavior, and impacts of EPs, emphasizing the need for integrated management approaches to minimize their long-term ecological and human health consequences.

Keywords: bioaccumulation, ecological disruption, emerging pollutants, environmental persistence, impact, pollution mitigation

DOI 10.56082/annalsarsciphyschem.2024.2.41

1. Introduction

The persistence of emerging pollutants (EPs) in the environment has become a pressing global concern, as these contaminants are increasingly detected in water, soil, air, and biota, often with unknown long-term consequences. Unlike conventional pollutants, EPs encompass a wide variety of pharmaceuticals, personal care products, industrial chemicals, pesticides, nanomaterials, and microplastics, many of which have not been fully regulated or systematically monitored. Advances in analytical techniques have led to the increased detection of these substances in diverse environmental matrices, raising concerns about their potential to disrupt ecosystems and threaten human health [1-4].

With industries producing and utilizing over 100,000 different substances, chemicals play a fundamental role in daily life. The global chemical sector significantly influences economic development and job creation. However, many of these substances are released into the environment, leading to widespread contamination of soil and water. Such pollutants pose serious risks to both ecosystems and human health, contributing to a range of adverse effects, including endocrine disruption, immunotoxicity, neurological impairments, and cancer.

While some emerging pollutants are newly introduced substances, others have been present in the environment for years but were previously overlooked due to analytical limitations or a lack of awareness regarding their ecological impact. Their persistence is primarily attributed to chemical stability, resistance to degradation, and widespread use in industrial and domestic applications. Many of these compounds resist natural attenuation processes such as biodegradation, photodegradation, and chemical transformation, allowing them to accumulate in ecosystems and persist over long timeframes. Their mobility further exacerbates the issue, as EPs can be transported over long distances via water currents, atmospheric deposition, and biological pathways, making them a transboundary concern [5, 6].

The bioactivity of EPs, even at trace concentrations, presents another challenge. While these contaminants may be present at levels as low as nanograms per liter (ng/L) in surface waters, their continuous input from wastewater, industrial discharges, and agricultural runoff contributes to chronic exposure for organisms and humans. Many EPs act as endocrine disruptors, neurotoxins, or carcinogens, with the potential to alter reproductive cycles, impact metabolic processes, and induce long-term health effects. In wildlife, exposure to pharmaceuticals, hormones, and synthetic chemicals has been linked to behavioral changes, reproductive disorders, and biodiversity loss. In humans, prolonged exposure to persistent pollutants such as per- and polyfluoroalkyl substances (PFAS), bisphenol A (BPA), and certain pharmaceuticals has been associated with cancer, endocrine dysfunction, and developmental disorders [7, 8].

From an economic and regulatory standpoint, the presence of EPs in the environment poses significant challenges. The costs associated with mitigating their impacts, including upgrading wastewater treatment facilities, remediating contaminated ecosystems, and addressing healthcare burdens related to pollutant exposure, place considerable strain on governments, industries, and communities. Current regulatory frameworks often lag behind scientific discoveries, with many emerging contaminants lacking standardized monitoring protocols or risk assessments. While initiatives such as the Stockholm Convention on Persistent Organic Pollutants and the Minamata Convention on Mercury have addressed certain classes of hazardous substances, many EPs remain unregulated at the global level, necessitating coordinated international efforts for their control and mitigation [9, 10].

This manuscript provides a comprehensive review of the persistence of emerging pollutants in the environment, highlighting their sources, mechanisms of accumulation, ecological and human health impacts, and potential mitigation strategies. Emerging pollutants (EPs) are a growing concern due to their resistance to natural degradation processes, which enables them to accumulate in ecosystems and pose significant long-term threats to both environmental and human health. This study aims to contextualize the importance of EPs, explore their mechanisms of persistence, and assess the ecological, human, and socio-economic risks associated with their presence in the environment. By synthesizing current research and advancements, the paper seeks to highlight the severity of this issue and propose actionable solutions that align with sustainable environmental management strategies.

The discussion begins with a detailed definition of emerging pollutants and their distinguishing characteristics, emphasizing their sources, pathways, and environmental behaviors. The focus then shifts to exploring the factors that contribute to their persistence, including their chemical stability, resistance to biodegradation, and interaction with environmental compartments such as water, soil, and air. By synthesizing the latest research on the topic, this work aims to enhance understanding of EP behavior in natural systems, inform regulatory developments, and contribute to the advancement of sustainable solutions for pollution management.

2. Emerging pollutants and their significance in the environment

Emerging pollutants (EPs) refer to a diverse group of chemical and biological substances that are not commonly monitored in the environment, but have the potential to cause significant ecological and human health impacts [3, 4].
Unlike conventional pollutants, EPs are often byproducts of modern industrial, agricultural, and domestic activities, including pharmaceuticals, personal care products, pesticides, nanomaterials, flame retardants, microplastics. They are labeled as "emerging" not because they are newly introduced into the environment but due to the growing recognition of their presence and potential hazards facilitated by advances in analytical detection techniques (Table 1) [8, 11-14]. Emerging pollutants pose a unique and escalating challenge due to their potential to disrupt ecosystems and public health. Despite their often low concentrations, their biological activity and cumulative effects can lead to significant ecological and health risks [15, 16].

Table 1. Key characteristics of emerging pollutants

Characteristic	*Description*
Persistence	Many EPs are resistant to natural degradation processes, enabling them to persist in environmental matrices such as water, soil, and air for extended periods.
Low concentrations	These substances are often detected at trace levels (e.g., ng/L to µg/L), which complicates their monitoring and assessment of toxicity.
Diverse sources	EPs originate from multiple sources, including industrial processes, agricultural runoff, wastewater treatment plants, and even household products.
Global presence	Due to their persistence and mobility, EPs are now detected worldwide, from urban centers to remote ecosystems such as the Arctic.

2.1. Impacts of emerging pollutants: Ecological, human health, and socio-economic consequences

Emerging pollutants (EPs) pose a growing environmental and public health concern due to their persistence, bioactivity, and widespread presence in ecosystems. These contaminants, which include pharmaceuticals, personal care products, pesticides, and industrial chemicals, often evade conventional treatment processes and accumulate in water, soil, and biota. Their continued release into the environment disrupts natural ecological functions, threatens biodiversity, and contributes to long-term health risks. Moreover, the socio-economic burden of managing EPs, ranging from remediation costs to healthcare expenses, underscores the urgency of developing sustainable mitigation strategies. This section explores the multifaceted impacts of EPs, highlighting their ecological consequences, human health risks, and economic implications.

2.1.1. Ecological impact

Emerging pollutants (EPs) pose a significant threat to ecosystems by altering the physiological and behavioral responses of organisms, leading to disruptions in natural ecological processes. These contaminants enter the environment through wastewater discharge, agricultural runoff, and industrial emissions, accumulating in aquatic and terrestrial habitats [17, 18]. One of the most concerning effects of EPs is their impact on the behavior, reproduction, and survival of various species. Pharmaceuticals, such as antidepressants and anxiolytics, have been shown to alter fish behavior, reducing predator avoidance and affecting feeding patterns. Similarly, endocrine-disrupting chemicals (EDCs), including certain pesticides, plasticizers, and industrial byproducts, interfere with hormonal regulation in wildlife, leading to reproductive abnormalities, reduced fertility, and developmental defects in offspring. Amphibians, fish, and invertebrates are particularly vulnerable to these disruptions, which can have cascading effects throughout food webs [19, 20].

Furthermore, many EPs exhibit persistence in the environment, allowing them to bioaccumulate in organisms and biomagnify as they move up the food chain. This is especially problematic for top predators, such as birds of prey, marine mammals, and large fish species, which experience higher contaminant loads due to their dietary habits. The accumulation of persistent pollutants, such as pharmaceuticals, flame retardants, and per- and polyfluoroalkyl substances (PFAS), has been linked to immune suppression, neurological impairments, and increased susceptibility to disease in wildlife [21-23]. The destabilization of ecosystems caused by EP exposure can lead to biodiversity loss and shifts in species composition. For instance, the presence of antibiotics in aquatic environments can alter microbial communities by selectively eliminating sensitive species while promoting the proliferation of antibiotic-resistant bacteria. These changes disrupt ecological balance and nutrient cycling, with potential consequences for water quality and ecosystem resilience [24].

Given these ecological risks, addressing the persistence and impact of EPs requires integrated monitoring programs, stricter regulations, and the development of environmentally friendly alternatives to minimize their release into natural ecosystems.

2.1.2. Human health concerns

The presence of emerging pollutants (EPs) in the environment poses a growing threat to human health, as these contaminants often persist in water, soil, and food sources, leading to continuous low-dose exposure. Many EPs, including pharmaceuticals, personal care products, pesticides, and industrial chemicals, exhibit biological activity even at trace concentrations, potentially causing long-term adverse health effects [15, 23].

One of the primary concerns associated with EP exposure is their impact on the endocrine system. Endocrine-disrupting chemicals (EDCs), such as bisphenol A (BPA), phthalates, and certain pesticides, can interfere with hormone signaling, leading to developmental disorders, reproductive issues, metabolic diseases, and an increased risk of hormone-related cancers. Studies have linked prenatal and early-life exposure to EDCs with neurodevelopmental impairments, obesity, and immune dysfunction, raising concerns about transgenerational health effects [25, 26].

Another major issue is the role of EPs in promoting antibiotic resistance. The widespread use and improper disposal of antibiotics have led to their continuous release into the environment, creating reservoirs of antibiotic-resistant bacteria in wastewater, agricultural runoff, and drinking water sources. This has severe implications for global healthcare, as the spread of resistant pathogens undermines the effectiveness of life-saving antibiotics, increasing the risk of untreatable infections, longer hospital stays, and higher mortality rates [27, 28].

Furthermore, the contamination of drinking water with EPs, including pesticides, per- and polyfluoroalkyl substances (PFAS), and heavy metals, presents a direct threat to public health, particularly in regions where water treatment infrastructure is inadequate. Chronic exposure to these contaminants has been linked to a range of health disorders, including cancer, neurological impairments, immune suppression, and cardiovascular diseases. Vulnerable populations, such as pregnant women, infants, and individuals with pre-existing health conditions, are particularly at risk from long-term EP exposure [29, 30].

Given these risks, there is an urgent need for improved water treatment technologies, stricter regulations on EP emissions, and greater public awareness of proper pharmaceutical and chemical disposal practices. Comprehensive risk assessments and long-term epidemiological studies are also necessary to fully understand the health implications of chronic EP exposure and to develop effective mitigation strategies [31].

2.1.3. Socio-economic implications

The persistence of emerging pollutants (EPs) in the environment has far-reaching socio-economic consequences, affecting public health systems, industries, and environmental management policies. The economic burden associated with EP contamination extends beyond direct remediation costs, encompassing healthcare expenses, reduced agricultural and fisheries productivity, and the long-term degradation of natural resources [2].

One of the most significant financial impacts of EPs is the cost of upgrading water treatment infrastructure to remove contaminants that evade conventional wastewater treatment processes. Advanced treatment technologies, such as membrane filtration, advanced oxidation processes, and activated carbon adsorption, require substantial investments in equipment, operational maintenance, and energy consumption. Many municipalities, particularly in low-income regions, lack the financial and technical capacity to implement such upgrades, leading to prolonged exposure to contaminated water supplies [32, 33].

The healthcare sector also bears a significant economic burden due to the long-term health effects associated with EP exposure. The increased prevalence of endocrine disorders, antibiotic-resistant infections, and chronic diseases linked to pollutants such as pesticides and pharmaceuticals results in rising medical costs, lost productivity, and higher insurance expenses. Antibiotic resistance alone is estimated to cost healthcare systems billions of dollars annually due to extended hospital stays, additional medical interventions, and higher mortality rates.

In addition to public health concerns, EPs negatively impact key economic sectors such as agriculture, fisheries, and tourism. Contaminated irrigation water can introduce toxic substances into crops, reducing agricultural yields and posing risks to food safety. Similarly, pollutants accumulating in fish and seafood not only threaten aquatic biodiversity but also reduce the marketability of fishery products, leading to economic losses for fishing communities. In areas dependent on ecotourism, environmental degradation caused by EP contamination can result in decreased revenue and job losses [24, 29].

Moreover, the remediation of ecosystems affected by EPs requires long-term financial and logistical commitments. Cleaning up polluted water bodies, rehabilitating contaminated soils, and restoring biodiversity demand extensive research, monitoring, and technological interventions. Without proactive mitigation strategies, the cumulative costs of environmental restoration will continue to escalate, placing additional strain on governments and businesses.

Addressing the socio-economic challenges posed by EPs requires a combination of preventive measures, policy reforms, and sustainable management strategies. Investments in green chemistry, stricter regulations on pollutant discharge, and incentives for industries to develop environmentally friendly alternatives can help minimize future economic burdens [34, 35]. Additionally, raising public awareness about the responsible use and disposal of pharmaceuticals, personal care products, and industrial chemicals is crucial in reducing EP contamination at the source [36]. By integrating economic and environmental policies, societies can work toward more cost-effective and sustainable solutions to mitigate the long-term impacts of emerging pollutants.

2.2. The issue of environmental persistence and its implications

Environmental persistence refers to the ability of a substance to remain in the environment over extended periods without significant degradation (Table 1). This characteristic is particularly concerning for emerging pollutants (EPs) because it amplifies their potential to cause long-term ecological and human health risks. Persistent substances resist natural breakdown processes, such as biodegradation by microorganisms, photodegradation by sunlight, or chemical degradation, allowing them to accumulate in environmental matrices like soil, water, and air. This persistence, combined with the widespread use of emerging pollutants, creates significant challenges in managing their environmental and societal impacts.

2.2.1. Mechanisms behind environmental persistence

The persistence of emerging pollutants in the environment is governed by a complex interplay of physicochemical properties, environmental conditions, and interactions with natural and anthropogenic factors. Unlike readily degradable contaminants, persistent pollutants resist natural attenuation processes, allowing them to accumulate in ecosystems over extended periods. Understanding the mechanisms that drive their persistence is crucial for assessing their long-term environmental impact and developing effective mitigation strategies [27, 36].

Key factors influencing environmental persistence include the chemical stability of pollutants, their affinity for environmental matrices, and their resistance to microbial degradation. Many emerging pollutants, such as pharmaceuticals, perfluoroalkyl substances (PFAS), and certain pesticides, exhibit high hydrophobicity, low volatility, and strong sorption to sediments and organic matter, which limits their mobility but prolongs their retention in soil and aquatic environments. Additionally, molecular structures containing halogenated bonds, aromatic rings, or complex functional groups enhance resistance to biodegradation, making these compounds particularly recalcitrant [37, 38].

Environmental conditions such as temperature, pH, redox potential, and the presence of co-contaminants further influence the degradation pathways and transformation rates of these pollutants. While some pollutants undergo abiotic degradation via hydrolysis, photodegradation, or oxidation, others persist due to limited exposure to these processes in subsurface environments or deep aquatic systems. In some cases, transformation products formed through partial degradation may exhibit equal or greater toxicity and persistence than their parent compounds, complicating risk assessments [39].

There are some primary mechanisms that contribute to the persistence of emerging pollutants in the environment, highlighting their interactions with natural systems and their resistance to degradation (Table 2) [7, 40-42]. A deeper understanding of these mechanisms is essential for designing effective remediation technologies and regulatory policies to minimize long-term ecological and human health risks.

Table 2. Factors and mechanisms that contribute to the persistence of emerging pollutants in the environment

Factors/Mechanisms	*Description*
Chemical stability	Many emerging pollutants, such as per- and polyfluoroalkyl substances (PFAS) and certain pesticides, possess strong chemical bonds (e.g., carbon-fluorine bonds) that resist natural degradation. This stability enables them to persist in the environment for decades, earning some substances the nickname "forever chemicals."
Resistance to biodegradation	Microorganisms in the environment often lack the enzymatic capacity to break down novel or synthetic compounds, especially those with complex molecular structures, as seen in pharmaceuticals and industrial chemicals.
Low volatility and high solubility	Some persistent pollutants, such as pharmaceuticals, dissolve easily in water, facilitating their movement through aquatic systems. This solubility contributes to their widespread distribution and persistence in water bodies.
Partitioning between environmental compartments	Persistent pollutants can accumulate in sediments, soils, or organisms, creating reservoirs that release the pollutants back into the environment over time, prolonging exposure.

2.2.2. Implications of environmental persistence

a. Accumulation in ecosystems

Emerging pollutants (EPs) accumulate in various environmental compartments, persisting in water bodies, sediments, soil, and the atmosphere due to their chemical stability and resistance to degradation. Many of these pollutants exhibit lipophilic properties, enabling their accumulation in environmental matrices and biological tissues, followed by long-range atmospheric transport. These attributes facilitate their bioaccumulation and biomagnification in animals, posing significant threats to human health and ecosystems [23, 43].

In aquatic ecosystems, pollutants such as pharmaceutical residues, pesticides, and industrial chemicals persist for extended periods, even after dilution. Pharmaceutical contaminants**,** including antibiotics, antidepressants, and hormone-based drugs, disrupt aquatic species at all trophic levels by altering behavior, reproduction, and metabolic processes [44].

For instance, exposure to endocrine-disrupting chemicals (EDCs) has been linked to impaired reproductive functions and sex reversal in fish populations, affecting species survival and biodiversity. Persistent pesticides and industrial chemicals further bind to soil particles or settle in sediments**,** contaminating agricultural lands and aquatic habitats (soil and sediments) and prolonging their environmental impact [15].

Bioaccumulation of these pollutants in terrestrial and aquatic organisms allows them to enter the human food chain through fish, amphibians, insects, livestock, fruits, vegetables, and other dietary sources. Livestock raised on contaminated feed or water sources may accumulate EPs in their tissues, passing them on to consumers through meat, milk, and eggs. The uptake of these pollutants by plants through irrigation or soil contamination poses additional concerns for agricultural sustainability and food security [6, 45].

Atmospheric transport further facilitates the global spread of EPs**.** Certain pollutants, such as persistent organic pollutants (POPs), microplastics, and volatile industrial chemicals**,** can travel long distances via air currents before being deposited far from their original sources. Studies have reported the presence of these pollutants in remote ecosystems, including the Arctic and high-altitude environments**,** where they accumulate in wildlife and indigenous food systems, raising concerns about long-term ecological and health consequences (Figure 1) [46].

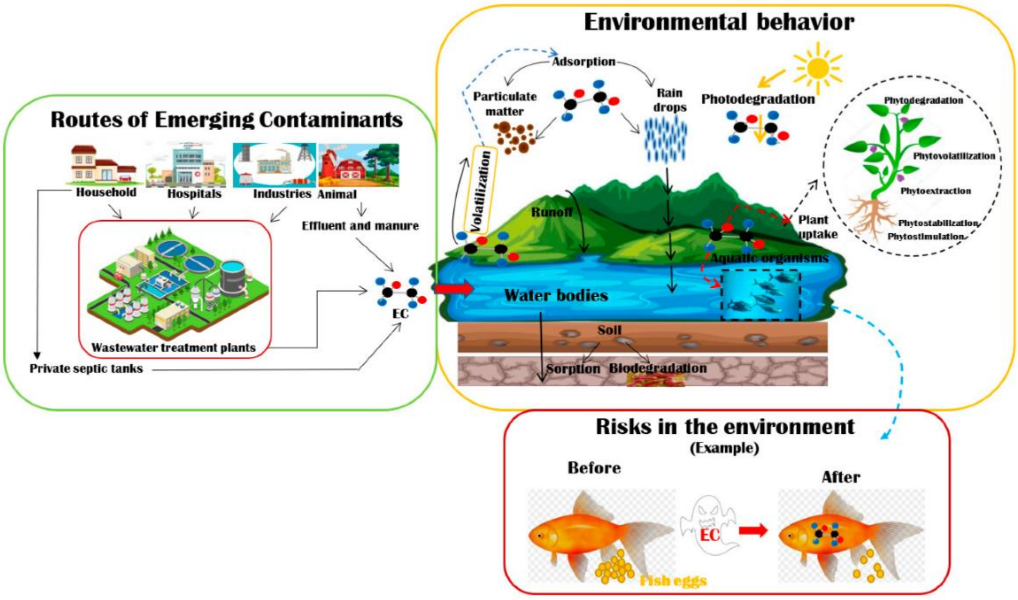

Figure 1. Routes of entry of ECs into the environment, its behavior, and effects (reused from Almeida-Naranjo et al., 2023 [46], under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/)

The widespread accumulation of EPs disrupts ecological balance, affecting ecosystem services such as water purification, soil fertility, and biodiversity conservation. Pollutant exposure has been linked to congenital abnormalities, immune system suppression, and increased mortality rates in wildlife [23]. Additionally, the loss of keystone species due to pollutant toxicity can trigger cascading effects throughout entire ecosystems, reducing their resilience to environmental stressors such as climate change and habitat degradation.

Given the persistence and mobility of emerging pollutants, urgent action is needed to monitor, regulate, and mitigate their environmental accumulation**.** Improved wastewater treatment technologies**,** stricter regulations on industrial discharges**,** and sustainable agricultural practices can help limit pollutant inputs into natural ecosystems. Moreover, enhanced biomonitoring programs are essential to track the long-term effects of EPs on biodiversity and human health, providing a scientific foundation for policy interventions and sustainable environmental management strategies [47].

b. Bioaccumulation and biomagnification

The persistence of emerging pollutants (EPs) in the environment facilitates their bioaccumulation in living organisms and their biomagnification through the food chain. Bioaccumulation occurs when pollutants are absorbed by an organism at a rate faster than they can be metabolized or excreted, leading to their accumulation in tissues over time. Biomagnification refers to the increasing concentration of these pollutants as they move up trophic levels, posing significant risks to both wildlife and human health [48, 49]. Many persistent pollutants, including heavy metals (e.g., mercury, lead, cadmium), persistent organic pollutants (POPs), pharmaceuticals, and industrial chemicals, exhibit high lipid solubility, enabling them to accumulate in fatty tissues. Lipophilic contaminants, such as polychlorinated biphenyls (PCBs), per- and polyfluoroalkyl substances (PFAS), and certain pesticides, persist within biological systems for long periods, exerting toxic effects even at low concentrations. These substances are readily absorbed by primary consumers such as plankton, aquatic invertebrates, and small fish, which are then consumed by larger predators, leading to a progressive increase in pollutant concentrations at higher trophic levels (Figure 1) [47].

Pesticide contamination in aquatic environments has led to its bioaccumulation in fish species, with particularly high concentrations found in top predators such as tuna, swordfish, and sharks. This poses serious risks to wildlife, which can impair reproduction, disrupt hormonal balance, and weaken immune responses. In humans, the consumption of mercury-contaminated seafood has been linked to neurological disorders, developmental impairments in children, and cardiovascular diseases. Similarly, PFAS, widely used in industrial and consumer products, have been detected in marine mammals, birds, and human blood samples, raising concerns about their long-term toxicity, endocrine-disrupting properties, and association with cancers and immune dysfunction.

In terrestrial ecosystems, pesticides and industrial pollutants accumulate in soil and vegetation, making their way into herbivorous animals, which are then consumed by predators. Birds of prey, carnivorous mammals, and humans are particularly vulnerable to the biomagnification of contaminants such as dioxins, PCBs, and flame retardants, which have been linked to fertility issues, birth defects, and organ damage [50-52].

The ecological consequences of bioaccumulation and biomagnification are far-reaching, affecting species survival, reproductive success, and ecosystem stability. Pollutants that accumulate in top predators can lead to population declines, disrupting food web dynamics and biodiversity. In addition, sub-lethal effects, such as behavioral changes, weakened immune systems, and genetic mutations, further compromise species resilience to environmental stressors [45].

Addressing the risks of bioaccumulation and biomagnification requires comprehensive pollutant management strategies, including stricter regulations on chemical discharges, phase-outs of persistent and bioaccumulative substances, and improved wastewater and industrial waste treatment [48, 53]. Public health initiatives should also promote awareness of seafood contamination risks, while conservation efforts must focus on monitoring pollutant levels in wildlife and protecting vulnerable species from exposure to hazardous substances.

c. Long-term toxicity

Persistent pollutants often exert chronic toxicity, even when present in the environment at low concentrations. Unlike acute toxicity, which results from short-term, high-dose exposure, chronic toxicity occurs over extended periods due to continuous environmental contamination [12, 54]. The prolonged presence of these pollutants ensures constant exposure for organisms, leading to cumulative physiological stress, reproductive impairments, developmental abnormalities, and increased mortality rates in both wildlife and humans (Figure 1) [47].

In wildlife, long-term exposure to persistent pollutants such as heavy metals, pesticides, pharmaceuticals, and endocrine-disrupting chemicals (EDCs) has been linked to reproductive failures, immune suppression, and altered growth patterns. For example, EDCs such as bisphenol A (BPA), dioxins, and phthalates interfere with hormonal signaling in vertebrates, leading to sex ratio imbalances, decreased fertility, and congenital deformities in affected species. In aquatic ecosystems, pollutants such as pharmaceutical residues and industrial chemicals persist for long periods, disrupting endocrine function, metabolism, and immune responses in fish, amphibians, and invertebrates. Low-dose but continuous exposure to antidepressants and other psychoactive pharmaceuticals has been shown to alter fish behavior, feeding habits, and predator avoidance, increasing their risk of predation and reducing population stability. Persistent pesticides, such as organochlorines and neonicotinoids, have also been implicated in the decline of pollinators, birds, and aquatic organisms, reducing biodiversity and threatening ecosystem health [55].

In humans, prolonged exposure to persistent pollutants has been linked to a wide range of chronic health disorders, including hormonal imbalances, metabolic diseases, neurodevelopmental disorders, immune dysfunction, and cancers. EDCs, which mimic or block natural hormones, have been associated with early puberty, infertility, thyroid disorders, and an increased risk of breast and prostate cancer. Heavy metal exposure, particularly from contaminated water and food sources, has been connected to cognitive impairments, kidney damage, and cardiovascular diseases. Additionally, exposure to persistent organic pollutants (POPs), such as polychlorinated biphenyls (PCBs) and dioxins, has been correlated with neurological disorders, weakened immune responses, and developmental delays in children [37, 56, 57].

One of the greatest challenges in addressing long-term toxicity is the delayed manifestation of health effects, making it difficult to establish direct causation between pollutant exposure and disease outcomes. Furthermore, pollutants can interact synergistically, amplifying their toxic effects and complicating risk assessments. Transgenerational toxicity is another growing concern, as some pollutants can alter genetic expression (epigenetic changes), affecting not only exposed individuals but also their offspring [58].

To mitigate the long-term toxic effects of persistent pollutants, preventative and regulatory measures are essential. Strengthening chemical regulations, improving waste management, and implementing advanced water treatment technologies can help reduce pollutant release into the environment. Additionally, long-term epidemiological studies, biomonitoring programs, and public health initiatives are crucial for understanding exposure risks and developing strategies to protect vulnerable populations from the harmful effects of chronic pollutant exposure.

d. Threats to water resources

Persistent pollutants pose a significant threat to global water quality and freshwater resources, as conventional wastewater treatment plants (WWTPs) are often ineffective at removing emerging pollutants (EPs). As a result, pharmaceuticals, pesticides, industrial chemicals, and endocrine-disrupting compounds are continuously discharged into natural water bodies, contaminating rivers, lakes, groundwater, and even drinking water supplies [59, 60]. Many EPs, including pharmaceutical residues, personal care products, microplastics, and per- and polyfluoroalkyl substances (PFAS), are designed to resist degradation, allowing them to persist in aquatic environments for extended periods. Once released into wastewater, these pollutants often bypass conventional treatment processes, as standard filtration and biological degradation methods are not optimized for their removal. As a result, WWTP effluents serve as continuous sources of EP contamination, allowing these substances to accumulate in surface water and infiltrate groundwater systems [46, 61] (Figure 1).

The contamination of drinking water sources is particularly concerning, as long-term exposure to low-dose EPs has been linked to adverse health effects such as hormonal disruptions, reproductive issues, antibiotic resistance, and increased cancer risks. Studies have detected traces of pharmaceuticals, pesticides, and industrial chemicals in treated drinking water, raising concerns about cumulative health effects from chronic exposure. Vulnerable populations, including infants, pregnant women, and individuals with compromised immune systems, face heightened risks from contaminated drinking water supplies [3, 62, 63].

In addition to human health risks, aquatic ecosystems suffer significant degradation due to EP contamination. Persistent pharmaceuticals, pesticides, and industrial solvents alter the behavior, physiology, and reproduction of aquatic organisms, leading to declining fish populations, reduced biodiversity, and ecosystem imbalances. Antibiotic residues, in particular, contribute to the proliferation of antibiotic-resistant bacteria, creating public health risks by reducing the effectiveness of medical treatments for bacterial infections.

Furthermore, climate change and increasing water scarcity exacerbate the challenges associated with EP contamination. As freshwater resources become more limited, reliance on wastewater reuse and desalination technologies is increasing. However, without effective advanced water treatment solutions, these alternative water sources may still contain residual pollutants, further compromising water safety [64, 65].

To address the growing threat of EPs to water resources, advanced treatment technologies such as membrane filtration (reverse osmosis, nanofiltration), advanced oxidation processes (AOPs), and adsorption techniques (activated carbon, biochar) are being explored to enhance pollutant removal. Additionally, policy interventions, including stricter regulations on industrial and pharmaceutical waste disposal, improved monitoring of drinking water contaminants, and the development of green chemistry alternatives, are essential for preventing pollution at the source.

Ultimately, safeguarding water quality requires a multi-pronged approach that combines technological innovation, regulatory enforcement, and public awareness to ensure that water resources remain clean, safe, and sustainable for future generations.

e. Global spread and transboundary effects

The persistence and mobility of emerging pollutants (EPs) enable them to transcend national and continental boundaries, making pollution a global issue that necessitates international cooperation for effective management. Many EPs, including persistent organic pollutants (POPs), per- and polyfluoroalkyl substances (PFAS), heavy metals, and microplastics, exhibit long-range environmental transport through air, water currents, and migratory species, leading to their widespread distribution across ecosystems. As a result, even remote and pristine environments that are far from industrial or urban centers have been found to contain significant levels of contamination [59, 66, 67]. Atmospheric transport is one of the primary mechanisms facilitating the global spread of EPs. Volatile and semi-volatile pollutants, such as pesticides, industrial solvents, and combustion byproducts, can be carried thousands of kilometers by wind currents before undergoing deposition in distant regions. For instance, studies have detected POPs in Arctic ice cores, indicating that these contaminants originate from industrial emissions in other parts of the world and are transported through atmospheric circulation. These pollutants accumulate in Arctic ecosystems, where they bioaccumulate in marine mammals, seabirds, and fish, ultimately affecting indigenous communities that rely on these species for subsistence [68, 69].

Aquatic transport also plays a critical role in the transboundary movement of pollutants. Rivers, ocean currents, and groundwater flows act as conduits, dispersing contaminants across borders. Pharmaceutical residues, pesticides, and industrial chemicals discharged into rivers and lakes can travel downstream into international waterways, affecting multiple countries along their course. Similarly, microplastics and persistent chemical pollutants in marine environments are distributed globally by ocean currents, leading to contamination in deep-sea ecosystems and remote island communities. These pollutants pose severe risks to marine biodiversity and endanger global fisheries, as contaminated seafood enters international markets, posing potential health risks to consumers [30, 59, 67].

Migratory species further contribute to the transboundary movement of pollutants. Birds, fish, and marine mammals that travel across vast distances can accumulate pollutants in one region and transport them to another through biological pathways. Studies have found high levels of mercury, PFAS, and PCBs in migratory seabirds and whales, highlighting the global nature of contaminant exposure and the difficulty of containing pollution within national borders.

Given the international scale of pollutant dispersion, addressing the spread of EPs requires coordinated global action. International agreements, such as the Stockholm Convention on Persistent Organic Pollutants, the Basel Convention on Hazardous Waste, and the Minamata Convention on Mercury, provide frameworks for controlling the production, use, and disposal of hazardous substances. However, many EPs, including pharmaceuticals, microplastics, and newly developed industrial chemicals, remain unregulated at the global level, highlighting the need for expanded international monitoring and policy frameworks [70, 71].

To mitigate the transboundary effects of EPs, countries must work together to enhance pollution monitoring networks, share scientific data, harmonize regulations, and implement stricter controls on pollutant emissions and waste management. Strengthening international collaboration will be essential for protecting ecosystems, human health, and global environmental security, ensuring that the impacts of pollution are addressed proactively rather than reactively.

3. Sources and types of emerging pollutants

Emerging pollutants (EPs) encompass a wide range of substances that originate from human and industrial activities and are increasingly detected in the environment. These pollutants are often unregulated and not fully addressed by conventional monitoring or treatment systems, yet they have the potential to disrupt ecosystems and human health. This chapter explores the major categories of EPs, their primary sources, and the emerging trends in their occurrence and identification.

3.1. Major categories of emerging pollutants

Emerging pollutants are highly diverse, encompassing substances with distinct chemical and biological properties, ranging from pharmaceuticals, personal care products, and endocrine-disrupting compounds to industrial chemicals, microplastics, and per- and polyfluoroalkyl substances (PFAS). Their varied origins, persistence, and potential toxicity make them a growing concern for environmental and human health (Figure 2) [3]. Some of the most prominent categories are described in Table 3 [22, 72-75].

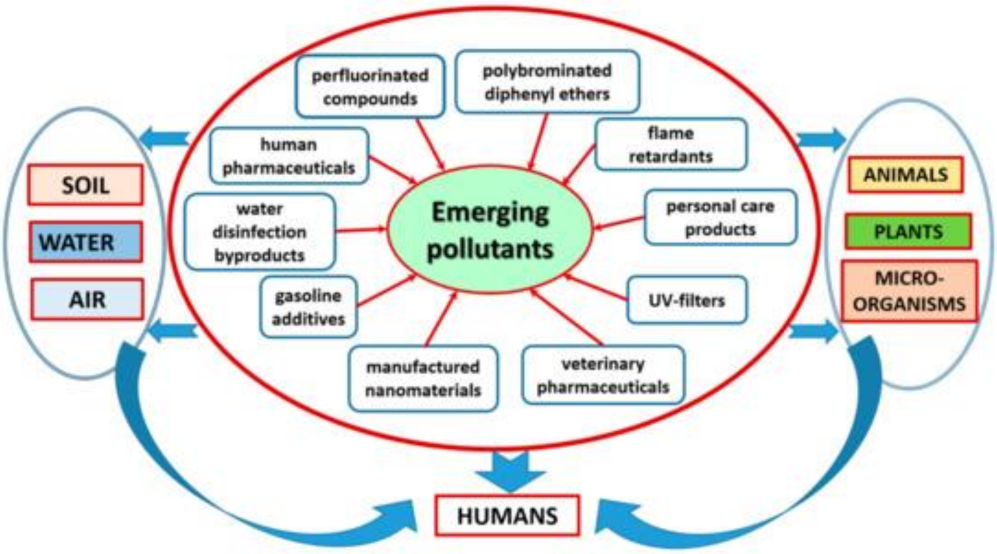

Figure 2. Categories of emerging pollutants that impact on soil, air, water, animals, plants, microorganisms and humans (reused from Vasilachi et al., 2021 [3], under the terms and conditions of the Creative Commons At-tribution (CC BY) license https://creativecommons.org/licenses/by/4.0/)

Table 3. Major categories of emerging pollutants

Nr. crt.	*Pollutant*	*Description*
1.	*Pharmaceuticals*	Medications such as antibiotics, analgesics, antidepressants, and hormonal drugs are widely used in human and veterinary medicine. Once consumed, a significant fraction of these drugs is excreted in unmetabolized or transformed forms, entering wastewater systems. Pharmaceuticals are particularly concerning because they are biologically active and can affect non-target organisms, leading to phenomena such as endocrine disruption in wildlife and the development of antibiotic-resistant bacteria.
2.	*Personal Care Products (PCPs)*	Products like shampoos, soaps, lotions, sunscreens, and cosmetics contain a range of chemicals, including parabens, microplastics, and ultraviolet (UV) filters. These substances often reach the environment through household wastewater. PCPs are concerning because their widespread use leads to constant low-level environmental exposure, which can disrupt aquatic life and bioaccumulate in organisms.
3.	*Industrial chemicals*	This category includes flame retardants, surfactants, solvents, and plasticizers such as bisphenol A (BPA) and phthalates. These chemicals are used in manufacturing processes and consumer products, with pathways to the environment including industrial effluents, accidental spills, and improper disposal. Many of these chemicals are persistent and toxic, contributing to long-term environmental contamination.
4.	*Pesticides*	Used extensively in agriculture and pest control, these substances often reach unintended environmental compartments through runoff, leaching, or aerial drift. Emerging concerns focus on newer pesticide formulations, including neonicotinoids and glyphosate, which are linked to declining pollinator populations and aquatic toxicity.
5.	*Nanomaterials*	With the rapid development of nanotechnology, nanoparticles such as titanium dioxide, silver nanoparticles, and carbon nanotubes are increasingly found in products ranging from electronics to sunscreens. Their small size and unique properties allow them to penetrate biological membranes and accumulate in organisms, raising concerns about their long-term ecological and health impacts.
6.	*Microplastics and plastic additives*	Microplastics, including primary microplastics (e.g., microbeads in cosmetics) and secondary microplastics (resulting from the breakdown of larger plastic items), are pervasive pollutants. Their persistence in ecosystems and ability to adsorb other pollutants make them a significant environmental concern.

3.2. Sources of emerging pollutants

Emerging pollutants enter the environment from a variety of sources, reflecting their widespread use in modern society. Recent monitoring studies have explored the distribution of emerging pollutants (EPs) in aquatic environments and their accumulation in various aquatic organisms. Wastewater treatment plants (WWTPs) serve as major pathways for EPs entering aquatic systems [24] and act as significant reservoirs for pollutants originating from industrial activities and biological processes [31]. On a global scale, research has further highlighted the movement of EPs from potential discharge sources to recipient ecosystems, including lakes, rivers, estuaries, and marine environments [61, 76, 77]. The spatial distribution of EPs in aquatic systems is influenced by the nature and diversity of pollution sources.

EPs can enter the environment through multiple pathways, such as wastewater treatment facilities, industrial processes, healthcare institutions, aquaculture systems, agricultural runoff, and land application of manure from livestock farming [76, 78]. Effluents containing persistent EPs from domestic, industrial, and medical sources may ultimately be discharged into various aquatic bodies (Figure 3) [3].

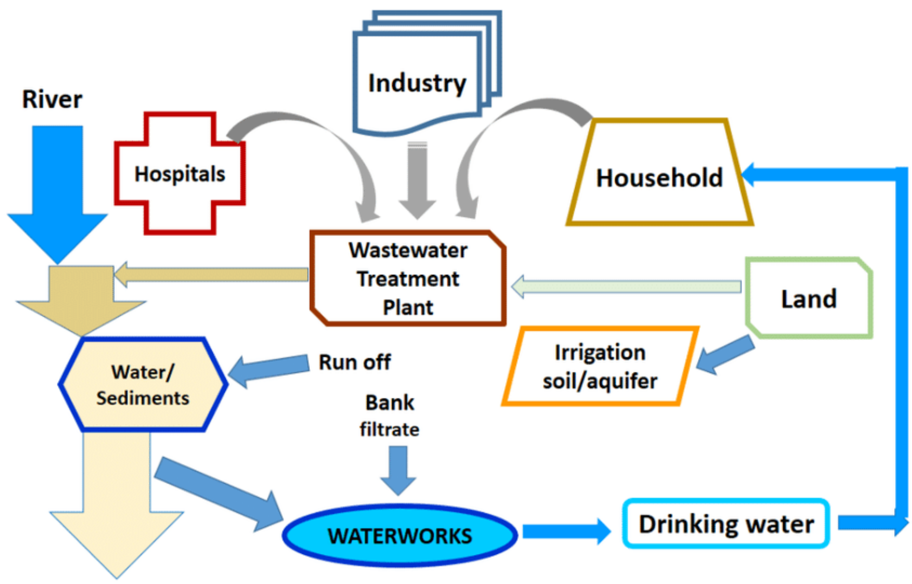

Figure 3. Origins of emerging pollutants and their routes in the environment (reused from Vasilachi et al., 2021 [3], under the terms and conditions of the Creative Commons At-tribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/)

Municipal and industrial wastewater treatment plants are significant pathways for EPs. While many pollutants are partially removed during treatment, residual concentrations persist in treated effluent and are discharged into water bodies.

Pharmaceuticals, personal care products, and industrial chemicals are commonly found in wastewater effluent, underscoring the limitations of conventional treatment technologies [3, 8, 19, 52]. Agricultural activities contribute to the release of pesticides, herbicides, veterinary drugs, and nutrients into surrounding ecosystems. Rainfall and irrigation can carry these pollutants into rivers, lakes, and groundwater, where they accumulate and pose risks to aquatic and terrestrial organisms [59, 79].

Urban areas contribute to pollution through stormwater that carries contaminants from roads, rooftops, and other impervious surfaces into nearby water bodies. Microplastics from tire wear, personal care products, and hydrocarbons from vehicle emissions are commonly detected in urban runoff [74, 80]. Everyday human activities, such as using personal care products, cleaning agents, and over-the-counter medications, contribute to EP release. Improper disposal of unused pharmaceuticals (e.g., flushing medications down the toilet) exacerbates this issue. Solid waste disposal sites are reservoirs of diverse pollutants, including pharmaceuticals, plasticizers, and flame retardants. Leachate from landfills can infiltrate groundwater or surface water, introducing a mix of contaminants [81, 82].

3.3. Emerging trends in pollution and newly identified pollutants

The landscape of emerging pollutants is continuously evolving due to technological advancements, shifts in consumption patterns, and improvements in analytical techniques. These factors contribute to the detection of previously unrecognized contaminants, many of which have uncertain environmental and health implications.

New pollutants are increasingly identified in various environmental compartments, including water, soil, and air. Pharmaceuticals and personal care products (PPCPs), per- and polyfluoroalkyl substances (PFAS), microplastics, and pesticide transformation products are among the most studied categories. These contaminants persist in the environment, often exhibiting bioaccumulative properties and toxic effects. Additionally, the rapid expansion of digital technologies has introduced pollution sources such as electronic waste-derived contaminants and rare earth elements released during mining and disposal processes [12, 83]. Analytical advancements, such as high-resolution mass spectrometry and remote sensing technologies, have enabled the detection of pollutants at trace levels, revealing contamination patterns that were previously overlooked [30, 84, 85]. Moreover, climate change is altering the transport, transformation, and bioavailability of many pollutants, increasing their environmental persistence.

The complexity of emerging pollutants challenges current mitigation strategies, as many conventional wastewater treatment plants and air filtration systems are ineffective against certain contaminants. Addressing these issues requires interdisciplinary research, adaptive regulatory measures, and the development of innovative remediation technologies. Some of the notable trends are presented in Table 4 [13, 18, 59, 74, 80].

Table 4. Key drivers and emerging trends in pollutant discovery and environmental impact

Key drivers	*Description*
Detection of previously unidentified pollutants	Recent advancements in analytical methods, such as high-resolution mass spectrometry, have enabled the identification of thousands of previously undetected contaminants. These include transformation products formed during chemical degradation or biological metabolism, which may be more toxic and persistent than their parent compounds.
Increased use of pharmaceuticals and personal care products	With the global rise in healthcare accessibility and the growing market for personal care products, the load of pharmaceuticals and PCPs in the environment is increasing. This trend is further amplified by the aging population in many countries, leading to higher medication use.
Expansion of nanotechnology applications	As nanotechnology continues to revolutionize industries, the release of engineered nanomaterials into the environment is expected to rise. Their unique properties and unknown long-term impacts make them a priority for future research.
Climate change and pollutant behavior	Changing climate conditions, such as increased temperatures and altered precipitation patterns, are influencing the transport, transformation, and persistence of pollutants. For instance, extreme weather events may mobilize pollutants from sediments into water bodies, increasing their bioavailability.
New classes of pollutants	Emerging classes of pollutants, such as pharmaceutical metabolites, novel pesticides, and bio-based plastic additives, are gaining attention for their potential environmental and health risks. These substances often lack regulatory oversight, creating challenges for effective management.
Globalization of pollutant transport	The interconnectedness of ecosystems means pollutants released in one region can affect distant environments. Persistent organic pollutants (POPs), for example, have been found in polar regions, highlighting the global nature of pollution.

4. Mechanisms of persistence in the environment

The persistence of emerging pollutants (EPs) in the environment refers to their ability to resist degradation and remain intact in environmental compartments over extended periods. This persistence is influenced by a combination of chemical properties, environmental factors, and interactions with natural degradation processes. Understanding the mechanisms behind this persistence is essential for assessing the long-term risks of EPs and developing effective mitigation strategies.

4.1. Key factors influencing persistence

The persistence of pollutants in the environment is determined by a combination of chemical, physical, and biological factors that influence their degradation, transport, and accumulation. Some contaminants degrade rapidly, while others remain in ecosystems for extended periods, posing long-term environmental and health risks [8, 59, 76].

Understanding the factors that govern persistence is crucial for assessing pollutant behavior and designing effective mitigation strategies. Emerging pollutants exhibit persistence in the environment due to several intrinsic and extrinsic factors (Figure 4) [45].

a. Chemical stability

Many EPs possess molecular structures with strong chemical bonds, such as carbon-fluorine bonds in per- and polyfluoroalkyl substances (PFAS). These bonds are highly resistant to chemical reactions, making PFAS and similar pollutants extremely stable and difficult to degrade. Other pollutants, such as certain pharmaceuticals, have complex aromatic structures that resist breakdown [86].

b. Resistance to degradation

- *Biodegradation resistance:* Microorganisms in the environment often lack the metabolic pathways to degrade synthetic or highly engineered compounds. For example, antibiotics and industrial chemicals are not readily biodegradable, leading to their accumulation in soils and water bodies [87, 88].
- *Hydrophobicity and lipophilicity:* Compounds with hydrophobic or lipophilic properties, such as persistent organic pollutants (POPs) and plasticizers, tend to accumulate in fatty tissues of organisms or bind tightly to organic matter in soils and sediments, protecting them from degradation processes [89, 90].

c. Partitioning behavior

Emerging pollutants often exhibit partitioning between different environmental compartments (e.g., water, soil, air). This behavior is influenced by properties such as solubility, volatility, and adsorption potential. For instance, volatile organic compounds (VOCs) can evaporate and enter the atmosphere, while non-volatile pollutants may bind to soil particles or dissolve in water [61, 91, 92].

d. Environmental conditions

- *Temperature:* Lower temperatures in polar and deep aquatic environments slow down chemical and biological degradation processes, enhancing persistence [55].
- *pH levels*: Extreme pH conditions can stabilize certain pollutants, preventing hydrolysis or other degradation reactions [93].

- *Presence of co-contaminants:* Other substances in the environment, such as heavy metals or organic matter, can inhibit degradation by binding to pollutants or altering microbial activity [94].

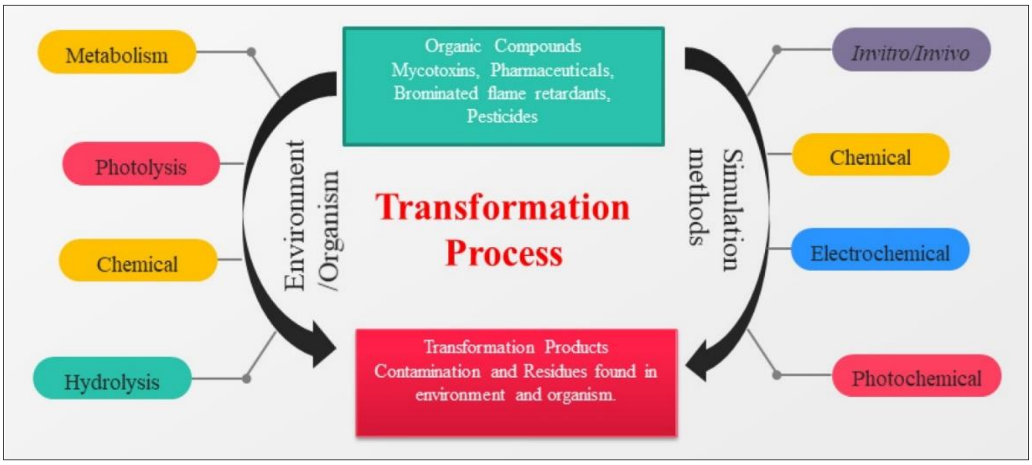

Figure 4. A diagram depicting the transformation processes that occur in organic compounds. General transformation processes in organisms and their environments are represented on the left, while the most frequent simulation approaches are shown on the right (reused from Suman et al., 2022 [45], under the terms and conditions of the Creative Commons At-tribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/)

4.2. Pathways and behavior in environmental compartments

Emerging pollutants exhibit diverse behaviors depending on the environmental compartments they occupy (Figure 5) [95].

a. Air

- Volatile pollutants, such as certain pesticides and industrial chemicals, can be transported long distances through the atmosphere. These pollutants may undergo chemical reactions with atmospheric components like ozone or hydroxyl radicals, although some persist as particulate matter [96].
- Once airborne, pollutants can deposit onto land or water surfaces through processes like wet or dry deposition, redistributing them across different ecosystems [97].

b. Water

- Many EPs are water-soluble and persist in aquatic systems. For instance, pharmaceutical residues are commonly detected in surface water, groundwater, and even drinking water supplies [6].

- Pollutants in water can undergo dilution, dispersion, or sorption onto sediments, with some accumulating in benthic layers where oxygen and microbial activity are limited, further enhancing their persistence.

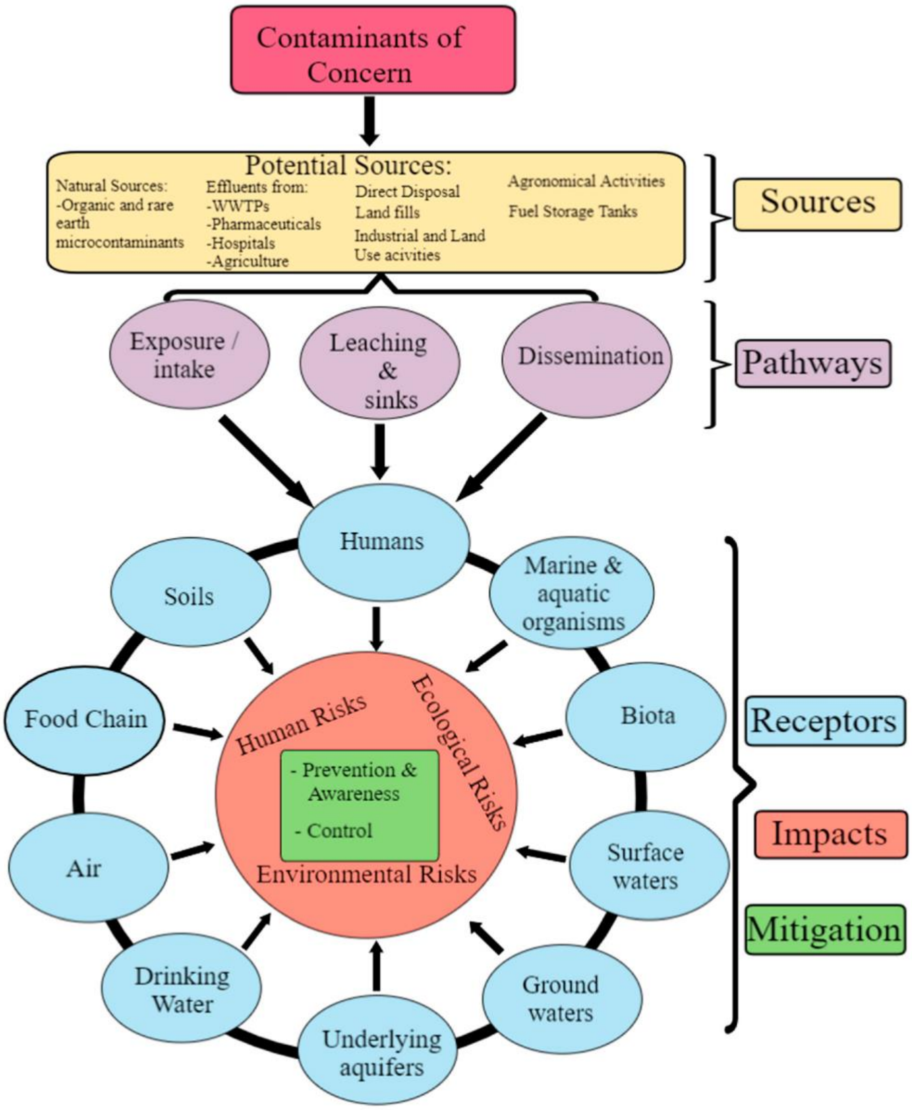

Figure 5. Flow of CoCs across various environmental compartments, following their introduction; these substances transform, giving rise to secondary contaminants that have the potential to impact human health. This dynamic interplay suggests that human beings play a dual role as both sources and recipients of these contaminants (reused from Baguma et al., 2023 [95], under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

c. Soil and sediments

- In terrestrial environments, pollutants like pesticides and industrial chemicals bind tightly to soil particles or organic matter. This reduces their bioavailability but increases their persistence, as they are shielded from degradation processes [98].
- In sediments, pollutants accumulate due to deposition from water or atmospheric sources. The anaerobic conditions in deeper sediment layers slow down degradation, allowing pollutants to persist for decades [99].

d. Biota

- Persistent pollutants often bioaccumulate in organisms due to their lipophilicity or inability to be metabolized. For example, endocrine-disrupting chemicals (EDCs) and PCBs accumulate in fatty tissues, leading to long-term exposure and potential biomagnification through food chains [100].

4.3. Interactions with natural processes

While some pollutants exhibit high resistance to degradation, they are continuously influenced by natural processes that affect their fate, transport, and persistence in the environment. Physical, chemical, and biological interactions can alter pollutant stability, modify their toxicity, or facilitate their removal from environmental compartments. These interactions play a crucial role in determining whether contaminants accumulate in ecosystems, undergo transformation into less harmful byproducts, or persist in bioavailable forms.

Key processes such as sorption, photodegradation, hydrolysis, oxidation-reduction reactions, and biodegradation influence the mobility and longevity of pollutants in air, water, and soil. Additionally, climatic and geological factors, such as temperature fluctuations, precipitation, and soil composition, further shape pollutant behavior (Table 5) [3, 6, 12, 59, 87, 101-105]. The involvement of microbial communities in biotransformation also dictates whether contaminants are broken down into benign compounds or converted into persistent intermediates.

Table 5. Natural processes influencing the fate and persistence of emerging pollutants

Process	*Description*
Biodegradation	Biodegradation is the breakdown of pollutants by microorganisms such as bacteria, fungi, and algae. However, many EPs are resistant to this process due to their synthetic nature or molecular complexity. For example: - *Primary biodegradation:* Involves the transformation of pollutants into intermediate metabolites, which may themselves be persistent or toxic. - *Complete mineralization:* Some pollutants are eventually broken down into inorganic substances like carbon dioxide and water, but this process is often slow or incomplete for EPs.

	Biodegradation rates depend on factors such as the availability of oxygen, nutrient levels, and microbial community composition.
Photodegradation	Photodegradation occurs when pollutants are broken down by sunlight, typically through reactions involving ultraviolet (UV) light. For instance, certain pesticides and pharmaceuticals degrade upon exposure to sunlight, but this process is limited to surface waters or areas with high light penetration. Photodegradation can result in byproducts that are more persistent or toxic than the parent compound, complicating environmental impacts.
Chemical degradation	Some pollutants degrade through chemical reactions such as hydrolysis, oxidation, or reduction. These reactions are influenced by environmental factors like pH, temperature, and the presence of reactive species (e.g., hydroxyl radicals in water). - Advanced oxidation processes (AOPs), which involve highly reactive oxidizing agents, are increasingly explored for degrading persistent pollutants in water treatment settings.
Sorption and desorption	Sorption refers to the binding of pollutants to surfaces such as soil particles or organic matter. This process can temporarily remove pollutants from active circulation but may lead to their release (desorption) under changing environmental conditions, such as pH shifts or microbial activity.
Transport and transformation	Emerging pollutants often undergo transformations as they move through different environments. For instance, pharmaceuticals may metabolize into transformation products in wastewater treatment plants or natural water systems. These transformation products can be more toxic or persistent, adding complexity to pollutant management.

Understanding these natural interactions is essential for assessing pollution risks, predicting environmental impacts, and developing remediation strategies that leverage natural attenuation mechanisms.

Conclusions

The persistence of emerging pollutants (EPs) in the environment raises critical concerns due to their resistance to degradation, widespread distribution, and potential adverse effects on ecosystems and human health. These pollutants, originating from industrial, agricultural, and domestic activities, enter environmental compartments through various pathways, including wastewater discharge, atmospheric deposition, and runoff. Their accumulation in water, soil, and biota leads to long-term contamination, bioaccumulation in organisms, and biomagnification through food chains.

The environmental behavior of EPs is influenced by their chemical stability, hydrophobicity, and interactions with natural processes such as sorption, transformation, and transport. While some EPs degrade through photodegradation, biodegradation, or chemical reactions, many persist due to their structural complexity or unfavorable environmental conditions. Their presence in remote ecosystems, including polar regions and deep-sea environments, highlights their mobility and the global nature of the problem.

The impacts of EPs extend beyond ecological disruption to significant socio-economic challenges. Their role in promoting antibiotic resistance, altering reproductive and metabolic functions in wildlife, and contaminating water resources underscores the need for improved treatment technologies and regulatory measures. Conventional wastewater treatment plants are often ineffective in fully removing EPs, necessitating the adoption of advanced treatment processes and stricter pollution control strategies.

Addressing the persistence of EPs requires a multidisciplinary approach involving enhanced environmental monitoring, regulatory updates, and sustainable pollutant management. Strengthening international collaboration, improving risk assessment methodologies, and promoting the responsible use and disposal of chemicals are essential steps toward mitigating their long-term environmental and health risks. Future efforts should focus on understanding pollutant transformation pathways, developing cost-effective remediation techniques, and reducing EP emissions at the source to protect ecosystems and public health.

R E F E R E N C E S

[1] Metcalfe C.D., (2013), Pharmaceutical contaminants of emerging concern in the environment, *Environmental Toxicology and Chemistry*, 32, 1683–1684.

[2] Puri M., Gandhi K., Kumar S., (2013), Emerging environmental contaminants: A global perspective on policies and regulations, *Journal of Environmental Management*, **332**, 117344, https://doi.org/10.1016/j.jenvman.2023.117344

[3] Vasilachi I.C., Asiminicesei D.M., Fertu D.I., Gavrilescu M. (2021), Occurrence and fate of emerging pollutants in water environment and options for their removal, *Water*, **13**, 181, http://doi.org/10.3390/w13020181

[4] Gavrilescu M., Demnerová K., Aamand J., Agathos S., Fava F., (2015), Emerging pollutants in the environment: present and future challenges in biomonitoring, ecological risks and bioremediation, *New Biotechnology*, **32**, 147-156.

[5] Shaheen J.F., Sizirici B., Yildiz I., (2022), Fate, transport, and risk assessment of widely prescribed pharmaceuticals in terrestrial and aquatic systems: A review, *Emerging Contaminants*, **8**, 216-228.

[6] Tong X., Mohapatra S., Zhang J., Tran N.H., You L., He Y., Gin K. Y-H., (2022), Source, fate, transport and modelling of selected emerging contaminants in the aquatic environment:

Current status and future perspectives, *Water Research*, **217**, 118418, https://doi.org/10.1016/j.watres.2022.118418

[7] Yadav D., Rangabhashiyam S., Verma P., Singh P., Devi P., Kumar P., Hussain C.M., Gaurav C.G., Kumar K.S., (2021), Environmental and health impacts of contaminants of emerging concerns: Recent treatment challenges and approaches, *Chemosphere*, 272, 129492, https://doi.org/10.1016/j.chemosphere.2020.129492

[8] Arman N.Z., Salmiati S., Aris A., Salim M.R., Nazifa T.H., Muhamad M.S., Marpongahtun M., (2021), A review on emerging pollutants in the water environment: existences, health effects and treatment processes, *Water*, **13**, 3258, https://doi.org/10.3390/w13223258

[9] Zolkefli N., Sharuddin S.S., Yuso M.Z.M., Ali Hassan M., Maeda T., Ramli N., (2020), A Review of current and emerging approaches for water pollution monitoring, *Water*, **12**, 3417, http://doi.org/10.3390/w12123417

[10] Satyanarayana G.N.V., Kumar A., Pandey A.K., Sharma M.T., Natesan M., Mudiam M.K.R. (2023), Evaluating chemicals of emerging concern in the Ganga River at the two major cities Prayagraj and Varanasi through validated analytical approaches, *Environmental Science* and *Pollution Research*, **30**, 1520–1539.

[11] Feng G., Huang H., Chen Y., (2021), Effects of emerging pollutants on the occurrence and transfer of antibiotic resistance genes: A review, *Journal of Hazardous Materials*, **420**, 126602, https://doi.org/10.1016/j.jhazmat.2021.126602

[12] Senthil Rathi B., Senthil Kumar P., Vo D.-V. N., (2021), Critical review on hazardous pollutants in water environment: Occurrence, monitoring, fate, removal technologies and risk assessment, *Science of The Total Environment*, **797**, 149134, https://doi.org/10.1016/j.scitotenv.2021.149134

[13] Kumar M., Sridharan S., Sawarkar A.D., Shakeel A., Anerao P., Mannina G., Sharma P., Pandey A., (2023), Current research trends on emerging contaminants pharmaceutical and personal care products (PPCPs): A comprehensive review, *Science of the Total Environment*, 859, 160031, https://doi.org/10.1016/j.scitotenv.2022.160031

[14] Mali H., Shah C., Raghunandan B.H., Prajapati A.S., Patel D.H., Trivedi U., Subramanian R.B., (2023), Organophosphate pesticides an emerging environmental contaminant: Pollution, toxicity, bioremediation progress, and remaining challenges, *Journal of Environmental Sciences*, 127, 234-250.

[15] Annamalai J., Namasivayam V., (2015), Endocrine disrupting chemicals in the atmosphere: their effects on humans and wildlife, *Environment International*, **76**, 78-97.

[16] Pan J., Liu P., Yu X., Zhang Z., Liu J., (2024), The adverse role of endocrine disrupting chemicals in the reproductive system, Frontiers in Endocrinology, **14**, 1324993, http://doi.org/10.3389/fendo.2023.1324993

[17] Melchor-Martínez E.M., Macias-Garbett R., Malacara-Becerra A., Iqbal H.M.N., Sosa-Hernández J.E., Parra-Saldívar R., (2021), Environmental impact of emerging contaminants from battery waste: A mini review, *Case Studies in Chemical and Environmental Engineering*, 3, 100104, https://doi.org/10.1016/j.cscee.2021.100104

[18] Chaturvedi P., Shukla P., Giri B.S., Chowdhary P., Chandra R., Gupta P., Pandey A., (2021), Prevalence and hazardous impact of pharmaceutical and personal care products and antibiotics in environment: A review on emerging contaminants, *Environmental Research*, 194, 110664, https://doi.org/10.1016/j.envres.2020.110664

[19] Gomes I.B., Maillard J.Y., Simões L.C., Simões M., (2020), Emerging contaminants affect the microbiome of water systems - strategies for their mitigation, *npj Clean Water* **3**, 39, https://doi.org/10.1038/s41545-020-00086-y

[20] Jan S., Mishra A.K., Bhat M.A., Bhat M.A., Jan A.T., (2023), Pollutants in aquatic system: a frontier perspective of emerging threat and strategies to solve the crisis for safe drinking water, *Environmental Science and Pollution Research*, **30**, 113242–113279.

[21] Morales M., Arp H.P.H., Castro G., Asimakopoulos A.G., Sørmo E., Peters G., Cherubini F., (2024), Eco-toxicological and climate change effects of sludge thermal treatments: Pathways towards zero pollution and negative emissions, *Journal of Hazardous Materials*, 470, 34242, https://doi.org/10.1016/j.jhazmat.2024.134242

[22] Mishra R.K., Mentha S.S., Misra Y., Dwivedi N., (2023), Emerging pollutants of severe environmental concern in water and wastewater: A comprehensive review on current developments and future research, *Water-Energy Nexus*, 6, 74-95.

[23] Sharma B.M., Bharat G.K., Tayal S., Nizzetto L., Čupr P., Larssen T., (2014), Environment and human exposure to persistent organic pollutants (POPs) in India: A systematic review of recent and historical data, *Environment International*, **66**, 48-64.

[24] Ulucan-Altuntas K., Manav-Demir N., Ilhan F., Gelgor H.B., Huddersman K., Tiwary A., et al., (2023), Emerging pollutants removal in full-scale biological treatment plants: a case study, *Journal of Water Process Engineering*, **51**, 103336, https://doi.org/10.1016/j.jwpe.2022.103336.

[25] Ahn C., Jeung E.-B., (2023), Endocrine-disrupting chemicals and disease endpoints, *International Journal of Molecular Sciences*, **24**, 5342, https://doi.org/10.3390/ijms24065342

[26] Ayaliew Werkneh A., Gebru S.B., Redae G.H., Tsige A.G., (2022), Removal of endocrine disrupters from the contaminated environment: public health concerns, treatment strategies and future perspectives - A review, *Helyion*, 8, e09206, https://doi.org/10.1016/j.heliyon.2022.e09206

[27] Cedeño-Muñoz J.S., Abiodun Aransiola S., Venkateswar Reddy K., (2024), Antibiotic resistant bacteria and antibiotic resistance genes as contaminants of emerging concern: Occurrences, impacts, mitigations and future guidelines, *Science of the Total Environment*, 952, 175906, https://doi.org/10.1016/j.scitotenv.2024.175906

[28] Baralla E., Demontis M.P., Dessì F., Varoni M.V., (2021), An overview of antibiotics as emerging contaminants: occurrence in bivalves as biomonitoring organisms, *Animals (Basel)*, 12, 3239, http://doi.org/10.3390/ani11113239 .

[29] Wang F., Xiang L., Sze-Yin Leung K. et al. (2024), Emerging contaminants: A one health perspective, *The Innovation*, 5, 100612, https://doi.org/10.1016/j.xinn.2024.100612

[30] Li X., Shen X., Jiang W., Xi Y., Li S. et al., (2024), Comprehensive review of emerging contaminants: Detection technologies, environmental impact, and management strategies, *Ecotoxicology and Environmental Safety*, **278**, 116420, https://doi.org/10.1016/j.ecoenv.2024.116420

[31] Kim H.M., Kang J.S., (2021), Metabolomic studies for the evaluation of toxicity induced by environmental toxicants on model organisms, *Metabolites*, **11**, 485, http://doi.org/10.3390/metabo11080485

[32] Zhang W., (2025), Water treatment technology for emerging contaminants, *Water*, **17**, 644, https://doi.org/10.3390/w17050644

[33] Kathi S., El Din Mahmoud A., (2024), Trends in effective removal of emerging contaminants from wastewater: A comprehensive review, *Desalination and Water Treatment*, 317, 100258, https://doi.org/10.1016/j.dwt.2024.100258

[34] Awewomom J., Dzeble F., Takyi Y.D. *et al.*, (2024), Addressing global environmental pollution using environmental control techniques: a focus on environmental policy and preventive environmental management, *Discover Environment*, **2**, 8, https://doi.org/10.1007/s44274-024-00033-5

[35] Dulio V., van Bavel B., Brorström-Lundén E., Harmsen J., Hollender J., Schlabach M., Slobodnik J., Thomas K., Koschorreck J., (2018), Emerging pollutants in the EU: 10 years of NORMAN in support of environmental policies and regulations, *Environmental Sciences Europe*, **30**, 5, https://doi.org/10.1186/s12302-018-0135-3

[36] Zaman W., Ali S., Akhtar M.S., (2024), Harnessing the power of plants: innovative approaches to pollution prevention and mitigation, *Sustainability*, **16**, 10587, https://doi.org/10.3390/su162310587

[37] Khan S., Naushad M., Govarthanan M., Iqbal J., Alfadul S.M., (2022), Emerging contaminants of high concern for the environment: Current trends and future research, *Environmental Research*, 207, 112609, https://doi.org/10.1016/j.envres.2021.112609

[38] Cousins I.T., Ng C.A., Wang Z., Scheringer M., (2019), Why is high persistence alone a major cause of concern?, *Environmental Sciences – Processes & Impacts*, **21**, 781-792.

[39] La Farré M., Pérez S., Kantiani L., Barceló D., (2008), Fate and toxicity of emerging pollutants, their metabolites and transformation products in the aquatic environment, *TrAC Trends in Analytical Chemistry*, 27, 991-1007.

[40] Bell K.Y., Wells M.J.M, Traexler K.A., Pellegrin M.-L., Morse A., Bandy J., (2011), Emerging pollutants, *Water*, 83, 1906-1984.

[41] Vejerano E.P., Rao G., Khachatryan L., Cormier S.A., Lomnicki S., (2018), Environmentally persistent free radicals: Insights on a new class of pollutants, *Environmental Science & Technology*, 52, 2468–2481.

[42] Meher A.K., Zarouri A., (2025), Environmental applications of mass spectrometry for emerging contaminants, *Molecules*, 30, 364, https://doi.org/10.3390/molecules30020364

[43] Zhang C., Barron L., Sturzenbaum S., (2021), The transportation, transformation and (bio)accumulation of pharmaceuticals in the terrestrial ecosystem, *Science of The Total Environment*, 781, 146684, https://doi.org/10.1016/j.scitotenv.2021.146684

[44] Shi Q., Xiong Y., Kaur P., Sy N.D., Gan J., (2022), Contaminants of emerging concerns in recycled water: Fate and risks in agroecosystems, Science of The Total Environment, 814, 152527, https://doi.org/10.1016/j.scitotenv.2021.152527

[45] Suman T.-Y., Kim S.-Y., Yeom D.-H., Jeon J., (2022), Transformation products of emerging pollutants explored using non-target screening: Perspective in the transformation pathway and toxicity mechanism - A review, *Toxics*, **10**, 54, https://doi.org/10.3390/toxics10020054

[46] Almeida-Naranjo C.E., Guerrero V.H., Villamar-Ayala C.A., (2023), Emerging contaminants and their removal from aqueous media using conventional/non-conventional adsorbents: A Glance at the relationship between materials, Processes, and Technologies, *Water*, **15**, 1626, https://doi.org/10.3390/w15081626

[47] Pires V.L., Novais S.C., Lemos M.F.L., Fonseca V.F., Duarte B., (2021), Evaluation of multivariate biomarker indexes application in ecotoxicity tests with marine diatoms exposed to emerging contaminants, *Applied Sciences*, **11**, 3878, https://doi.org/10.3390/app11093878

[48] Chormare R., Kumar M.A., (2022), Environmental health and risk assessment metrics with special mention to biotransfer, bioaccumulation and biomagnification of environmental pollutants, *Chemosphere*, **302**, 134836, https://doi.org/10.1016/j.chemosphere.2022.134836

[49] Tongo I., Onokpasa A., Emerure F. *et al.* (2022), Levels, bioaccumulation and biomagnification of pesticide residues in a tropical freshwater food web, *International Journal of Environmental Science and Technology*, **19**, 1467–1482 (2022). https://doi.org/10.1007/s13762-021-03212-6

[50] Cheng H., Lv C., Li J., Wu D., Zhan X., Song Y., Zhao N., Jin H., (2022), Bioaccumulation and biomagnification of emerging poly- and perfluoroalkyl substances in marine organisms, *Science of The Total Environment*, 851, 158117, https://doi.org/10.1016/j.scitotenv.2022.158117

[51] Martins M.F., Costa P.G., Bianchini A., (2023), Bioaccumulation and potential impacts of persistent organic pollutants and contaminants of emerging concern in guitarfishes and angelsharks from Southeastern Brazil, *Science of The Total Environment*, 893, 164873, https://doi.org/10.1016/j.scitotenv.2023.164873

[52] Bhatt V., Chauhan J.S., (2023), Microplastic in freshwater ecosystem: bioaccumulation, trophic transfer, and biomagnification, *Environmental Science and Pollution Research*, **30**, 9389–9400.
[53] Savoca D., Pace A., (2021), Bioaccumulation, biodistribution, toxicology and biomonitoring of organofluorine compounds in aquatic organisms, *International Journal of Molecular Sciences*, **22**, 6276, https://doi.org/10.3390/ijms22126276
[54] Mohamed B.A., Fattah I.M.R., Yousaf B. *et al.*, (2022), Effects of the COVID-19 pandemic on the environment, waste management, and energy sectors: a deeper look into the long-term impacts, *Environmental Science and Pollution Research*, **29**, 46438–46457.
[55] Borga K., McKinney M.A., Routti H., Fernie K.J., Giebichenstein J., Hallangerc I., Muire D.C.G., (2022), The influence of global climate change on accumulation and toxicity of persistent organic pollutants and chemicals of emerging concern in Arctic food webs, *Environmental Science Processes & Impacts*, 24, 1544-1576.
[56] An D., Na J., Song J., Jung J., (2021), Size-dependent chronic toxicity of fragmented polyethylene microplastics to *Daphnia magna*, *Chemosphere*, **271**, 129591, https://doi.org/10.1016/j.chemosphere.2021.129591
[57] Impellitteri F., Multisanti C.R., Rusanova P., Piccione G., Falco F., Faggio C., (2023), Exploring the impact of contaminants of emerging concern on fish and invertebrates physiology in the Mediterranean Sea, *Biology*, **12**, 767, https://doi.org/10.3390/biology12060767
[58] Wu Z., Wang L., Chen W., Wang Y., Cui K., Chen W., Liu J., Jin H., Zhou Z. (2024), Reproductive toxicity and multi/transgenerational effects of emerging pollutants on C. elegans, *Toxics*, 12, 785, https://doi.org/10.3390/toxics12110785
[59] Morin-Crini N., Lichtfouse E., Liu G. *et al.* (2022), Worldwide cases of water pollution by emerging contaminants: a review, *Environmental Chemical Letters*, **20**, 2311–2338.
[60] Ouda M., Kadadou D., Swaidan B., Al-Othman A., Al-Asheh S., Banat F., Hasan S.W., (2021), Emerging contaminants in the water bodies of the Middle East and North Africa (MENA): A critical review, *Science of the Total Environment*, **754**, 142177, https://doi.org/10.1016/j.scitotenv.2020.142177
[61] Pamuru S.T., Forgione E., Croft K., Kjellerup B.V., Davis A.P., (2022), Chemical characterization of urban stormwater: traditional and emerging contaminants, *Science of the Total Environment*, **813**, 151887, http://dx.doi.org/10.1016/j.scitotenv.2021.151887
[62] Maddela N.R., Ramakrishnan B., Kakarla D., Venkateswarlue K., Megharaj M., (2022), Major contaminants of emerging concern in soils: a perspective on potential health risks, *RSC Advances*, 12, 12396, http://doi.org/10.1039/d1ra09072k
[63] Burgos-Aceves M.A., Abo-Al-Ela H.G., Faggio C., (2021), Physiological and metabolic approach of plastic additive effects: Immune cells responses, *Journal of Hazardous Materials*, 404, Part A, 124114, https://doi.org/10.1016/j.jhazmat.2020.124114
[64] Richardson S.D., Ternes T.A., (2022), Water analysis: Emerging contaminants and current issues, Analytical Chemistry, 94, 382–416.
[65] Valbonesi P., Profita M., Vasumini I., Fabbri E., (2021), Contaminants of emerging concern in drinking water: Quality assessment by combining chemical and biological analysis, *Science of The Total Environment*, 758, 143624, https://doi.org/10.1016/j.scitotenv.2020.143624
[66] Podder A., Anwar Sadmani A.H.M., Reinhart D., Chang N.-B., Goel R., (2021), Per and poly-fluoroalkyl substances (PFAS) as a contaminant of emerging concern in surface water: A transboundary review of their occurrences and toxicity effects, Journal of Hazardous Materials, 419, 126361, https://doi.org/10.1016/j.jhazmat.2021.126361
[67] Bard S.M., (1999), Global transport of anthropogenic contaminants and the consequences for the arctic marine ecosystem, *Marine Pollution Bulletin*, 38, 356-379.

[68] Vorkamp K., Rigét F.F., (2014), A review of new and current-use contaminants in the Arctic environment: Evidence of long-range transport and indications of bioaccumulation, *Chemosphere*, 111, 379-395.
[69] de Wit C.A., Vorkamp K., Muir D., (2022), Influence of climate change on persistent organic pollutants and chemicals of emerging concern in the Arctic: state of knowledge and recommendations for future research, *Environmental Science Processes & Impacts*, 24, 1530, http://doi.org/10.1039/d1em00531f
[70] Ebinghaus R., Barbaro E., Bengtson Nash S., (2023), Berlin statement on legacy and emerging contaminants in polar regions, *Chemosphere*, 327, 138530, https://doi.org/10.1016/j.chemosphere.2023.138530
[71] Biswas S. et al., (2025), *Evaluating Regulatory Approaches to Emerging Pollutants*. In: *Biotechnological Interventions in the Removal of Emerging Pollutants*, *Interdisciplinary Biotechnological Advances*, Dey S., Bhattacharya S. (Eds), Springer, Singapore, https://doi.org/10.1007/978-981-97-9922-0_2
[72] Calvo-Flores G.G., Isac-García J., Dobado J.A., (2018), *Emerging Pollutants: Origin, Structure, and Properties*, Wiley-VCH, Weinheim, Germany.
[73] Senthil Rathi B., Senthil Kumar P., (2021), Application of adsorption process for effective removal of emerging contaminants from water and wastewater, *Environmental Pollution*, 280, 116995, https://doi.org/10.1016/j.envpol.2021.116995
[75] Trinh M.M., Chang M.B., (2018), Review on occurrence and behavior of PCDD/Fs and dl-PCBs in atmosphere of East Asia, *Atmospheric Environment*, 180, 23–36.
[76] Ahmad H.A., Ahmad S., Cui Q., Wang Z., Wei H., Chen X. et al., (2022), The environmental distribution and removal of emerging pollutants, highlighting the importance of using microbes as a potential degrader: a review, *Science of the Total Environment*, **809**, 151926, http://dx.doi.org/10.1016/j.scitotenv.2021.151926
[74] Wiest L., Gosset A., Fildier A., et al., (2021), Occurrence and removal of emerging pollutants in urban sewage treatment plants using LC-QToF-MS suspect screening and quantification, *Science of The Total Environment*, 774, 145779, https://doi.org/10.1016/j.scitotenv.2021.145779
[78] Abukari A., Kaba J.S., Dawoe E., Abunyewa A.A., (2022), A comprehensive review of the effects of biochar on soil physicochemical properties and crop productivity, *Waste Disposal and Sustainable Energy*, **4,** 343-359.
[79] Al-Hazmi H.E., Mohammadi A., Hejna A. et al., (2023), Wastewater reuse in agriculture: Prospects and challenges, *Environmental Research*, 236, 116711, https://doi.org/10.1016/j.envres.2023.116711
[80] Choi Y., Lee J.-H., Kim K. et al., (2021), Identification, quantification, and prioritization of new emerging pollutants in domestic and industrial effluents, Korea: Application of LC-HRMS based suspect and non-target screening, *Journal of Hazardous Materials*, 402, 123706, https://doi.org/10.1016/j.jhazmat.2020.123706
[81] GodvinSharmila V., Shanmugavel S.P., Tyagi V.K., Banu J.R., (2023), Microplastics as emergent contaminants in landfill leachate: Source, potential impact and remediation technologies, *Journal of Environmental Management*, 343, 118240, https://doi.org/10.1016/j.jenvman.2023.118240
[82] Nika M.-K., Alygizakis N., Arvaniti O.S., Thomaidis N.S., (2023), Non-target screening of emerging contaminants in landfills: A review, *Current Opinion in Environmental Science & Health*, 32, 100430, https://doi.org/10.1016/j.coesh.2022.100430
[83] Zhong M., Wang T., Zhao W. et al., (2022), Emerging organic contaminants in Chinese surface water: Identification of priority pollutants, *Engineering*, 11, 111-125.
[84] Hassan M.H., Khan R., Andreescu S., (2022), Advances in electrochemical detection methods for

measuring contaminants of emerging concerns, *Electrochemical Science Advances*, **2**, e2100184 http://doi.org/10.1002/elsa.202100184
[85] Ruan T., Pengyang L., Wang L., Li T., Jiang G., (2023), Identification and prioritization of environmental organic pollutants: From an analytical and toxicological perspective, *Chemical Reviews*, **123**, 10584–10640.
[86] Vale F., Sousa C.A., Sousa H., Santos L., Simões M., (2022), Parabens as emerging contaminants: Environmental persistence, current practices and treatment processes, Journal of Cleaner Production, 347, 131244, https://doi.org/10.1016/j.jclepro.2022.131244
[87] Li S., Yang L., Yang S., Zheng H., (2023), Recent advances in biodegradation of emerging contaminants - microplastics (MPs): Feasibility, mechanism, and future prospects, *Chemosphere*, 331, 138776, https://doi.org/10.1016/j.chemosphere.2023.138776
[88] Jan-Roblero J., Cruz-Maya J.A., (2023), Ibuprofen: Toxicology and biodegradation of an emerging contaminant, *Molecules*, **28**, 2097, https://doi.org/10.3390/molecules28052097
[89] Gao X., Li J., Xu Y., Zhou Q., Ma M., Wang Z., (2022), Passive sampling hydrophilic and hydrophobic bisphenol analogues using hydrophilic-lipophilic balance sorbent-embedded cellulose acetate membrane in surface waters, *Science of The Total Environment*, **839**, 156239, https://doi.org/10.1016/j.scitotenv.2022.156239
[90] Xu Y., Luo Z., Tao Y., Xu M., Liao J., (2022), Transforming hydrophobicity of high-density polyethylene surface to hydrophilicity and superoleophobicity by surface grafted with polyvinyl alcohols for oil contaminants cleanup, *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 655, 130313, https://doi.org/10.1016/j.colsurfa.2022.130313
[91] Xu R., Liu S., Pan Y.-F., et al., (2024), Steroid metabolites as overlooked emerging contaminants: Insights from multimedia partitioning and source–sink simulation in an estuarine environment, *Journal of Hazardous Materials*, 461, 132673, https://doi.org/10.1016/j.jhazmat.2023.132673
[92] Wang S., Ding G., Liu Y., et al., (2022), Legacy and emerging persistent organic pollutants in the marginal seas of China: Occurrence and phase partitioning, *Science of the Total Environment*, 827, 154274, https://doi.org/10.1016/j.scitotenv.2022.154274
[93] Mordechay E.B., Mordehay V., Tarchitzky J., Chefetz B., (2022), Fate of contaminants of emerging concern in the reclaimed wastewater-soil-plant continuum, *Science of the Total Environment*, 822, 153574, https://doi.org/10.1016/j.scitotenv.2022.153574
[94] Zhao H., Yang M., Chen B., Liu B., Zhang B., (2025), Transport of microplastic-antibiotic co-contaminants in tidal zones, *Environmental Pollution*, 126072, https://doi.org/10.1016/j.envpol.2025.126072
[95] Baguma G., Bamanya G., Gonzaga A., Ampaire W., Onen P., (2023), A systematic review of contaminants of concern in Uganda: Occurrence, sources, potential risks, and removal strategies, *Pollutants*, 3, 544–586.
[96] Biswas P., Vellanki B.P., Kazmi A.A., (2022), Investigating a broad range of emerging contaminants in a set of anthropogenically impacted environmental compartments, *Science of The Total Environment*, 824, 153757, https://doi.org/10.1016/j.scitotenv.2022.153757
[97] Gwenzi W., (2022), *Emerging Contaminants in the Terrestrial-Aquatic-Atmosphere Continuum: Occurrence, Health Risks and Mitigation*, Elsevier, Amsterdam.
[98] Sarkar B., Mukhopadhyay R., Ramanayaka S., Bolan N., Ok Y.S., (2021), The role of soils in the disposition, sequestration and decontamination of environmental contaminants, Philosophical Transactions of the Royal Society B, **36**, https://doi.org/10.1098/rstb.2020.0177
[99] Li B., Xu D., Zhou X., Yin Y., Feng L., Liu Y., Zhang L., (2023a), Environmental behaviors of emerging contaminants in freshwater ecosystem dominated by submerged plants: A review, Environmental Research, 227, 115709, https://doi.org/10.1016/j.envres.2023.115709

[100] Eze C.G., Okeke E.S., Nwankwo C.E., et al., (2024), Emerging contaminants in food matrices: An overview of the occurrence, pathways, impacts and detection techniques of per- and polyfluoroalkyl substances, *Toxicology Reports*, **12**, 436-447.

[101] Sanchez W., Egea E., (2018), Health and environmental risks associated with emerging pollutants and novel green processes, *Environmental Science and Pollution Research*, **25**, 6085–6086.

[102] Overton O.C., Olson L.H., Majumder S.D., Shwiyyat H., Foltz M.E., Nairn R.W., (2023), Wetland removal mechanisms for emerging contaminants, *Land*, **12**, 472, https://doi.org/10.3390/land12020472

[103] Lee B.C.Y., Lim F.Y., Loh W.H., Ong S.L., Hu J., (2021), Emerging contaminants: An overview of recent trends for their treatment and management using light-driven processes, *Water*, 13, 2340, https://doi.org/10.3390/w13172340

[104] Liu T., Sathishkumar K., Zhang H., et al., (2024), Frontiers in environmental cleanup: Recent advances in remediation of emerging pollutants from soil and water, *Journal of Hazardous Materials Advances*, 16, 100461, https://doi.org/10.1016/j.hazadv.2024.100461

[105] Sánchez M., Ruiz I., Soto M., (2022), The potential of constructed wetland systems and photodegradation processes for the removal of emerging contaminants - A review, *Environments*, **9**, 116, https://doi.org/10.3390/environments9090116