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THE FATE AND EFFECTS OF EMERGING POLLUTANTS IN THE ENVIRONMENT

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ABSTRACT: *Emerging pollutants (EPs), widely designated as Contaminants of Emerging Concern (CECs), encompass a diverse array of both anthropogenic and naturally occurring chemical substances that have historically remained outside the scope of formal environmental monitoring programs and regulatory classification. The group spans a broad chemical spectrum, ranging from antibiotics, synthetic hormones, and personal care products to agrochemicals, manufactured nanomaterials, microplastic particles, and recalcitrant industrial chemicals, including per- and polyfluoroalkyl substances (PFAS). EPs exhibit a pronounced resistance to elimination by standard wastewater treatment infrastructure, which contributes to their sustained presence in aquatic, soil, and atmospheric environments. Entry pathways into the environment encompass effluent discharges from both treated and untreated wastewater systems, runoff from cultivated lands, atmospheric deposition, and contamination leaching from solid waste facilities. Collectively, these routes have resulted in their detection in surface waters, groundwater, soil profiles, sediment beds, and the tissues of living organisms worldwide. The environmental and ecological ramifications of EPs' presence are wide-ranging: these substances induce chronic sub lethal harm in non-target species, impair endocrine regulatory functions, accelerate the development of antibiotic-resistant bacterial populations, and alter the structural and functional properties of microbial assemblages. Terrestrial systems face diminished biodiversity and restricted plant productivity. Managing this multifaceted environmental challenge will require the combined application of cutting-edge treatment technologies, substantive reform of existing effluent regulations, and the construction of globally integrated and sustained monitoring frameworks.*

KEYWORDS: Contaminants, microplastics, nanomaterials, pharmaceuticals, pollution, toxicity.

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INTRODUCTION

Emerging pollutants (EPs), alternatively termed contaminants of emerging concern (CECs), form a structurally diverse collection of synthetic and naturally derived chemical compounds and biological agents that currently fall outside established regulatory oversight, yet are consistently detected in water bodies, soil matrices, atmospheric compartments, and biological tissues, frequently at concentrations that surpass expected background levels (Disner, 2025; Nishmitha *et al.*, 2025; Habimana, 2025). Within this classification fall pharmaceuticals, personal care product constituents, agrochemicals, engineered nanomaterials, microplastic particles, and PFAS compounds, as shown in Table 1, many of which are not adequately degraded within conventional wastewater infrastructure due to their structural complexity, thereby accumulating in the environment and entering food chains (Bu & Ma, 2025; Gimeno *et al*., 2016; Puri *et al*., 2023; Zandaryaa, 2025). The hazards posed by this category of substances span multiple dimensions, including disruption of hormonal systems, damage to cellular genetic material, facilitation of antimicrobial resistance, reduction of biological diversity, and interference with the functional dynamics of aquatic and terrestrial ecosystems (Dang *et al*., 2021). In contrast to historical legacy pollutants, EPs have entered the scientific spotlight largely as a consequence of their increasing detection rates and confirmed toxic potential, even when comprehensive risk characterization remains incomplete. Investigating this class of substances demands the deployment of sophisticated analytical instrumentation and is complicated further by the continual expansion of the chemical and biological universe of compounds that satisfy the criteria for EP classification. Societal engagement and pre-emptive management strategies are fundamental to addressing the EP challenge, since post-contamination environmental remediation carries prohibitive financial and technical costs (Miller *et al.*, 2020).

Table 1: Major Emerging Contaminants with Examples

	Contaminant Type	**Example**
1.	Microplastics	Polystyrene, Polypropylene, Polyethylene
2.	Pharmaceuticals	Ibuprofen, Naproxen, Carbamazepine, Triclosan
3.	Personal care products	Triclocarban, Benzophenone-3, Parabens
4.	Per- or Poly-Fluoroalkyl Substances (PFAS)	Perfluorooctane Sulphonic Acid (PFOS), Perfluorooctanoic Acid (PFOA)
5.	Nanoparticles	Silver, Titanium dioxide

(**Source**: *Nishmitha et al., 2025*)

Emerging pollutants include several broad categories of substances that vary in origin, chemical structure, and environmental behavior. Figure 1 shows major sources of PFAS in the environment.

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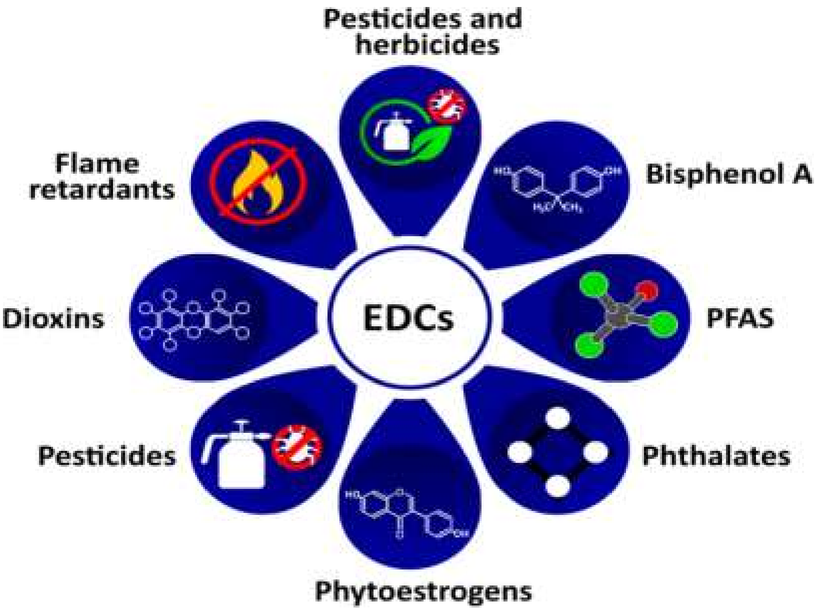
Figure 1: Sources of PFAS in the environment

Source: (*Boahen et al., 2025)*

Industrial Chemicals and Additives: including plasticizers such as phthalates, brominated flame retardants, including polybrominated diphenyl ethers (PBDEs), per- and polyfluoroalkyl substances (PFAS), and surfactants, as shown in Figure 2, are predominantly released from manufacturing operations and exhibit notable persistence and toxic potential (Nishmitha *et al*., 2025).

Figure 2: Endocrine-disrupting chemicals



(**Source:** *Boahen et al., 2025*)

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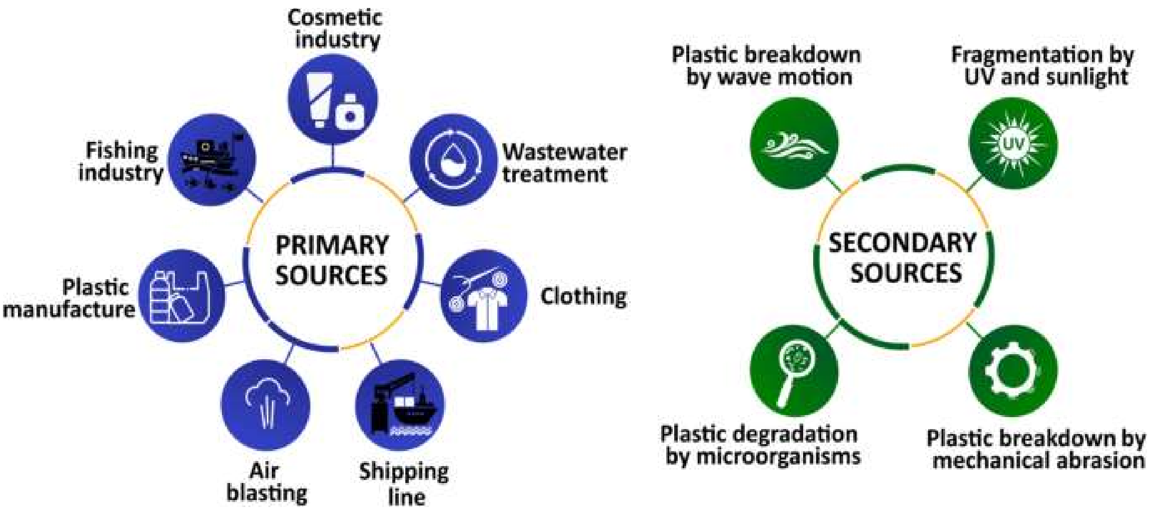
Pesticides and Herbicides: Widely deployed in agricultural production and tend to persist in aquatic and soil environments, causing harm to non-target organisms and contributing to biodiversity decline (Miller *et al*., 2020).

Nanomaterials, which are engineered at the nanoscale for use in electronics, pharmaceutical applications, and cosmetics, are increasingly detected in water bodies and soils, though their environmental and health implications remain largely uncharacterized (Gimeno *et al*., 2016). Figure 3 shows the primary and secondary sources of micro and nanoplastics in the environment.

Figure 3: Primary and Secondary Sources of Micro and Nanoplastics



(Source: Nishmitha *et al.,* 2025)

Natural Toxins and Cyanotoxins: Produced by certain algal and bacterial species, they are increasing in prevalence in response to eutrophication and climate variability, and are capable of inducing acute poisoning and chronic adverse effects in both aquatic organisms and human populations (Nguyen, 2024).

Major Routes of Entry of Emerging Pollutants into the Environment

Major routes of entry include metabolic excretion via urine and feces following therapeutic use, direct discharge from wastewater treatment facilities where removal is incomplete, agricultural surface runoff carrying animal waste-derived pharmaceuticals and pesticide residues, and inappropriate disposal of unused medications or discharges from manufacturing facilities. These pathways underscore the critical need for advanced treatment technologies and more stringent regulatory oversight to curtail widespread environmental contamination (Zhu *et al*., 2024; Ojija, 2024).

Wastewater Treatment Plant Effluents

One of the predominant pathways by which emerging pollutants reach the environment is through effluent discharge from wastewater treatment plants (WWTPs) (Disner, 2025), as illustrated in Figure 4. Both municipal and industrial wastewaters carry heterogeneous mixtures of pharmaceuticals, personal care product ingredients, hormones, and other

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synthetic compounds originating from domestic, hospital, and industrial uses (Chiaia-Hernández *et al*., 2022). Despite the incorporation of advanced biological treatment stages, WWTPs frequently fail to achieve complete removal of these micropollutants owing to their complex and varied chemical structures (Devasena *et al.,* 2025). This inadequacy results in the discharge of residual parent compounds, metabolic byproducts, and transformation intermediates into receiving surface waters. Hospitals and pharmaceutical manufacturing installations represent significant point sources of antibiotic residues and antimicrobial-resistant bacteria in treatment effluents (Díaz-Cruz *et al*., 2009).

Figure 4: Municipal wastewater discharged into surface waters

Industrial Discharges

A diverse array of industrial sectors contributes substantial burdens of EPs to the environment, either through direct discharges or via indirect transport pathways. Pharmaceutical manufacturing, chemical synthesis, textile processing, electroplating, printing, and energy production are among the industries releasing effluents rich in hazardous organic compounds, industrial solvents, synthetic dyes, and heavy metals, as depicted in Figure 5 (Giannakis *et al*., 2021). These pollutants enter the environment through direct discharge into water bodies or indirectly through soil infiltration and groundwater recharge (Tarfeen *et al*., 2022). PFAS compounds are particularly prominent in industrial waste streams; their exceptional chemical stability leads to long-term environmental contamination extending well beyond initial disposal sites (Li & Zhang, 2021; Shah *et al*., 2024). Nanomaterials increasingly employed in industrial production processes may also escape containment through aqueous or airborne emission pathways, presenting novel monitoring and control challenges (Zhang *et al*., 2025; Kümmerer & Al-Ahmad, 2024).

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Figure 5: Industrial Waste Discharge into Lands and Rivers

Agricultural Runoff and Leaching

Agricultural operations represent major diffuse sources of EPs in the environment. Pesticides, herbicides, veterinary pharmaceutical compounds, fertilizer formulations, and land application of manure collectively introduce a suite of contaminants to soils and water bodies through surface runoff and subsurface percolation to groundwater systems (Boxall, 2012; Milojevic & Cydzik-Kwiatkowska, 2021). These chemical compounds frequently undergo partial degradation within soil matrices but persist long enough to contaminate adjacent streams, rivers, and aquifer systems (Ahogle *et al.,* 2023). The expanding incorporation of nanomaterials into agricultural practice for pesticide delivery or soil conditioning may generate additional novel contaminant pathways. The presence of antibiotic residues in livestock waste further facilitates the dissemination of antibiotic resistance genes throughout environmental systems (Muñoz & Guieysse, 2022; Li *et al.,* 2024).

Landfill Leachate

Landfill facilities accumulate enormous quantities of discarded consumer goods, pharmaceutical products, and plastic materials that undergo slow degradation over time, releasing complex contaminant mixtures (Moeckel *et al.,* 2020). Leachate generated by rainfall infiltration through landfill deposits transports microplastic particles, chemical residues, heavy metals, and other pollutants into soil and groundwater systems (Chamas *et al.,* 2020). Inadequately managed landfills, particularly prevalent in developing regions, function as persistent reservoirs and continuous emission sources for EPs, as exemplified by Figure 6. Leachates containing antibiotic residues and personal care product compounds aggravate pollution risks and promote the dissemination of antibiotic resistance within ecosystem communities (Zhu *et al.,* 2024).

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Figure 6: Improper waste disposal leading to the release of EPs into the terrestrial environment

Atmospheric Deposition and Airborne Transport

Certain EPs are subject to volatilization processes or are adsorbed onto airborne particulate matter, enabling their dispersal through the atmosphere (Montero-Montoya *et al.,* 2018). Atmospheric transport mechanisms allow these pollutants to be deposited in regions geographically distant from their emission sources, including remote and otherwise pristine environments (Munoz & Guieysse, 2022). Volatile organic compounds (VOCs), selected pesticide formulations, and combustion-derived nanoparticles constitute categories of EPs capable of long-range atmospheric dispersal (Montero-Montoya *et al.,* 2018). Their deposition onto soil and water surfaces integrates into local contamination cycles, complicating efforts to trace emission sources and define spatial contamination patterns (Campos *et al.,* 2023).

Domestic and Commercial Sources

Household products, including detergents, personal care formulations, cleaning agents, and flame-retardant-treated materials, continuously release chemical compounds into domestic wastewater networks. These substances ultimately reach treatment facilities or, in the absence of adequate infrastructure, directly enter water bodies (Muir *et al.,* 2017). Sunscreen formulations containing UV-filtering compounds, synthetic musk fragrances, and antibacterial agents such as triclosan exemplify such contributors. Their widespread and continuous use results in persistent environmental loading, often at sub-therapeutic but biologically active concentrations (Sharma & Skaff, 2023).

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Aquaculture and Fish Farming

Intensive aquaculture operations employ antimicrobial agents, antifouling compounds, and other pharmaceutical substances to manage disease and maintain stock health (Muir *et al.,* 2017). The incomplete degradation or inadequate removal of these substances in aquatic environments surrounding fish farming operations introduces EPs directly into aquatic ecosystems (Bowes *et al.,* 2020). These compounds have raised concerns regarding negative impacts on aquatic biodiversity and the development of antimicrobial resistance within aquaculture-associated effluents, underscoring the need for regulatory oversight focused on sustainable aquaculture management practices (Bouki *et al*., 2020). Figure 7 depicts fishing activities in contaminated water bodies.

Figure 7: Fishing in polluted waters

(**Source:** *Alamy, 2023)*

Table 2: showing common routes for pharmaceuticals, micro plastics and PFAS into the environment.

Pathway	Description	Examples
Wastewater Discharge	Untreated or partially treated sewage is released into water bodies from urban and industrial sources (Bu *et al*., 2025; Li *et al*., 2024).	Antibiotics and hormones via effluents (Yang *et al.,* 2025).
Agricultural Runoff	Pesticides and biosolids wash from fields into rivers during precipitation (Li *et al.,* 2024).	Plasticizers from manure (Bu *et al.,* 2025).
Atmospheric Deposition	Airborne transport and wet/dry deposition far from	PFAS from emissions (Li *et al*., 2024).

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	origins (Li *et al.,* 2024).	
Industrial Effluents	Direct manufacturing discharges into soil and water (Bu *et al.,* 2025).	Flame retardants and microplastics (Li *et al.,* 2024).

The Fate of Emerging Pollutants in the Environment

The degradation and transformation of emerging contaminants constitute critical determinants of their environmental fate and overall impact (Stolte *et al*., 2008; Chakraborty *et al.,* 2023). These processes involve both biotic and abiotic mechanisms that act to break down or chemically alter parent compounds, frequently generating transformation products (TPs) or metabolites of varying toxicological significance (Dharupaneedi *et al*., 2019). Biotic processes include microbial catabolism and enzymatic transformations, through which microorganisms or biological enzymes convert contaminants into less toxic or more readily excreted forms (Suman *et al.*, 2022). Abiotic processes encompassing photolysis, hydrolysis, oxidation, and reduction also play significant roles, typically initiated by solar radiation or chemical reactions in aquatic and soil matrices that disrupt chemical bonds and alter pollutant structures (Suman *et al.,* 2022). The transformation products generated through these pathways may differ substantially from their parent compounds in terms of toxicity, environmental persistence, and bioaccumulation potential, necessitating consideration of degradation intermediates alongside parent compounds in comprehensive environmental risk assessments (Gimeno *et al.,* 2016).

Biodegradation

Biodegradation of ECs represents a fundamental natural attenuation process whereby microorganisms, including bacteria and fungi, decompose complex synthetic or naturally occurring pollutants into simpler, less harmful products (Ahmed *et al*., 2022). This process is central to mitigating the ecological impacts of contaminants, including pharmaceuticals, pesticide residues, plasticizers, and microplastic particles, which are increasingly identified in aquatic and terrestrial environments (Chakraborty *et al.,* 2023; Kumar & Shukla, 2023). The biodegradation process involves several sequential mechanistic steps: microbial colonization of the contaminant surface, physical and enzymatic fragmentation of large molecules into smaller components, cellular assimilation of these fragments by microbial cells, and complete mineralization, converting organic pollutants into inorganic end-products such as carbon dioxide, water, and biomass (Anand *et al*., 2023; Baaloudj *et al.,* 2025). Biodegradation efficiency is regulated by the chemical characteristics of the pollutant, including its molecular architecture, aqueous solubility, and inherent toxicity; environmental parameters, including temperature, pH, and oxygen availability; the composition of the resident microbial community; and the presence of co-metabolites or chemical cofactors that facilitate breakdown (Silva *et al.,* 2019; Xu *et al*., 2021). Advanced molecular tools, including omics platforms encompassing genomics, proteomics, and metabolomics, have transformed the understanding of the microbial genes, enzymatic systems, and metabolic pathways involved in contaminant degradation. Integration of these approaches with metabolic engineering strategies enables enhancement of natural biodegradation capabilities, facilitating more efficient metabolism of target pollutants or enabling the degradation of recalcitrant substances previously resistant to biological breakdown (Chakraborty *et al.,* 2023). This environmentally sound and cost-effective approach holds significant potential for large-scale

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remediation of contaminated soils and wastewater systems, reducing the toxicity and persistence of ECs and thereby safeguarding both ecological and human health (Kannan *et al*., 2025; Chakraborty *et al.,* 2023).

Comparison of biodegradation rates and pathways for plastics, pharmaceuticals, and PFAS

The biodegradation rates and pathways of plastics, pharmaceuticals, and per- and polyfluoroalkyl substances (PFAS) differ significantly due to their distinct chemical structures and environmental persistence (Cai, 2023; Chamas *et al.,* 2020; UK Government, 2024). Plastic biodegradation, especially for conventional plastics like polyethylene (PE) and polypropylene (PP), is typically slow due to their high molecular weight and hydrophobicity (Chamas *et al.,* 2020). Biodegradable plastics such as polylactic acid (PLA) degrade faster, sometimes 20 times faster, in land environments compared to HDPE, aided by microbial consortia that break down polymer chains into simpler monomers (Cai, 2023; Li *et al.*, 2024). Microorganisms, including bacteria and fungi, employ enzymatic pathways involving hydrolases, oxygenases, and peroxidases to cleave plastic polymers into smaller fragments, eventually mineralizing them to water and carbon dioxide (Cai, 2023; Li *et al*., 2024). However, complete mineralization of conventional plastics in natural environments may take decades or longer due to slow enzymatic action and environmental limitations (Chamas *et al.,* 2020). In contrast, pharmaceuticals generally degrade faster than plastics due to their smaller molecular size and more reactive functional groups (Wang *et al.,* 2024). Microbial enzymatic pathways, including cytochrome P450 monooxygenases, hydrolases, and reductases, transform pharmaceuticals via hydroxylation, conjugation, and cleavage reactions (Wang *et al.,* 2024). Degradation rates vary by compound structure and environmental factors, and some pharmaceuticals produce persistent transformation products with unknown toxicity (Wang *et al.,* 2024). Their biodegradation can occur within days to weeks in wastewater treatment systems, but incomplete removal is common (Wang *et al.,* 2024). PFAS are among the most recalcitrant emerging pollutants due to their strong carbon-fluorine bonds, which are highly resistant to microbial and chemical degradation (UK Government, 2024). Conventional biodegradation processes are largely ineffective; PFAS persist in the environment for decades, necessitating advanced treatment methods such as oxidation or adsorption (UK Government, 2024). Limited microbial degradation of PFAS has been reported with low rates, involving defluorination pathways mainly under anaerobic conditions, but these pathways remain poorly understood and inefficient (UK Government, 2024). Table 3 presents the biodegradation rates and pathways of these plastics, pharmaceuticals, and PFAS.

Table 3: Summary Table of Biodegradation Rates and Pathways

Pollutant Type	Approximate Biodegradation Rate	Main Biodegradation Pathways	Enzymes/Mechanisms	Notes
Plastics (e.g., PE)	Very slow; decades to centuries (for non-biodegradable)	Hydrolysis, oxidation, and enzymatic cleavage	Hydrolases, oxygenases, peroxidases	Biodegradable plastics like PLA degrade faster (weeks to months) (Cai, 2023; Chamas *et al.,*

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				2020)
Pharmaceuticals	Faster; days to weeks	Hydroxylation, conjugation, and cleavage	Cytochrome P450 monooxygenases, reductases	Transformation products may persist (Wang *et al.,* 2024)
PFAS	Extremely slow; decades or more	Limited microbial defluorination (anaerobic)	Poorly understood; potential anaerobic enzymes	Highly resistant C-F bonds; conventional treatment largely ineffective (UK Government, 2024)

Photodegradation

Photodegradation is a crucial natural attenuation process for emerging pollutants in the environment, involving the breakdown of contaminants upon exposure to light, primarily solar radiation (Bester *et al.*, 2025; Huber *et al.,* 2005). This process occurs either directly, where the pollutant absorbs photons, causing chemical bond cleavage, or indirectly, where light-activated catalysts generate reactive species such as hydroxyl radicals (OH^-), superoxide anions (O^{2-}), and photogenerated holes that attack pollutant molecules (Sichel *et al.,* 2011). Emerging pollutants such as pharmaceuticals, pesticides, plastic additives (e.g., Bisphenol A), and persistent organic pollutants undergo photodegradation in water and air, reducing their toxicity and facilitating subsequent biodegradation. Photocatalysts like titanium dioxide (TiO_2) and advanced composites significantly enhance photodegradation efficiency by generating electron-hole pairs under light irradiation (Kuang *et al.,* 2016; Deng *et al.,* 2017). These reactive species oxidize pollutants (e.g., Bisphenol A and tetracycline), breaking them down into intermediate products and eventually mineralizing them to carbon dioxide, water, and inorganic ions (Saravanan *et al.,* 2022). Experimental studies indicate hydroxyl radicals and photogenerated holes are the predominant reactive species in photodegradation mechanisms, with superoxide radicals playing a lesser role depending on pollutant properties and photocatalyst band potentials (Premjit *et al.,* 2022). The presence of ions or organic matter can affect the efficiency of photodegradation by competing for reactive species or adsorbing onto catalyst surfaces (Kuang *et al.,* 2016). Photodegradation leverages solar energy and often employs heterogeneous photocatalysts to generate highly reactive intermediates that transform recalcitrant emerging pollutants into less harmful substances (Saravanan *et al.,* 2022). This environmentally friendly treatment holds promise for mitigating contamination in aquatic and atmospheric environments (Kondamareddy *et al.,* 2018).

Key reactive species in the photodegradation of emerging pollutants primarily include hydroxyl radicals (-OH), superoxide anion radicals (O^{2-}), singlet oxygen ($^1O_2$), and photogenerated holes (h^+). These species are highly reactive and play distinct roles in oxidizing and breaking down pollutant molecules (Kuang *et al.,* 2016; Kondamareddy *et al.,* 2018; Zhang *et al.,* 2022). Hydroxyl radicals are among the most potent oxidizing agents produced during photodegradation, typically generated when photogenerated holes react with water or hydroxide ions adsorbed on catalyst surfaces (Kuang *et al.,* 2016). These radicals

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attack a wide array of organic pollutants by abstracting hydrogen atoms, adding to double bonds, or oxidizing functional groups, leading to molecular fragmentation and mineralization into CO_2 and H_2O. Their rapid and non-selective oxidative action makes them central in degrading pharmaceuticals, dyes, and plastic additives (Kondamareddy *et al.,* 2018; Zhang *et al.,* 2022). Superoxide radicals formed by electron reduction of oxygen molecules during photocatalysis can initiate secondary radical formation, such as hydrogen peroxide and hydroxyl radicals. O^{2-} contributes to pollutant degradation through oxidation reactions, yet its reactivity is generally lower than that of hydroxyl radicals. In some dye degradation systems, superoxide radicals play a significant role, especially for certain anionic chemicals (Kuang *et al.,* 2016; Kondamareddy *et al.,* 2018). Singlet oxygen is another reactive oxygen species generated by energy transfer from excited photocatalysts or via photosensitized reactions. $^1O_2$ participates in the selective oxidation of certain organic pollutants and can contribute to indirect photodegradation pathways (Zhang *et al.,* 2022). Photogenerated holes in the valence band of semiconducting photocatalysts are strong oxidants that can directly oxidize pollutants or react with surface-bound water species to produce hydroxyl radicals. These holes drive initial pollutant degradation steps and contribute significantly (often over 60%) to total degradation in many systems (Kuang *et al.,* 2016). Photodegradation is exemplified in how the hydroxyl radical degrades ibuprofen. The hydroxyl radical (·OH) attack on ibuprofen involves hydrogen abstraction and addition reactions leading to the formation of hydroxylated intermediates and eventual degradation products. The simplified balanced reactions below illustrate the main pathway of hydroxyl radical attacking ibuprofen ($C_{13}H_{18}O_2$):

Hydrogen Abstraction

·OH abstracts H from ibuprofen's isobutyl chain:
$C_{13}H_{18}O_2 + \cdot OH \rightarrow C_{13}H_{17}O_2\cdot + H_2O$ (Miranda *et al.*, 2021).

Radical Addition

·OH adds to the aromatic ring:
$C_{13}H_{18}O_2 + \cdot OH \rightarrow [C_{13}H_{19}O_3]\cdot$ (hydroxycyclohexadienyl radical) (Miranda *et al.,* 2021).

Peroxyl Radical Formation

The carbon radical forms a peroxyl radical:
$C_{13}H_{17}O_2\cdot + O_2 \rightarrow C_{13}H_{17}O_4\cdot$ (He *et al.,* 2014).

Hydroxylated Products

Further reactions produce 2-hydroxyibuprofen:
$C_{13}H_{18}O_2 + \cdot OH \rightarrow C_{13}H_{18}O_3$ (Miranda *et al.,* 2021).

Mineralization

Complete breakdown occurs:
$C_{13}H_{18}O_2 + 15\cdot OH \rightarrow 13CO_2 + 18H_2O$ (He *et al.,* 2014).

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Volatilization

Volatilization constitutes an important environmental fate process for EPs, involving their transfer from aqueous, soil, or surface matrices into the gaseous phase. This process is driven by the compound's vapor pressure and by ambient environmental parameters, including temperature and wind velocity, and serves to reduce contaminant concentrations in aquatic systems while potentially dispersing them over the atmosphere (Chiou, 2000). For semi-volatile EPs, including certain pharmaceutical compounds and PFAS, volatilization competes with other removal mechanisms, with greater volatility facilitating evasion from sedimentary sinks while simultaneously risking long-range atmospheric dispersal (Habimana *et al.,* 2025). Short-chain PFAS exhibit higher volatility relative to their long-chain counterparts, a characteristic that influences their global environmental distribution (Higgins & Luthy, 2006). Volatilization rates increase with ambient temperature and decrease under high humidity conditions. In sedimentary environments, this process can promote re-emission of previously deposited contaminants, thereby prolonging ecosystem exposure (Valderrama *et al.,* 2023).

Sorption to Sediments

Sorption to sediments represents a critical mechanism for the removal of EPs from the water column through binding interactions with mineral or organic phases. Hydrophobic compounds partition into sediment organic carbon fractions based on their organic carbon-normalized partition coefficient (Koc), while ionizable or charged pollutants interact electrostatically with clay mineral surfaces, retarding their aqueous mobility. PFAS sorption is strengthened with increasing perfluorocarbon chain length due to hydrophobic interactions; though shorter-chain variants exhibit greater mobility under dynamic flow conditions (Higgins & Luthy, 2006). Physicochemical environmental parameters, including pH and ionic strength, modulate the extent of sorption, with optimal binding typically occurring under near-neutral pH conditions (Valderrama *et al*., 2023). Organic carbon content dominates partitioning behavior for nonpolar hydrophobic contaminants, while mineral surfaces are more important for polar compounds. Progressive sedimentation can enhance organic matter content over time, increasing contaminant retention. Sorption thus functions as an environmental sink, but desorption under altered environmental conditions can remobilize sequestered contaminants.

Hydrolysis

Hydrolysis contributes to the degradation of EPs through nucleophilic attack by water molecules, a process commonly catalyzed under conditions of extreme pH. Labile compounds such as certain pesticide formulations undergo pseudo-first-order hydrolysis, generating transformation products of reduced toxicity, though many pharmaceutical compounds display minimal reactivity under neutral environmental conditions (Bu *et al*., 2025). Reaction rates are dependent on molecular structure, with ester linkages hydrolyzing considerably faster than amide bonds, while sediment surfaces can accelerate surface-mediated hydrolysis reactions (Habimana *et al*., 2025). This abiotic transformation process competes with biodegradation in aqueous environmental matrices. Acidic and alkaline conditions both accelerate hydrolysis rates relative to neutral pH, and reaction kinetics conform to Arrhenius principles, approximately doubling with every 10°C rise in temperature. While hydrolysis contributes to the natural attenuation capacity of aquatic

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environments, the process proceeds too slowly to achieve adequate transformation of many persistent EPs within relevant environmental timeframes. Table 4 provides a summary of the environmental fate of selected EPs.

Table 4: Summary of the fate of some emerging pollutants in the environment

Process	Description	Environmental Impact
Biodegradation	Microbial degradation is often partial with toxic metabolites (Silva *et al.*, 2019).	Incomplete breakdown of drugs like tenofovir (Silva *et al.,* 2019).
Photodegradation	Sunlight-driven breakdown in surface waters (Li *et al.,* 2024).	Effective for sun-exposed antibiotics (Li *et al.,* 2024).
Adsorption	Binding to sediments or biota, promoting accumulation (Li *et al.,* 2024).	PFAS uptake in plants via soil (Bu *et al.,* 2025).
Long-Range Transport	Dispersal via currents, wind, or migration (Li *et al.,* 2024).	Global distribution through food chains (Yang *et al.,* 2024).

Factors Influencing the Distribution of Emerging Pollutants

The spatial and temporal distribution of emerging contaminants is shaped by the interplay of natural and anthropogenic factors. Hydrological conditions govern whether contaminants are diluted or concentrated in receiving water bodies, with corresponding effects on persistence and toxicity (Zhang *et al.*, 2018). The treatment efficiency of wastewater treatment plants (WWTPs) constitutes another key regulatory factor, as inadequate treatment can lead to the release of untreated or partially treated contaminants into the environment (Puri *et al*., 2023). The stringency of regulatory frameworks also exerts influence, with more rigorous regulatory provisions leading to improved monitoring coverage and lower ambient contaminant concentrations (Schriks *et al.*, 2010).

Land use and population density exert significant controlling influences on EP contamination levels. Densely populated urban areas experience elevated contamination burdens attributable to industrial discharges, municipal waste streams, and pharmaceutical consumption patterns (Kumar *et al*., 2021). Agricultural activities contribute through pesticide and herbicide applications, veterinary drug use, and manure-derived chemical inputs that leach into water bodies or accumulate in agricultural soils (Disner, 2025). Areas under intensive cultivation tend to exhibit elevated contaminant concentrations. The intrinsic physicochemical properties of individual contaminants also determine their partitioning behavior: hydrophilic compounds remain predominantly in aqueous phases, whereas hydrophobic compounds partition preferentially into sediment organic matter or soil organic fractions (Ealias *et a*l., 2024). Compound volatility and biodegradability further dictate environmental fate trajectories; volatile contaminants may be transferred to the atmospheric compartment, while non-biodegradable substances persist and create conditions for prolonged ecosystem exposure (Egbuna *et al.,* 2021).

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Climate and seasonal variations further modulate contaminant mobility in the environment; precipitation events and associated surface runoff can mobilize contaminants from terrestrial to aquatic systems, whereas drought conditions may concentrate pollutants through reduced dilution capacity (Saravanan *et al.,* 2022). Temperature influences both the rates of chemical transformation reactions and microbial metabolic activity, with the potential to either accelerate environmental degradation or alter the toxicological potency of transformation products (Chiaia-Hernandez *et al*., 2022). Sediment-contaminant interactions are critically important in governing accumulation dynamics. The binding of contaminants to sediments creates localized concentration hotspots in riverbeds and estuarine environments, which may function as long-term pollution sources through episodic desorption. These interactions depend on sediment characteristics, including particle size distribution and organic matter content, alongside the chemical properties of individual contaminants (Li *et al.,* 2024). Climate change significantly modulates the degradation and ultimate fate of EPs, including pharmaceuticals, microplastics, PPCPs, and PFAS, in Nigeria through alterations of key environmental parameters, including ambient temperature, precipitation patterns, and frequency of extreme weather events (Intergovernmental Panel on Climate Change, 2022). Elevated temperatures accelerate both microbial decomposition and photolytic degradation of these contaminants in surface waters and soils, though these processes frequently generate more persistent and toxic metabolites, complicating assessments of environmental persistence and mobility (Zhang *et al*., 2021). In Nigeria, intensification of flood events in southern regions, including Lagos and the Niger Delta, driven by more frequent heavy rainfall episodes, remobilizes pollutants from urban stormwater, informal waste disposal sites, and petroleum-impacted areas into major rivers and coastal lagoon systems, amplifying dispersal and bioavailability (Enete & Achike, 2008). Conversely, prolonged drought periods in northern Sahelian regions, including the Lake Chad basin, concentrate these pollutants in diminishing water bodies, reducing dilution capacity and extending environmental half-lives, as documented for pharmaceutical residues in shrinking aquifer systems (Richard *et al*., 2023). Rising sea levels exacerbate salinization and coastal erosion along Nigeria's coastline, liberating previously sorbed pollutants, including PFAS, from sedimentary deposits into groundwater systems, while disrupting natural attenuation mechanisms, including volatilization and plant uptake (Nigerian Meteorological Agency, 2023). These climate-driven shifts amplify bioaccumulation in aquatic species and food crops, posing direct risks to food security and public health in Nigerian agricultural communities (World Bank, 2022). In Nigeria's context, climate change is progressively transforming the environmental fate of EPs from relatively localized degradation to widespread and increasingly difficult-to-mitigate dispersal, underscoring the urgent need for integrated adaptation strategies (United Nations Environment Programme, 2021).

Long-range transport also contributes substantially to environmental contamination burdens. Persistent organic pollutants and pharmaceuticals have been detected in remote regions, including the Arctic and Antarctic, underscoring the necessity for global cooperation in environmental monitoring and mitigation efforts (Silva *et al*., 2019). Biological factors such as microbial metabolic activity also influence contaminant distribution patterns; specific bacterial and fungal taxa can metabolize pharmaceutical compounds and organic pollutants, though transformation efficiency varies depending on ambient environmental conditions and the adaptive capacity of the microbial community (Ojija, 2024). Human activities, including improper disposal of hazardous materials, illegal dumping, and the use of untreated

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wastewater for agricultural irrigation, further aggravate contamination (Diaz-Cruz *et al*., 2009).

Bioaccumulation and Effects of Emerging Pollutants through Food Webs

The bioaccumulation of EPs across food web structures has emerged as a critical issue for both environmental management and public health, as contaminants persist in ecosystems while resisting removal by conventional treatment processes (Al-Amin *et al*., 2020; Biswas *et al*., 2022). These substances undergo initial uptake by organisms at lower trophic positions, including algae, zooplankton, and benthic invertebrates, and are subsequently transferred and progressively magnified as they ascend through aquatic and terrestrial food networks to fish, birds, and mammals (Figure 7), ultimately reaching humans at the apex of the trophic hierarchy (Gaines *et al*., 2023; Yu *et al*., 2023). Trophic transfer can result in contaminant concentrations in apex consumers that far exceed ambient environmental concentrations, contributing to endocrine disruption, immunotoxicity, reproductive impairment, neurotoxicity, and developmental effects in exposed organisms (Evich *et al*., 2022; Kumar *et al*., 2021). Understanding and characterizing the bioaccumulation dynamics and toxic effects of EPs across interconnected food networks is therefore essential for robust risk assessment, ecosystem protection, and the design of effective monitoring, regulatory, and mitigation frameworks (UK Environmental Agency, 2024; UK Government, 2024).

Bioaccumulation and Effects of Pharmaceuticals through Food Webs

Pharmaceuticals are increasingly recognized as emerging contaminants in aquatic and terrestrial ecosystems due to their persistent presence and potential biological effects. These compounds enter the environment primarily through wastewater discharge and can persist in water, sediment, and biota, leading to bioaccumulation and transfer through food webs (Ortúza *et al,* 2022; Gómez-Regalado *et al.,* 2023). Bioaccumulation of pharmaceuticals varies widely among compounds and ecosystems. Studies have shown that some pharmaceuticals undergo trophic magnification, increasing in concentration as they move up the food chain, while others exhibit trophic dilution or no significant accumulation (Sokołowski *et al.,* 2024; Xie *et al.,* 2017). For example, ciprofloxacin has been demonstrated to biomagnify in Arctic benthic food webs, with trophic magnification factors (TMF) greater than 1.0, indicating increasing concentrations in higher trophic levels (Sokołowski *et al.,* 2024). In contrast, pharmaceuticals like carbamazepine and diclofenac often show low or unclear biomagnification patterns, possibly due to metabolism or limited assimilation efficiency in organisms (Xie *et al.,* 2017). Pharmaceutical accumulation is tissue-specific in fish and aquatic invertebrates, with higher concentrations often detected in metabolically active organs such as liver and brain compared to muscle tissues, reflecting the pharmacokinetics within organisms (Xie *et al.,* 2017). Benthic organisms, which ingest contaminated sediments, play a vital role in transferring pharmaceuticals into aquatic food webs, serving as a pathway for exposure to higher trophic levels (Ortúza *et al,* 2022). The ecological effects of pharmaceutical bioaccumulation include endocrine disruption, altered reproduction, and behavioral changes in aquatic organisms. These sub-lethal effects can cascade through food webs, potentially altering species interactions and ecosystem functions (Gómez-Regalado *et al.,* 2023). Risk assessment frameworks, therefore, increasingly consider the trophic transfer of pharmaceuticals to predict cumulative impacts in the environment (Sokołowski *et al.,* 2024).

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Pharmaceutical residues are increasingly acknowledged as ECs of growing significance in both aquatic and terrestrial systems due to their environmental persistence and documented biological effects. These compounds enter ecosystems predominantly through wastewater discharge and can persist in water, sediment, and biological tissues, leading to bioaccumulation and trophic transfer (Ortúzar *et al.*, 2022; Gómez-Regalado *et al.*, 2023). The extent of pharmaceutical bioaccumulation varies considerably across compounds and ecosystem types. Research has documented trophic magnification of certain pharmaceuticals, with concentrations increasing at successive trophic levels, while others exhibit trophic dilution or negligible accumulation patterns (Sokołowski *et al*., 2024; Xie *et al*., 2017). For example, ciprofloxacin has been shown to exhibit biomagnification in Arctic benthic food webs, with trophic magnification factors (TMF) exceeding 1.0, indicating increasing tissue concentrations at higher trophic levels (Sokołowski *et al*., 2024). In contrast, compounds such as carbamazepine and diclofenac typically display low or ambiguous biomagnification patterns, possibly attributable to metabolic transformation or limited assimilation efficiency in exposed organisms (Xie *et al*., 2017). Pharmaceutical accumulation in fish and aquatic invertebrates is tissue-specific, with elevated concentrations commonly detected in metabolically active organs, including liver and brain tissue, relative to muscle, reflecting pharmacokinetic distribution within organisms (Xie *et al*., 2017). Benthic organisms ingesting contaminated sediments serve as important conduits for pharmaceutical transfer into aquatic food webs, functioning as exposure pathways for higher trophic levels (Ortúzar *et al*., 2022). Ecological effects of pharmaceutical bioaccumulation include endocrine disruption, altered reproductive function, and behavioral modifications in aquatic organisms, with sub-lethal effects capable of cascading through food networks to alter species interactions and ecosystem-level functions (Gómez-Regalado *et al*., 2023). Risk assessment frameworks are increasingly incorporating trophic transfer dynamics of pharmaceuticals to predict cumulative environmental impacts (Sokołowski *et al*., 2024).

Bioaccumulation and Effects of Personal Care Products (PCPs) through Food Webs

Personal care product (PCP) ingredients derived from sunscreens, detergents, and disinfectant formulations are recognized ECs that undergo bioaccumulation in food webs largely owing to their widespread release into aquatic and terrestrial systems through wastewater discharge and other pathways (Carter *et al*., 2024). The degree to which PCPs bioaccumulate depends on their chemical properties, ambient environmental conditions, and the physiological characteristics of organisms within the food web (Muir *et al*., 2017). Investigations have documented the accumulation of various PCP chemicals in aquatic species, including fish, with bioaccumulation factors varying widely across compound classes. Antidepressants and benzodiazepines among PPCPs show relatively elevated bioaccumulation in fish plasma, indicating their potential for trophic transfer and biomagnification (Muir *et al*., 2017). The extent of PCP bioaccumulation is influenced by pH, the presence of surfactants, and suspended solid concentrations, making exposure concentrations variable and challenging to predict using models alone (Muir *et al*., 2017; Carter *et al*., 2024). In terrestrial systems, PCPs can enter agricultural soils through application of biosolids or irrigation with contaminated water, subsequently accumulating in food crops and transferring to herbivores, thereby introducing these contaminants into terrestrial food webs and posing risks to human health via agricultural food chains (Wang *et al*., 2025). Metabolic transformation in plants can partially degrade these compounds, but significant accumulation, particularly in root tissues, has been documented for compounds including diclofenac and sulfamethoxazole,

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accompanied by the formation of metabolites that may retain their own toxicological activity (Wang *et al*., 2025). Ecological effects include toxicity to aquatic organisms, disruption of normal physiological function, and potential alterations in food web structure through multi-trophic level effects (Carter *et al*., 2024).

Bioaccumulation and Effects of PFAS through Food Webs

PFAS bioaccumulation through food webs occurs predominantly in aquatic environments, where these compounds accumulate in the tissues of organisms, including fish (Al-Amin *et al.,* 2020; Gaines *et al*., 2023). PFAS compounds bearing eight or more perfluorinated carbon atoms are typically the most abundant in aquatic food networks and exhibit the highest bioaccumulation potential, driven by partitioning into phospholipid bilayers and binding to plasma proteins within biological systems (Evich *et al*., 2022; Nzeribe *et al*., 2019). Renal excretion contributes minimally to the elimination of these longer-chain variants, predisposing them to persistent biological accumulation (UK Environmental Agency, 2024; UK Government, 2024). Shorter-chain PFAS exhibit distinct physiological behavior, including partial renal elimination, though protein-binding dynamics remain critical for understanding their bioaccumulation characteristics (Al-Amin *et al.,* 2020; Evich *et al.*, 2022). Bioaccumulation in aquatic food webs poses risks to seafood-consuming populations, with common contaminants including PFOA and PFOS traceable to dietary seafood alongside co-occurring toxins including mercury and organochlorine pesticides (Gaines *et al.*, 2023; Nzeribe *et al*., 2019). Contemporary food web bioaccumulation models incorporate mechanistic processes, including phospholipid partitioning, protein binding, membrane transport kinetics, and renal elimination, to improve predictions of PFAS accumulation in fish for use in risk assessments and fish consumption advisories (UK Environmental Agency, 2024; UK Government, 2024). PFAS bioaccumulation also extends to terrestrial systems, where biomagnification can occur through soil-plant-animal pathways, generating exposure risks for wildlife and human populations reliant on these systems (Evich *et al*., 2022; Gaines *et al*., 2023). Health consequences of PFAS bioaccumulation include thyroid dysfunction, immunosuppression, and reproductive impairment in wildlife, alongside human health risks encompassing hormonal disruption, reduced birth weight, and elevated cancer risk (Al-Amin *et al*., 2020; Nzeribe *et al.,* 2019). PFAS with shorter perfluorinated carbon chains display distinct pharmacokinetic behavior relative to their longer-chain counterparts, including partial renal clearance, though interactions with plasma proteins remain a determining factor governing accumulation dynamics in exposed organisms (Al-Amin *et al.,* 2020; Evich *et al.*, 2022). For populations with elevated fish and seafood consumption, the bioaccumulation of PFOA and PFOS in aquatic food webs presents a significant dietary exposure pathway, with contamination profiles in marketed seafood frequently compounded by co-occurring environmental toxins such as mercury and organochlorine pesticide residues (Gaines *et al*., 2023; Nzeribe *et al.,* 2019). Sophisticated mechanistic food web bioaccumulation models that account for phospholipid partitioning behavior, plasma protein binding dynamics, transmembrane transport kinetics, and renal elimination rates have been developed to generate more reliable predictions of PFAS tissue concentrations in fish, thereby supporting evidence-based risk assessment and fish consumption advisory frameworks (UK Environmental Agency, 2024; UK Government, 2024). PFAS bioaccumulation is not confined to aquatic systems; terrestrial biomagnification pathways involving soil-to-plant uptake, subsequent transfer to herbivores, and predation by higher-order consumers generate

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meaningful exposure risks for both land-dwelling wildlife and human populations dependent on agricultural food production systems (Evich *et al*., 2022; Gaines *et al*., 2023).

Bioaccumulation and Effects of Microplastics through Food Webs

Microplastics (MPs), plastic particles smaller than 5 mm in dimension, have achieved ubiquitous distribution as environmental pollutants in aquatic and marine ecosystems globally (Jahedi & Fard, 2025). Their incorporation into food webs occurs primarily through ingestion by primary consumers, including zooplankton and filter-feeding bivalves that ingest waterborne particles (Kumar *et al*., 2021). These microplastics subsequently transfer upward through trophic levels via predation, resulting in progressive bioaccumulation across multiple aquatic taxa (Cverenkárová *et al*., 2021). A key mechanistic determinant of microplastic bioaccumulation is the balance between ingestion rates, dietary composition, and gut retention times within different organisms. Theoretical food web modeling frameworks such as MICROWEB simulate trophic transfer of MPs, demonstrating accumulation within organisms and propagation through food webs based on physiological and feeding behavioral parameters (Diepens & Koelmans, 2018). Unlike dissolved chemical contaminants, the physical retention dynamics of MPs significantly influence organismal concentrations. MPs additionally function as vectors for hydrophobic organic contaminants (HOCs) and heavy metals, adsorbing these pollutants from the surrounding environment and potentially enhancing their bioaccumulation and biomagnification risks. For example, microplastic ingestion can enhance bioaccumulation of polycyclic aromatic hydrocarbons (PAHs) by altering metabolization dynamics in Arctic food webs (Diepens & Koelmans, 2018). Field data on MP biomagnification across trophic levels remain ambiguous; MPs tend to accumulate within trophic levels, but clear evidence of systematic biomagnification is limited (Miller *et al.,* 2020). Biological effects in microplastic-exposed organisms include gastrointestinal blockage, impaired feeding efficiency, and energy depletion, as well as chemical toxicity through leaching of plastic additives and adsorbed environmental contaminants (Biswas *et al*., 2022). These effects can impair growth, reproductive success, and survival, with potential cascading effects on population and community dynamics (McHale *et al*., 2024).

Organisms exposed to microplastics experience a spectrum of biological impacts, encompassing mechanical injury through gut obstruction, compromised foraging behavior, and energetic depletion, as well as chemically mediated toxicity arising from the leaching of plasticizer additives and the delivery of adsorbed environmental contaminants (Biswas *et al*., 2022). Collectively, these stressors reduce growth rates, impair reproductive output, and diminish survival rates, with community- and ecosystem-level consequences that propagate through predator-prey networks (McHale *et al*., 2024). A further dimension involves the colonization of microplastic surfaces by microbial communities, which may include opportunistic pathogens capable of influencing microbial food web dynamics and facilitating horizontal gene transfer. From a public health standpoint, the integration of microplastics into the tissues of commercially harvested fish and shellfish constitutes a route of human dietary exposure that warrants sustained investigation and risk characterization (Yu *et al*., 2023). Advancing the scientific understanding of exposure mechanisms, trophic transfer efficiencies, and long-term health outcomes associated with microplastic contamination across food web pathways remains an important priority for both ecological research and regulatory policy development (McHale *et al*., 2024).

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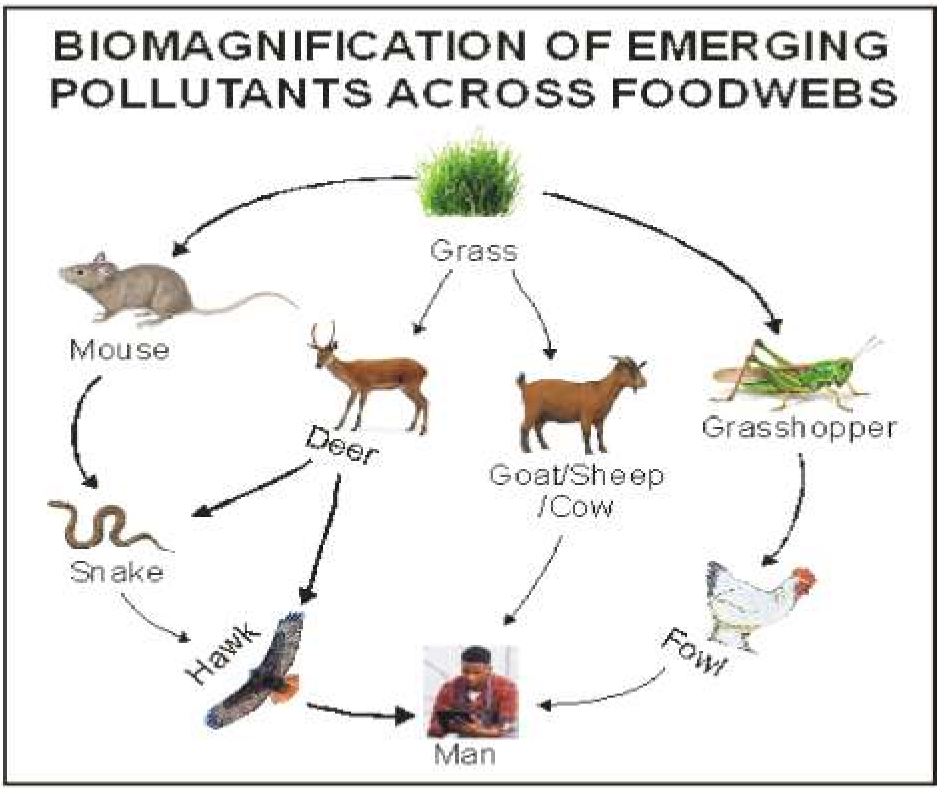
Bioaccumulation and Effects of Nanoparticles through Food Webs

Nanoparticles bioaccumulate in food webs primarily through ingestion and environmental uptake by organisms across multiple trophic levels, with their distinctive physicochemical properties governing tissue distribution, retention behavior, and toxicological effects (Kümmerer *et al*., 2024). Entry routes encompass direct uptake from aquatic or soil phases and dietary transfer through consumption of contaminated prey organisms (Dang *et al*., 2021). Following organismal uptake, nanoparticles distribute to various tissues depending on particle size, shape, surface charge, and chemical composition, with smaller and less soluble particles tending to persist and bioaccumulate more intensively (Sustainability-directory, 2025). Trophic transfer of nanoparticles can lead to bioaccumulation and, in some cases, biomagnification, though the magnitude varies considerably with particle type and ecological context (Devasena *et al*., 2022). For example, silver nanoparticles (AgNPs) have shown biomagnification in certain aquatic systems with trophic magnification factors exceeding 1, while other nanoparticle types exhibit variable transfer efficiencies dependent on physiological and ecological variables (Dang *et al*., 2021). Bioaccumulation mechanisms include endocytic cellular uptake and membrane-mediated transport, frequently resulting in accumulation within cellular and organ compartments, with limited metabolic transformation and slow excretion rates enhancing persistence and toxicological risk (Devasena *et al*., 2022). Toxicological effects manifest through oxidative stress induction, inflammatory responses, cellular dysfunction, and disruption of gut microbiota, with potential consequences for organismal survival and reproduction cascading through food web dynamics (Dube *et al*., 2023; Devasena *et al*., 2022). Figure 8 shows the biomagnification of ECs across foodwebs.

Figure 8: Showing biomagnification of emerging pollutants across foodwebs



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Bioaccumulation and Bioconcentration Factors: BAF and BCF

In environmental toxicology, **BAF (Bioaccumulation Factor)** and **BCF (Bioconcentration Factor)** quantify how pollutants like PFOS or pesticides concentrate in organisms relative to ambient water (Arnot & Gobas, 2006). BAF measures total uptake from all routes: water, diet, and sediment, providing a realistic wild exposure metric. In contrast, BCF isolates water-only absorption, typically from lab tests excluding food (USEPA, 2009). For instance, a BAF of 100 L/kg wet weight means an organism like fish holds 100 times more chemical per kg tissue than in the surrounding water (Illés *et al.,* 2013). BAF often exceeds BCF in nature due to dietary magnification, making it critical for food chain risk assessments. Values above 1000 flag high persistence concerns, as seen in PFOS bioaccumulation in fish muscle (1,000–10,000 L/kg) and human serum (Cousins *et al.,* 2020). These metrics guide regulations on emerging contaminants, emphasizing dietary pathways in predators and humans. BAF values for emerging contaminants like PFAS (e.g., PFOS), pharmaceuticals (e.g., ibuprofen), and pesticides vary widely by species, tissue, and compound, as shown in Table 5

Table 5: BAF for Emerging Contaminants (L/kg wet weight)

Organism	Contaminant	Tissue	BAF Value	Reference Citation
Fish (Sea bass)	Pesticides	Muscle	10–500	Kasiotis *et al.,* 2024
Fish (Sole)	Trace metals	Muscle	<100	Kasiotis *et al*., 2024
Fish (various)	PFOS (C8)	Muscle	1,000–10,000	Cousins *et al.,* 2020
Gammarids (invert)	PFOS	Whole	100–1,000	Cousins *et al.,* 2020
Crucian carp	Cypermethrin	Gill	5,000+	Wang *et al.* ,2025
Humans (blood)	PFOS	Serum	5,000–20,000 (est.)	Houde *et al.,* 2011
Molluscs	PFCAs	Whole	50–500	Cousins *et al*., 2020

Human Health Impacts of Emerging Pollutants

ECs encompassing pharmaceuticals, personal care product ingredients, and microplastic particles present escalating risks to human health (Bala *et al*., 2022). These frequently unregulated and poorly characterized substances can contaminate water supplies, food production systems, and broader ecosystems, generating complex and multifaceted health hazards (Blair *et al*., 2013). Human health effects may include endocrine disruption, promotion of antimicrobial resistance, and other long-term impacts that require public health systems to develop more sophisticated monitoring and response frameworks (Allen *et al*., 2022). The growing body of evidence regarding mechanisms and effects of these

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contaminants underscores the urgent need for regulatory authorities to revise and strengthen safety standards to adequately protect public health (Moeckel *et al.,* 2020).

Endocrine Disruption

EDCs, including bisphenol A (BPA) and phthalates, have been extensively investigated for their capacity to interfere with hormonal regulatory systems in the human body (Chen *et al.,* 2025). These compounds can mimic, antagonize, or otherwise perturb natural hormonal signaling, potentially generating adverse health consequences (Marlatt, 2022). Specifically, BPA and phthalates have been associated with obesity, altered reproductive behavior, and diminished fertility in both humans and wildlife populations (Pulusu *et al*., 2025). The mechanisms through which these compounds exert their biological effects include binding to hormone receptor proteins, interference with hormone biosynthesis, and disruption of signal transduction pathways (Alsalihy *et al.*, 2024). The pervasive presence of these chemicals in environmental matrices, attributable principally to widespread industrial and consumer product usage, necessitates rigorous research to fully elucidate their mechanisms of action and characterize their long-term health and ecosystem impacts. Development of safer chemical alternatives and more stringent regulatory measures is essential to mitigate their widespread adverse effects (Pulusu *et al.,* 2025).

Neurological Effects

Recent scientific investigations have highlighted the neurotoxic properties of specific pesticide formulations and industrial chemical compounds, documenting their capacity to induce neurological injury in human populations (Li *et al*., 2024). These substances have been increasingly recognized for their ability to interfere with neurochemical processes, contributing to neurodevelopmental abnormalities and elevating the risk of neurodegenerative conditions, including Alzheimer's and Parkinson's diseases (Kumar *et al.*, 2021). Chronic exposure, even at sublethal doses, has been associated with progressive neurotoxic consequences. Research has elucidated the mechanisms through which these compounds induce neurotoxicity, including disruption of neurotransmitter systems, promotion of oxidative stress, and direct neuronal injury (Gómez-Regalado *et al.,* 2023). This accumulating evidence supports the case for stringent regulatory action and expanded research into the full extent of neurological health impacts, and for the development of effective prevention and mitigation strategies (Gómez-Regalado *et al*., 2023).

Carcinogenic Effects

Emerging evidence from recent studies demonstrates associations between PFAS exposure and elevated cancer risk, including breast malignancies, attributable to their endocrine-disrupting activity and interference with hormonal signaling pathways (Evich *et al*., 2022). Prolonged low-level PFAS exposure appears to increase breast cancer risk through estrogenic mimicry and promotion of tumor proliferation in mammary tissue (Al-Amin *et al*., 2020). These epidemiologically documented associations underscore the critical importance of expanded research on PFAS carcinogenic mechanisms and strategies for exposure reduction (Gaines *et al*., 2023). The prevalence of microplastic particles and engineered nanomaterials in diverse consumer goods and industrial processes has also generated concern about their potential to contribute to cancer development, as these minute particles may interact with biological systems in complex and currently unpredictable ways (Esterhuizen &Kim, 2022).

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Immune System Impacts

Recent investigations have demonstrated that environmental pollutants, including heavy metals and industrial process byproducts, can impair immune system function, potentially predisposing exposed individuals to autoimmune conditions (Zoeller *et al*., 2022). These substances can attenuate immune responses, increasing susceptibility to infectious diseases and severe allergic reactions. Pollutants alter immunological tolerance, modify immune cell function, and disrupt gut microbiome homeostasis, which plays a central role in maintaining immune balance (Al-Amin *et al*., 2020). For example, trichloroethylene has been shown to compromise gut barrier integrity, while cadmium exposure is associated with inflammatory pathologies. These compounds also modify epigenetic regulatory mechanisms implicated in autoimmune disease pathogenesis (Kumar *et al.,* 2021). The strength of this evidence calls for accelerated research and more stringent regulatory standards to reduce environmental exposures and protect immunological health (Osuoha *et al*., 2023).

Cardiovascular Implications

The cardiovascular consequences of EC exposure represent an area of particular concern, with documented associations between these contaminants and the development and progression of cardiovascular pathologies, including hypertension, atherosclerosis, and myocardial infarction (Ortúzar *et al*., 2024). The mechanisms through which these compounds exert harmful cardiovascular effects are diverse, ranging from direct interference with intracellular signaling pathways to induction of oxidative stress and systemic inflammation (Ortúzar *et al.,* 2024). The metabolic consequences of EC exposure are equally alarming, with studies demonstrating their capacity to disrupt endocrine function, impair glucose homeostasis, and contribute to metabolic syndrome, including obesity, type 2 diabetes mellitus, and non-alcoholic fatty liver disease (Streit *et al*., 2021). Recent investigations have linked PFAS exposure specifically to cardiovascular and metabolic disturbances, including hyperlipidemia, diabetes, hypertension, and elevated serum cholesterol, mediated through oxidative stress pathways and modifications to lipid metabolism (Dimitrakopoulou *et al*., 2024). These metabolic perturbations elevate long-term risks of cardiac disease, cerebrovascular events, and type - 2 diabetes (Heberer *et al*., 2002). PFAS compounds may additionally promote systemic inflammation and metabolic dysfunction that collectively amplify cardiovascular disease risk. Expanded research is required to fully characterize these effects and provide evidence for effective public health interventions (Evich *et al*., 2022).

Respiratory Effects

Industrial pollutants, especially fine particles, are a major threat to lung health, causing asthma and Chronic Obstructive Pulmonary Disease (COPD), a progressive respiratory condition characterized by persistent airflow limitation due to airway and/or alveolar abnormalities, typically caused by significant exposure to noxious particles or gases. It encompasses emphysema (damage to air sacs) and chronic bronchitis (inflammation of the bronchial tubes), leading to symptoms like shortness of breath (especially during activity), chronic cough with mucus (phlegm), wheezing, frequent chest infections, and fatigue that worsens over time (Kolpin *et al.,* 2012). The EPA warns that these particles can cause severe asthma attacks and hospital visits (US EPA, 2025). Studies show that long-term exposure to these pollutants increases asthma risk in kids and worsens COPD in adults, with year-round

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exposure heightening asthma rates in children and exacerbating COPD symptoms in adults (Gomez-Regalado *et al.,* 2023**).**

Ecological Impacts of Emerging Contaminants

ECs pose substantial threats to wildlife populations, ecosystem function, and biological diversity. The ecological consequences of EC exposure represent a recognized global environmental concern.

Impacts on Wildlife

Progress in environmental analytical methodology has enabled the identification of a widening suite of CECs encompassing polybrominated diphenyl ethers (PBDEs) and PFAS in Arctic environments thousands of kilometers from their emission sources, demonstrating the capacity of atmospheric and oceanic transport mechanisms to redistribute these substances on a hemispheric scale (Al-Amin et al., 2020). Field investigations have documented substantial adverse impacts of ECs, including diclofenac, ivermectin, DDT, mercury, lead, arsenic, bisphenol A, phthalates, oxybenzone, and 17α-ethinyloestradiol on wildlife populations, manifesting as acute poisoning events, chronic sublethal impairment, population-level effects mediated through prey species losses, and indirect ecological disruption (Kolpin et al., 2012). Scientific documentation of the harmful consequences of EDC-containing contaminants from pharmaceutical and personal care product sources on the reproductive health, developmental progression, and physiological condition of marine organisms has intensified concern over these pollution streams (Heberer et al., 2002). The catastrophic collapse of vulture populations across South Asia, attributable to diclofenac exposure through the carcasses of treated livestock, represents one of the most instructive examples of the ecosystem-scale consequences that can result from inadequately managed EC contamination (Osuoha et al., 2023). Developing and scaling effective EC removal technologies is therefore indispensable for the long-term protection of wildlife populations and the preservation of biodiversity-dependent ecosystem services (Ortizar et al., 2024).

Effects on Ecosystems

Agricultural runoff laden with excess nutrients and chemical pollutants disrupts ecosystem nutrient cycling, leading to eutrophication processes that accelerate the ecological aging of freshwater and coastal systems (Gómez-Regalado et al., 2023). This acceleration promotes excessive algal proliferation and dissolved oxygen depletion, with cascading adverse effects on aquatic biodiversity (Evich et al., 2022). Additionally, emerging threats from microplastic contamination further degrade habitat quality, impacting both the physical environment and the organisms dependent upon it (Gaines et al., 2023). Microplastics present ingestion hazards to wildlife and disrupt habitats, with emerging evidence suggesting they may alter soil nutrient dynamics through effects on leaching processes (Al-Amin et al., 2020). These findings highlight the complex interactions between diverse pollutant classes and fundamental ecosystem processes, underscoring the urgency of targeted mitigation efforts (Heberer et al., 2002).

The accelerating prevalence of microplastic contamination constitutes an additional and increasingly documented stressor on habitat quality, affecting both the physical characteristics of environments and the health and behavior of organisms dependent on them (Gaines *et al.*, 2023). Studies indicate that microplastic particles create ingestion hazards for

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diverse wildlife species and may modify soil nutrient dynamics by altering leaching processes, adding a physicochemical dimension to their ecological impacts beyond direct biological harm (Al-Amin *et al*., 2020). Taken together, these observations underscore the intricate and multi-pathway nature of pollutant interactions with fundamental ecosystem processes, making the development of effective mitigation interventions a matter of considerable urgency (Heberer *et al*., 2002).

Biodiversity Loss

The introduction of toxic pollutants into ecosystems produces measurable reductions in species diversity, with particularly severe consequences for sensitive species that cannot sustain normal survival and reproduction under contaminated conditions (Chakraborty *et al.,* 2023). Prolonged EC exposure can induce genomic alterations that diminish genetic diversity and reduce population resilience to environmental stressors (Gałęziewska *et al*., 2025). These pollutants modify gene expression patterns in aquatic species through direct water exposure and indirectly through food chain transfer, generating widespread ecological and molecular disruption (Diepens & Koelmans, 2018). This includes systemic multi-organ toxicity in aquatic plants and biofilm communities, illustrating the extensive ecological consequences of environmental pollutant loading (Cverenkárová *et al*., 2021).

Regulatory Measures and Policies

Escalating global chemical production across an expanding range of applications demands a rigorous hazard assessment and management frameworks to adequately protect public health and environmental quality (Wang *et al*., 2025). Regulatory measures and policies play a central role in governing the production, use, and disposal of chemical substances to minimize These regulatory frameworks aim to balance industrial innovation with the imperative to protect environmental quality and the health of organisms across all biological scales (Li *et al*., 2024). A cornerstone of chemicals governance is national-level regulation, including the European REACH framework and assessment systems operated by the US EPA and China's Ministry of Ecology and Environment, which require chemical manufacturers to conduct comprehensive safety evaluations prior to market introduction (Zandaryaa *et al*., 2025). However, the effectiveness and equity of regulatory efforts depend critically on robust implementation and enforcement mechanisms (Alam *et al.,* 2025). Internationally, corresponding governance frameworks within which expert scientific bodies assess chemical data on hazard profiles, exposure levels, bioaccumulation potential, and toxicity include the Basel Convention on hazardous wastes, the Rotterdam Convention on hazardous substance information exchange, the Stockholm Convention on POPs, and the Minamata Convention on mercury (EPA, 2025). potential harms (European Chemicals Agency, 2025). The Globally Harmonized System of Classification and Labelling of Chemicals represent a significant UN-level initiative to standardize global chemical management and risk communication (UNEP, 2023). The OECD and its member states have developed internationally recognized tools for chemical testing, evaluation, and management (Helwig *et al.*, 2018).

Outside the OECD, the Inter-Organization Programme for the Sound Management of Chemicals provides targeted support to emerging economies and developing nations where rapidly expanding chemical industries and consumer markets increasingly require chemical governance infrastructure and capacity (Garduño-Jiménez *et al.*, 2025). The Sustainable Development Goals, adopted by the UN General Assembly in 2015, include provisions

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addressing sound chemical and waste management throughout their entire life cycles and reducing chemical releases into air, water, and land environments (UNEP, 2023). Achieving the stated goal of preventing significant adverse effects of chemical pollution on human health and ecosystems will require substantially expanded commitment, as documented in UNEP's Global Chemicals Outlook II (Wang *et al*., 2025). The documented contributions of chemical pollution to global biodiversity loss (Alam *et al*., 2025), human disease burden (European Chemicals Agency, 2025), soil and water quality degradation (Zandaryaa *et al.,* 2025), stratospheric ozone depletion (Helwig *et al*., 2018), and climate change (EPA, 2025) underscore the urgency of this governance challenge.Regulatory decision-makers must weigh economic, social, and environmental considerations when designing sound chemical management measures (National Law Review, 2025). Where scientific evidence demonstrates environmental harm from EDC exposure, PFAS contamination, and other chemical threats, regulators may impose restrictions, bans, or emission limits (Wang *et al*., 2025). These measures are grounded in scientific evidence and designed to protect vulnerable populations and sensitive ecosystems (Li *et al*., 2024). The precautionary principle represents an important complementary strategy requiring preventive action under conditions of scientific uncertainty about potential harms; when evidence is inconclusive, regulators should adopt cautious approaches pending clarification of risk (UNEP, 2023; Alam *et al*., 2025). The 2030 Agenda for Sustainable Development, adopted by the United Nations General Assembly, explicitly addresses the necessity for sound chemicals and waste management across entire life cycles and the reduction of chemical releases to environmental media (UNEP, 2023).However, substantive gaps remain between current trajectories and the stated objective of preventing significant adverse effects of chemical pollution on human health and the environment, as comprehensively documented in UNEP's Global Chemicals Outlook II (Wang et al., 2025). Scientific evidence firmly establishes that chemical contamination drives global biodiversity erosion (Alam *et al*., 2025), contributes to the burden of non-communicable and infectious diseases (European Chemicals Agency, 2025), accelerates soil and water quality degradation (Zandaryaa *et al*., 2025), depletes stratospheric ozone (Helwig *et al*., 2018), and amplifies climate change impacts (EPA, 2025).

Regulatory decision-making in the chemicals domain requires careful balancing of economic development interests, social equity considerations, and environmental protection imperatives (National Law Review, 2025). Where scientific evidence substantiates environmental harm attributable to EDCs, PFAS, or other chemical hazard categories, regulatory authorities retain the mandate to impose use restrictions, market prohibitions, or emissions limits on implicated substances (Wang *et al*., 2025). Such interventions are grounded in systematic risk assessment and calibrated to safeguard vulnerable human populations and sensitive ecosystems (Li *et al*., 2024). The precautionary principle provides an important supplementary decision-making framework, requiring protective regulatory action under conditions of unresolved scientific uncertainty, and directing authorities to adopt conservative risk management positions pending clarification from ongoing research (UNEP, 2023; Alam *et al.*, 2025).

One of the 17 Sustainable Development Goals (SDGs), launched by the UN General Assembly in 2015, addresses the sound management of chemicals and all wastes throughout their life cycles and decreasing their release into air, water, and land (UNEP, 2023). However, more effort is needed to achieve the goal of preventing significant adverse effects of chemical pollution on human health and the environment, as stated in the United Nations

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Environment Programme's Global Chemicals Outlook II (Wang *et al.,* 2025). It is well documented that chemical pollution causes a wide range of damages to human and ecosystem health at local, regional, and global scales (Li *et al.,* 2024). Among other factors, pollution is responsible for global biodiversity loss (Alam *et al.,* 2025), human diseases (European Chemicals Agency, 2025), soil and water degradation (Zandaryaa *et al.,* 2025), stratospheric ozone depletion (Helwig *et al.,* 2018), and climate change (EPA, 2025).

Policymakers need to balance economic, social, and environmental arguments when deciding on measures for the sound management of chemicals (National Law Review, 2025). Where there is evidence of environmental impact and harm from exposure to, e.g., endocrine-disrupting chemicals, PFAS, and many other chemicals, regulators may impose restrictions, bans, or set limits on emissions and discharges into the environment (Wang *et al.,* 2025). These measures are often based on scientific evidence and aim to protect vulnerable populations and ecosystems (Li, 2024). Here, the precautionary principle is an important strategy that requires taking preventive action in the face of uncertainty about potential harm (UNEP 2023). Where scientific evidence is inconclusive, regulators should opt for a cautious approach and impose restrictions until further research clarifies potential risks (Alam *et al.,* 2025).

Efforts to improve the handling of chemicals go beyond their production and application stages to include properly disposing of waste and recycling products containing dangerous substances (Garduño-Jiménez *et al.,* 2025). While progress has been made in many areas, there is an urgent need for a more consistent alignment of all actors on this common goal of chemical safety (European Chemicals Agency, 2025). International cooperation is therefore essential to address the global nature of pollution by chemicals and waste (EPA, 2025). Recently, scientists asked for the establishment of an overarching international body to facilitate and foster broad bidirectional science-policy interactions on chemicals and waste (Helwig *et al.,* 2018). Such a science-policy panel (SPP) must address chemical pollution's multifaceted and heterogeneous impacts that often show dynamic development (Li *et al.*, 2024). The scope of this new SPP goes beyond the remit of the above-mentioned existing bodies because their scopes and mandates are limited to certain chemicals, geographical areas, or jurisdictions (UNEP, 2023). Rather, the SPP needs to work on the large array of "chemicals of emerging concern" and novel waste streams, besides the well-described legacy pollutants, trying to avoid "analysis paralysis" (the inability of decision making by over analysis or overthinking) (Wang *et al.* 2025). The SPP must establish and enforce a strict conflict-of-interest policy (Alam *et al.*, 2025). In particular, experts with a conflict of interest connected to a financial or material gain would pose a high risk of conflicting and/or incompatible outcomes or delayed implementation of solutions in the decision-making process and should not be allowed to participate in the core work of the SPP, but they may still participate and contribute as observers (European Chemicals Agency, 2025). Independent audits should be established to verify compliance with conflict-of-interest provisions to recommend corrective action if necessary and ensure that the outputs of SPPs are transparent, impartial, credible, and scientifically robust (Zandaryaa *et al.,* 2025).

The new SPP, currently prepared by the United Nations Environment Programme (UNEP) Open-ended Working Group, is expected to strengthen these efforts by recognizing the interconnectedness of global chemical trade and pollution (UNEP, 2023). Through regulatory measures, society can harness the benefits of chemicals while minimizing the adverse effects of hazardous chemicals (Li *et al*., 2024).

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Research Needs and Gaps in Knowledge

The growing concern over emerging contaminants highlights the critical need to identify knowledge gaps and prioritize research areas. Holistic risk assessments that consider not only individual contaminants but also their synergistic and antagonistic effects are essential for understanding cumulative risks. Significant gaps remain in understanding how emerging contaminants interact with different environmental matrices, necessitating further investigation into their environmental fate and transport mechanisms (Tan *et al.,* 2025). While some short-term effects are reported, comprehensive long-term studies are notably scarce, limiting insights into chronic impacts (Zandaryaa *et al.,* 2025). Most research and data originate from developed countries, underscoring an urgent need for studies focused on low-income and developing nations, where risks may be higher but remain understudied (Garduño-Jiménez, 2025). Addressing these gaps requires localized field studies that account for unique ecological and geographical conditions, especially in developing regions (Tan *et al.,* 2025). International collaborations and funding initiatives are keys to supporting extended research projects on long-term environmental and health impacts. Building local research capacity through grants and training on advanced analytical techniques enhances data collection and interpretation in underrepresented areas (Garduño-Jiménez, 2025). A multidisciplinary approach incorporating scientists and local stakeholders can better capture socio-economic and cultural dimensions of contamination, improving understanding and solutions (Qadeer *et al.,* 2025). Policy-relevant research aimed at developing affordable and practical contaminant management methods should be encouraged to guide effective regulation, particularly in resource-limited countries (Tan *et al.,* 2025).

Importance of Public Awareness and Education

Public awareness and education are essential for combating emerging contaminants, enabling early intervention to prevent health risks and encouraging proactive behaviors like selecting eco-friendly products and sustainable practices (Benameur *et al.,* 2025; Disner, 2025). Nairobi's "Green Neighborhoods" project trained residents to report industrial discharges, enhancing regulatory enforcement (Disner, 2025) and the EU's "Eco-Label" scheme drove industry shifts toward sustainable practices amid rising public preference for certified products. Additional global efforts, such as WWF's "Your Plastic Diet" campaign highlighting microplastics in food chains and Surfers Against Sewage's UK roadshows on water pollution, demonstrate how awareness amplifies advocacy for systemic change (WWF, 2024; SAS, 2024). By bridging knowledge gaps, these initiatives foster collective action, accelerate policy reforms, and support comprehensive environmental protection against emerging threats (Li *et al.,* 2024; White House OSTP, 2024).

Nigeria implements several public awareness programs targeting emerging pollutants, primarily plastics, air pollution, and waste as proxies for broader contaminants. These efforts, driven by NGOs, government, and partners, focus on education, clean-ups, and behavior change (Egbuna *et al.,* 2021).

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