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Emerging Contaminants (PFAS, Microplastics, Pharmaceuticals): Detection, Fate, and Remediation Strategies – A Review

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Abstract- Emerging contaminants like per- and polyfluoroalkyl (PFAS), microplastics, and pharmaceuticals are increasingly considered threats to environmental and human health because of their persistence, bioaccumulation tendency, and complex ecosystem interactions. This review consolidates current understanding of their sources, ecological behaviour, detection methods, and remediation strategies. It highlights the critical need for comprehensive approaches, advanced monitoring technologies, and policy measures to reduce their adverse effects.

Keywords: Detection, Emerging Contaminants, Environmental Fate, Microplastics, PFAS, Pharmaceuticals, Remediation

I. INTRODUCTION

"Emerging contaminants" refer to synthetic and natural chemicals that are typically not monitored but can enter the environment, potentially harming ecological and human health. PFAS, microplastics, and pharmaceuticals are particularly alarming because of their extensive use and durability. These substances often evade standard wastewater treatments and build up in ecosystems, creating long-term risks (Singh et al., 2024). This review aims to comprehensively analyse their origins, environmental behaviour, detection methods, and removal strategies.

II. SOURCES AND ENVIRONMENTAL FATE

2.1 PFAS

PFAS are a large family of synthetic organofluorine chemicals used since the mid-20th century for their water, oil, and heat-resistant properties. Applications include firefighting foams, industrial surfactants, nonstick coatings, textiles, and various consumer products (Wee, 2023). Manufactured, industrially used, and even legacy consumer products cause PFAS air, soil, and water contamination. This makes point sources – manufacturing sites, military bases (firefighting foam), and chemical plants – related to high PFAS local concentrations. Weathered treated products, landfills, and biosolid applications are diffuse sources of low-level contamination (EPA, 2024). The diversity of PFAS in chain length and functional groups is significant. Long-chain PFAS will sorb and bioaccumulate in soils, while short-chain PFAS will remain mobile in water and air and cause long-range transport. This is particularly the case for PFAS persistence in drinking water sources (Ahrens & others summarised in Wee, 2023). Processes that dictate the environmental fate of PFAS include transport (advection, atmospheric deposition), limited recalcitrant biodegradation, and water to solids partitioning, with transformation to persistent products in some cases. For instance, precursor degradation to PFOA/PFOS. Conventional PFAS treatment and remediation methods are limited and counterproductive. Advanced oxidation, adsorption (granular activated carbon, ion exchange), and combined methods are promising but are also constrained by trade-offs. Conventional methods are limited in recalcitrance, persistent biodegradation, and the transformation of unknown toxicity.

2.2 Sources and Environmental Fate of Microplastics

There are two primary sources of microplastics (particles <5 mm). First, primary microplastics are manufactured for certain products (e.g., microbeads, pre-production pellets). Second, secondary microplastics are created from the breakdown of larger plastic products through mechanical abrasion, UV light, and biological action (Osman et al., 2023). Some of the most significant sources include urban runoff, wastewater effluent (from laundering clothes), tyre and road wear, agricultural plastic (mulch films), and improper waste management containing macroplastics allowed to degrade in the environment (Thompson et al., 2024). After being released, microplastics travel through the air and are transported by water and sediment, settling in soils and water bodies (rivers, lakes, oceans). Their small size means various organisms can ingest them and act as a vehicle for contaminated particles (persistent organic pollutants, metals) and microbes. Environmental microplastic distribution depends on polymer shape, density, and biofouling degree. Low-density microplastics are transported on the water's surface and over great distances, while the denser microplastics settle in sediments and become trapped for decades. Fragmentation to nanoplastics occurs in situ and increases the microplastic reactivity and bioavailability. Recent monitoring activities show that microplastics are ubiquitous. Their presence from remote soils to agricultural fields and ocean gyres showcases the versatility and systemic nature of the source-to-sink problem.

2.3 Sources and Environmental Fate of Pharmaceuticals

Pharmaceutical active compounds (PhACs) enter the environment primarily through human and veterinary excretion, improper disposal (flushing unused drugs), effluent from wastewater treatment plants (WWTPs), and agricultural runoff where veterinary medicines are applied (Nguyen, 2024). Hospitals, pharmaceutical manufacturing effluents, and intensive livestock operations are important point sources that can produce localised hotspots of elevated concentrations. Conventional WWTPs are not designed to eradicate many PhACs; removal efficiencies vary widely by compound and treatment technology, leaving residues in treated effluent and in sewage sludge (which may be applied to soils), thus enabling recurring environmental inputs (Paíga et al., 2025). In aquatic systems, pharmaceuticals undergo dilution, sorption, phototransformation, hydrolysis, and biodegradation; however, many compounds or their metabolites are persistent enough to produce chronic, sublethal effects on non-target organisms (endocrine disruption, behavioural changes). The environmental fate of pharmaceuticals is compound-specific: polar, persistent molecules remain mobile in water, while hydrophobic compounds sorb to sediments and bioaccumulate. Growing evidence links chronic low-dose exposures to ecological impacts and selective pressure for antimicrobial resistance, driving research into advanced treatment (ozonation, activated carbon, advanced membranes) and source control strategies.

III. DETECTION TECHNOLOGIES

3.1 Analytical Methods

Recent advancements include using aptamers—DNA or RNA sequences that bind specifically to contaminants—making detection and quantification more precise. Often seen as the chemical equivalents of antibodies, aptamers improve targeted analysis. Non-target analysis and suspect screening with high-resolution (HR) mass spectrometry (MS) are also progressing. This technique measures exact masses to four or five decimal places for molecular and fragment ions, usually providing specific molecular formulas and helping identify unknown compounds (Richardson & Manasfi, 2024).

Ion mobility spectrometry-mass spectrometry (IMS-MS) is a growing technique in analytical science that is increasingly being applied in environmental research. Often, ion mobility complements liquid chromatography (LC) by adding a separation step based on ion cross-section, which helps identify unknown compounds, especially isomers, in complex environmental samples. For instance, linear per- and polyfluoroalkyl substances (PFAS) can be distinguished from their branched isomers, aiding their detection and identification. Folkerson et al. (2023) reported that PFAS analysis was conducted using online high-resolution Chemical Ionisation Mass Spectrometry (CIMS) with an iodide reagent ion and offline UPLC-MS/MS.

Per- and polyfluoroalkyl substances (PFAS) used in various industrial applications are pollutants of concern for the environment and human health. Drinking water consumption is one key exposure pathway to PFAS, as recently highlighted by multiple studies on their occurrence in tap water.
Bottled water is available worldwide. However, measuring PFAS at very low concentrations—such as parts-per-trillion (ng/L) or parts-per-quadrillion (pg/L)—remains challenging. (Itumoh et al, 2024).

Quantifying PFAS at expected levels of part-per-quadrillion (pg/L) and part-per-trillion (ng/L) in drinking water demands extensive sample pre-concentration. Proper sample preparation and analytical conditions are crucial for ensuring precision, accuracy, and low detection limits (LOD). Techniques to analyse PFAS in drinking water typically use liquid chromatography combined with mass spectrometry (LC-MS), often tandem MS (LC-MS/MS), as outlined in EPA methods.

Less common techniques include ion mobility spectrometry (IMS), laser-based methods, and other alternative approaches. IMS is a new separation method that differentiates ions in instruments based on their charge, shape, and size in the gas phase. A direct link exists between the ion's drift time through the gas and its size, which is typically described as the collision cross-section (CCS). (Li et al., 2022.)
Laser diode thermal desorption atmospheric pressure chemical ionisation (LDTD/APCI) and Orbitrap mass spectrometry were evaluated for 15 PFAS in different water matrices.

No chromatographic separation was needed for tap and surface waters, reducing analysis time to under 20 seconds. However, off-line SPE continued to be necessary for sample pre-concentration. (Kirkwood-Donelson, et al, 2023)

Mass spectrometry imaging (MSI) is an emerging technique for detecting contaminants. It has been recently used to visualise the spatial distribution of pharmaceuticals within organisms, improving our understanding of their fate and interactions. (Wang, et al, 2024)
Chromatography Trends. LC, ultraperformance LC (UPLC), GC, and GCxGC are widespread and typically coupled to MS or MS/MS. Applications using supercritical fluid chromatography (SFC), while still somewhat limited, continue to grow. SFC allows the separation of highly polar compounds that often cannot be separated using LC (including hydrophilic interaction liquid chromatography [HILIC]). An example includes the identification of new halosulfonic acid DBPs in drinking water using SFC-MS. (Shen et al., 2024).

3.2 Sensor-Based Technologies

Sensor-Based Technologies
Traditional methods for detecting ECs and pathogens in wastewater, such as chromatography and culture-based techniques, are often time-consuming, labour-intensive, and require sophisticated laboratory equipment. For this reason, there has been a growing interest in applying biosensors to quantify these environmental contaminants (Guliy et al, 2022).

Biosensors are sophisticated analytical devices integrating a biological recognition element with a physicochemical transducer to detect a specific analyte. The biological recognition component, called bioreceptors, may include entities like enzymes and aptamers. (Fdez-Sanromán et al, 2025).
Recent advancements in biosensor technology have led to the development of more innovative and practical solutions for organophosphate detection (Phetduang et al, 2025). For the detection of herbicides such as triazines and phenylureas, which disrupt the photosynthetic process, biosensors have been developed that incorporate chloroplast or thylakoid membrane receptors, as well as unicellular algae (Kasuno et al, 2023). These biological components enable direct interaction with herbicides, facilitating sensitive detection (Koblížek et al, 2002).

Unlike the traditional analytical methods mentioned above, biosensors offer several advantages, including the following:

Rapid detection: Biosensors measure almost instantaneously, making them suitable for large–scale monitoring and quick decision-making. (Chen et al., 2024).

High sensitivity and specificity: the bioreceptors ensure high precision and enhanced sensitivity in detecting target analytes, e.g. aptamer-based biosensors have been proven efficient in identifying pharmaceuticals and heavy metal contaminants. (Materon et al, 2020).

On-site monitoring: Biosensors allow on-site monitoring, eliminating sample transportation and allowing in-situ contaminant detection. (Polat et al., 2022).

Following the benefits of biosensors, it has become a powerful tool for monitoring the presence of contaminants in wastewater, contributing substantially to improved human health and the environment (Pal et al, 2025).

Biosensors integrate a biological recognition element with a transducer that converts the resulting physicochemical reaction into a measurable signal. These devices usually comprise a bioreceptor, a transducer, and a signal processor as their main components (Vo et al, 2024).

IV. HEALTH AND ECOLOGICAL IMPACTS

4.1 PFAS Toxicity

PFAS compounds are highly persistent and bioaccumulate in food chains and human tissues (Khan et al., 2023). Chronic exposure to PFAS has been linked to endocrine and metabolic disruption. For example, studies report that PFAS exposure can alter thyroid and sex hormones, impair liver and kidney function, and suppress immune responses (Du et al., 2024). Epidemiological and experimental data also associate PFAS with increased risks of certain cancers (notably kidney, testicular, and prostate cancers) (Mišľanová & Valachovičová, 2025). Because long-chain PFAS accumulate in organisms over time, their impacts magnify with exposure: wildlife and humans at the top of food webs show the highest PFAS burdens and related health effects (Ecke et al., 2025).

4.2 Microplastics in the Food Chain

Aquatic organisms readily ingest microplastics, which can cause physical and chemical harm. Ingested microplastics may lodge in the gut and other tissues, blocking digestive tracts and irritating intestinal surfaces (Carbery et al., 2018; Ziani et al., 2023). Laboratory studies confirm that microplastics can cause inflammation and reduced feeding efficiency in zooplankton, bivalves, and fish (Ziani et al., 2023). In some cases, gut blockage by plastic fragments leads to “false satiation,” malnutrition and even death (Ziani et al., 2023).

- Physical injury: Microplastic fragments and fibres can abrade or block the digestive lining, causing stress, inflammation or reduced nutrient uptake (Ziani et al., 2023).
- Chemical transport: Microplastics sorb contaminants and additives (e.g. plasticisers, persistent organics). After ingestion, these chemicals can leach into tissues and disrupt biological systems – for example, by mimicking hormones or triggering oxidative stress (Ziani et al., 2023).
- Trophic transfer: Microplastics accumulate in prey species and can transfer up the food chain. Numerous studies have found microplastic particles in fish and shellfish. For example, a recent U.S. study detected microplastics in 99% of sampled fish and shrimp (Johnson, 2025). Microplastic fibres and beads can move from an animal’s gut into muscle tissue (Johnson, 2025). As predators consume contaminated prey, plastics (and associated toxins) biomagnify in predators’ bodies (Johnson, 2025; Ziani et al., 2023).
- Human exposure: Because seafood is contaminated, humans ingest microplastics through diet. The prevalence of plastics in seafood and drinking water raises concerns about chronic health effects (hormonal, immunological, or developmental) that are still under investigation (Johnson, 2025; Ziani et al., 2023).

Together, these effects mean that microplastics can harm aquatic organisms at multiple biological levels and carry pollutants into human food sources. Their ubiquity and persistence make microplastic pollution a growing ecological and potential health problem.

4.3 Pharmaceutical Residues

Pharmaceuticals (including prescription drugs, over-the-counter medications, and personal care products) are increasingly detected in aquatic environments (Ślósarczyk et al., 2021). These bioactive chemicals can disrupt an organism's physiology even at trace concentrations. For example, synthetic hormones from contraceptives (like 17α-ethinylestradiol) are potent endocrine disruptors: levels as low as 5–6 ng/L in water can feminise male fish and reduce fertility (Selwe et al., 2022). Many pharmaceuticals mimic or block natural hormones, leading to endocrine imbalance in exposed wildlife (Yuan et al., 2023).

- Endocrine disruption: In wastewater, steroid hormones and hormone-like drugs can bind to animal endocrine receptors. This hormonal interference (e.g. estrogenic or anti-androgenic effects) can cause reproductive anomalies (feminisation, reduced fertility), developmental abnormalities, and weakened immune defences (Yuan et al., 2023).
- Antibiotic resistance: Antibiotics released into water select for resistant microbes. Environmental antibiotic residues promote the proliferation of antimicrobial resistance genes (ARGs) in bacteria (Henderson et al., 2025). Resistant bacteria can spread to humans and wildlife, undermining medical treatments. Antibiotics can also kill or inhibit beneficial microbes in aquatic ecosystems, disrupting community structure.
- Microbial community effects: Pharmaceuticals alter microbial populations and ecosystem functions. For example, antibiotics in water can inhibit bacteria responsible for nitrogen cycling and organic matter decomposition (Eapen, 2024). Such disruptions can cascade, affecting the ecosystem's water quality and nutrient availability. Other drugs (e.g. antidepressants, antiseptics) can similarly shift microbial community composition and behaviour (Eapen, 2024).

Even at low concentrations, pharmaceutical pollutants can have outsized ecological impacts. By acting as hormone mimics or antibiotics, they disturb normal physiology in non-target aquatic species and promote resistance traits in microbes (Yuan et al., 2023). These effects compound in vulnerable ecosystems (e.g. shallow lakes, estuaries) where dilution is limited, making effective monitoring and mitigation essential.

V. REMEDIATION STRATEGIES

5.1. Adsorption & separation

Because PFAS are highly persistent, a common remediation strategy is capturing or concentrating the PFAS before destruction or disposal. For example, a recent review (Zang *et al.,* 2025) in *Environmental Science: Advances* indicates that adsorption is currently the most frequently used technology for PFAS removal from water. However, regeneration of sorbents and removal of short-chain PFAS remain challenging. Similarly, membrane separation (NF/RO) is used to reject PFAS from aqueous streams, as Lu et al. (2023) reviewed for landfill leachate applications.

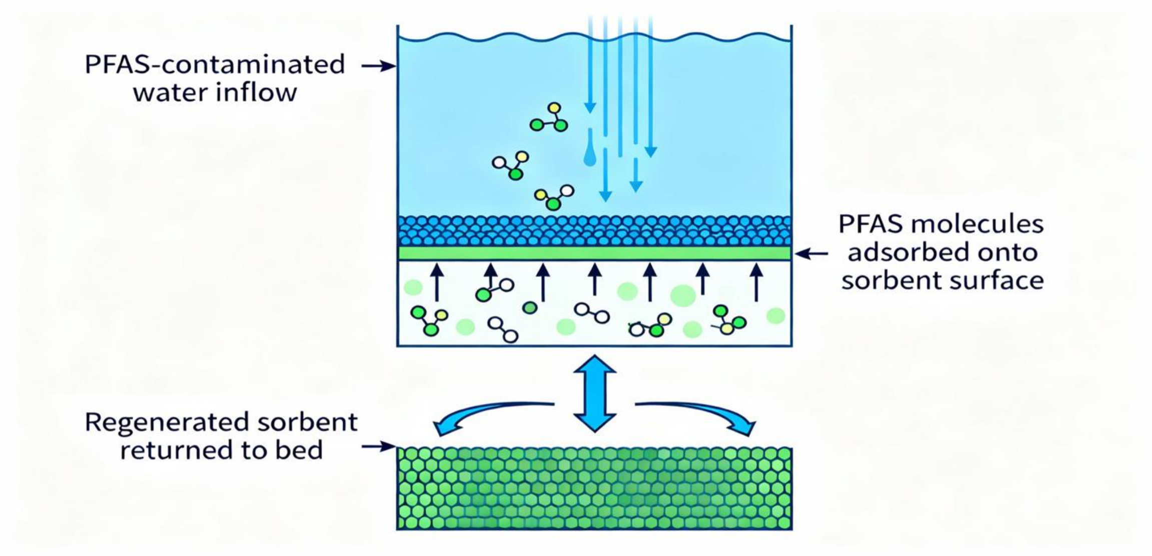

Figure 1: Adsorption of PFAS using regenerated sorbets

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5.2. Destruction/degradation

Since PFAS resist biodegradation, destruction methods follow capture. Meegoda *et al.* (2022) review outlines technologies including electrochemical oxidation, sonolysis, plasma treatment and high-temperature catalytic treatments for PFAS destruction. These methods can achieve very high removal efficiencies under laboratory conditions; for example, electrochemical oxidation in lab studies can reduce PFAS concentrations by 90-99.999% (CDM Smith insight), though full-scale implementation remains limited.

5.3. Soil / solid contamination remediation

For PFAS-contaminated soils, Napoli *et al*. (2025) review immobilisation, extraction/mobilisation and destructive technologies, emphasising sustainability and scalability of the chosen approach.

5.4. Hybrid trains & key considerations

The consensus of recent reviews (e.g., Zang *et al*., 2025) is that no single treatment alone suffices; instead, treatment trains combining capture (adsorption/separation) and destruction (electrochemical/thermal) are most promising. Key issues to manage include the PFAS-laden residuals (spent sorbent or concentrate), energy demands of destructive processes, and verifying transformation products and complete defluorination.

5.5. Microplastics (MPs)

5.5.1. Physical Treatment

For microplastics, the first line of remediation is physical separation: coagulation, flocculation, sedimentation, sand filtration, and membrane filtration in wastewater treatment plants. For example, one review reports that WWTPs with primary + secondary treatment achieve about 88 % removal of MPs on average; with tertiary treatment up to ~94 % (Iyare *et al.,* 2020). Membrane filtration is one of the most promising methods for small plastics (micro/nano). A review reports micro- and nanoplastics removal by membrane filtration (Bodzek & Bodzek, 2025).

5.5.2. Adsorption / Advanced Remediation

Adsorption-based approaches for microplastics are also explored. Ho *et al. (2025) focused on adsorption-based removal of microplastics and nanoplastics, describing mechanisms (electrostatic, hydrogen bonding, hydrophobic) and reporting that* carbon-based and metal-based adsorbents dominate research. In addition, Rim *et al.* (2025) review on Electrochemical Advanced Oxidation Processes (EAOPs) for microplastics was identified (though still emerging).

5.5.3. Hybrid/Nano-Material Approaches

Emerging work explores functionalized membranes and nanofiber filters (e.g., PVDF nanofibers modified with biosurfactants and metal oxides) for greater MP removal. While still lab-scale, these show high permeabilities and removal rates (De Rosset *et al.,* 2025).

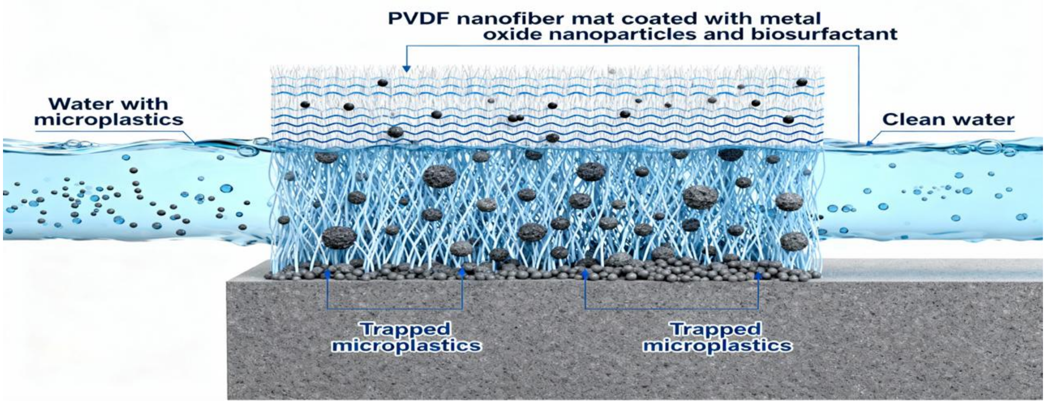

Figure 2: Microplastics removal with PVDF nano fibers modified with metal oxides and bio surfactants.

5.6. Pharmaceuticals

5.6.1. Adsorption Technologies

Adsorption remains a widely applied strategy for removing pharmaceuticals (PPCPs) in water and wastewater. Zumra & Ahmed (2025) report adsorption removal efficiencies for pharmaceuticals using carbon-based materials (28–99.7 %), zeolites (37–100 %), MOFs (~86–99.3 %) and polymers (~70–98.2 %). Modified zeolites in particular have

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been highlighted for combined adsorption and catalytic oxidation roles (Serna-Galvis *et al.,* 2024).

5.6.2. Advanced Oxidation Processes (AOPs) & Hybrid Systems

Various AOPs (ozonation, Fenton/photo-Fenton, UV/H_2O_2, electrochemical oxidation) are employed for complex pharmaceuticals or where high removal is required. Kanakaraju *et al. (2025) detail* the progress in AOPs for pharmaceuticals, noting their potential and limitations such as by-product formation, high energy demands and the challenge of neutral pH operation. Hybrid systems combining adsorption + AOP (or AOP + biological treatment) are increasingly recommended to improve removal and reduce harmful transformation products. For example, adsorption followed by AOP was identified as a promising route (Mansouri *et al.,* 2021).

5.6.3. Biological Treatment

Although insufficient for pharmaceuticals, supplementary biological treatment (e.g., algae-based reactors, biofilms) or combined systems can help polish effluent after adsorption/AOP. For example, microalgae ponds achieved moderate (40-60 %) removal for many pharmaceuticals by Garcia-Galan *et al*. (2020).

VI. POLICY AND GOVERNANCE

6.1 Regulatory Frameworks

The worldwide management of emerging contaminants faces inconsistent regulations because PFAS and other specific chemical groups receive fast regulatory progress, but microplastics and numerous pharmaceutical residues remain without adequate oversight. The United States government has strengthened its efforts to regulate PFAS substances at the federal level. The EPA has established the PFAS Strategic Roadmap, which led to the development of enforceable regulations through the National Primary Drinking Water Regulation (NPDWR) for particular PFAS compounds. The new regulations demonstrate a transition from research-based assessment to legally binding standards (U.S. Environmental Protection Agency 2024a; U.S. Federal Register 2024). The measures deliver immediate health protection while generating increased requirements for monitoring systems, laboratory facilities, and remediation technology development (Office of Science and Technology Policy 2023).

The European Union has established its own regulatory framework for PFAS through EU regulations and guidance documents, which now treat PFAS as a group of concern while moving toward restrictions that cover production and usage stages. The EU has established pioneering environmental risk assessment procedures for medicinal products through its guidance documents, representing a pharmaceutical environmental risk management breakthrough during regulatory decision-making. (European Commission 2025). The EU projects are outstanding examples demonstrating how to establish cross-sectoral rules that link product clearance to environmental impact assessments throughout product life cycles.

The regulatory framework for microplastics and pharmaceutical residues lacks standardised endpoints that match PFASs. National plastic pollution prevention strategies that reduce macroplastic inputs and control primary microplastics represent important progress, but they do not establish specific concentration limits for microplastics in water bodies. (U.S. Environmental Protection Agency 2024b). The governance of pharmaceuticals exists in disarray because environmental risk evaluations occur during marketing permission processes, but enforcement and monitoring programs for pharmaceutical residues remain insufficient in numerous countries. (European Commission 2025).

The different levels of regulatory action between PFAS and microplastics and pharmaceuticals reveal three essential policy requirements: (1) Standardized analytical methods and detection thresholds must be established to enable monitoring consistency between different geographic areas and (2) Timelines for regulation need to match available laboratory and treatment capabilities and (3) Policy frameworks should implement lifecycle reduction strategies through eco-design and take-back programs in addition to traditional end-of-pipe solutions. (U.S. Federal Register 2024; U.S. Environmental Protection Agency 2024a).

6.2 Public Engagement

The successful management of emerging contaminants depends heavily on public understanding and active involvement. Educational programs, stakeholder meetings, and prominent take-back programs have successfully changed public behaviour by reducing improper pharmaceutical disposal and boosting support for source-reduction initiatives.

The public can be influenced through long-term behavioural changes through visible pollution campaigns about plastic waste. However, microplastics' invisible nature and chemical pollutants make communication more challenging.

Public engagement programs succeed when they deliver specific guidance alongside straightforward monitoring data and enable community members to participate in decision-making. Combining medication take-back programs with public awareness initiatives leads to decreased pharmaceutical waste entering sewage systems and reduced wastewater contamination from pharmaceuticals. The public's demand for PFAS has led to accelerated regulatory actions and expanded funding for cleanup operations and monitoring systems. The success of public involvement depends on three essential elements, which include (a) offering basic behavioural options, (b) uniting public awareness with physical infrastructure, such as collection sites and waste management facilities, and (c) clearly showing community-based monitoring data.

The process of engagement should not be treated as an optional step. Including affected groups, including industry representatives, citizens, and municipal bodies, at the beginning of policy discussions leads to valid and workable solutions. The delivery of public information materials should focus on showing people how to minimise risks and present available legislative options to gain their compliance support. Public education programs achieve their best results following regulatory objectives such as new drinking-water standards. This helps communities grasp the necessity for change and the methods through which it will be implemented. Developing policy-relevant science requires standardised detection protocols, toxicological assessments of mixed substances, and proven restoration effectiveness benchmarks. The OSTP, EPA, and other large-scale government reports identify these research needs while promoting funding for method creation and laboratory testing that generates reliable data for regulatory purposes. (US Environmental Protection Agency, 2024b; CalSPEC/(UC Davis, 2023).

6.3 Research and Collaboration

Multidisciplinary research and sustained international collaboration are necessary to address emerging pollutants' governance and policy issues. Science necessary for policy must support the standardisation of detection methods, comparative toxicology of complex combinations, and proven standards of restoration performance. These research priorities are underscored in extensive government reports (e.g., OSTP, EPA) and calls for investment in method development and inter-laboratory studies to yield reproducible, regulatory-grade data (Office of Science and Technology Policy, 2023; U.S. Environmental Protection Agency, 2024a).

International collaboration can help develop in several respects. The former involve common monitoring databases and standardised protocols to avoid duplication and enable comparisons across jurisdictions; the latter have the contribution of structured financing and collaboration networks leading to multi-site studies that encapsulate environmental variability and socioeconomic contexts; and the third are collaborative efforts that help standard-setting by using a wide range of technical skills. Helpful procedures to address this challenge are, among others, those multisectoral monitoring teams, policy-science interfaces of the sponsored variety of UNEP, and regional legislative harmonisation attempts through common analytical standards (Li et al., 2024; ResearchGate review, 2022). However, if research is getting done, the work must be deeply interwoven with policy translation. Scientists must focus on low-cost, already established monitoring tools and strong decision-support systems that policymakers can consider when weighing the trade-offs between mitigation strategies. When appropriate, co-developing research, in which regulators, the public and scientists work collaboratively to create agendas to protect the public interest, can help produce findings that are as impactful and socially palatable as possible. Such translational research will be a necessary complement to regulatory development. It will also end some of the most salient feedback loops that can underpin the intersection of evidence generation and governance. (U.S. Environmental Protection Agency, 2024a; European Commission, 2025). The comparison of policy and governance can be seen in Figure 1 below.

Figure 1: Comparison of Policy and Governance on Emerging Contaminants (PFAS, Microplastics, Pharmaceuticals)

Policy Area	United States	European Union	Africa	Global Insights
Regulatory Framework	In the U.S., there are clear PFAS rules. EPA imposed new drinking water limits and developed a national plan to limit the release of these chemicals. There is less regulation for microplastics and medicine. (U.S. EPA, 2024a; Federal Register, 2024)	The EU considers PFAS a set of hazardous chemicals under its REACH law. New rules also require drug companies to consider how medicines affect the environment. (European Commission, 2025)	African countries have only a few strict laws on PFAS or microplastics. Most emphasise plastic waste and water safety, but lack detailed chemical control. (Li et al., 2024)	Around the world, most countries are faster to act on PFAS than microplastics or medications. Reviews say there are calls for stronger and more uniform laws. (ResearchGate review, 2022)
Enforceable Standards	PFAS have official limits in drinking water. For other pollutants, there are no national limits yet. (U.S. EPA, 2024b)	EU countries are establishing set limits on PFAS, but not on microplastics or medicines. (European Commission, 2025)	Most African countries have no fixed quantities for emerging contaminants or limits for their impact, but a few others test for water quality. (Li et al., 2024)	Worldwide studies have found that most countries have no quantitative limits and require better lab standards. (Li et al., 2024.)
Monitoring and Research	EPA supports new lab methods and monitoring tools designed to detect PFAS. (OSTP, 2023)	The EU encourages standards testing and cooperation between countries. (European Commission, 2025)	Little research is available, but international groups are developing training and data collection projects. (Li et al., 2024)	Global reviews recommend shared data systems and international monitoring. (ResearchGate review, 2022)
Public Engagement	EPA runs awareness campaigns on PFAS and plastics. Take-back programs help people dispose of medicines safely. (CalSPEC/UC Davis, 2023)	Europe promotes open communication on environmental issues and educates on pollution. (European Commission, 2025)	There are a few public awareness campaigns, but NGOs and local groups increase interest in plastic waste. (Li et al., 2024)	Public campaigns which mix education and solutions work best. (ResearchGate review, 2022)
Collaboration	Communities, academic institutions, and	EU countries fund research and rules under	African countries rely on international aid	The reviewed studies have suggested Global

	government organisations cooperate to enhance cleanup and monitoring. (OSTP, 2023)	REACH. (European Commission, 2025)	and cooperation in their research and cleaning. (Li et al., 2024)	cooperation in data sharing, financing, and the exchange of expertise. (Li et al., 2024; ResearchGate review, 2022).
	Limited lab capacity and slow development of microplastic testing standards. (U.S. EPA, 2024a)	Due to industry differences, applying the same standard throughout the pharmaceutical and PFAS industries is challenging. (European Commission, 2025)	Limited funding, bad waste management, and limited data on new pollutants. (Li et al., 2024))	On a global basis, the unequal progress and poor coordination impede efficient control. (ResearchGate review, 2022)

VII. CONCLUSION

Emerging contaminants such as PFAS, microplastics, and pharmaceuticals pose a complex challenge that demands coordinated scientific, technological, and policy responses. Advances in detection and remediation, backed by strong governance frameworks and public involvement, are vital to reduce their risks and safeguard environmental and human health.

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