



Unraveling the complexities of microplastics and PFAS synergy to foster sustainable environmental remediation and ecosystem protection: A critical review with novel insights

Md. Saiful Islam ^a, Kartikeya M. Kekre ^a, Tanishka Abhijit Shah ^a, Pei-Chien Tsai ^{b,c}, Vinoth Kumar Ponnusamy ^{b,d}, Gangadhar Andaluri ^{a,*}

^a Department of Civil and Environmental Engineering, College of Engineering, Temple University, Philadelphia, PA 19122, USA

^b Department of Medicinal and Applied Chemistry, Kaohsiung Medical University (KMU), Kaohsiung, 807, Taiwan

^c Department of Computational Biology, Institute of Bioinformatics, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, Tamil Nadu, 602105, India

^d Research Center for Precision Environmental Medicine, Kaohsiung Medical University (KMU), Kaohsiung, 807, Taiwan

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ABSTRACT

Microplastics (MPs) and polyfluoroalkyl substances (PFASs) have emerged as emerging contaminants, drawing global attention due to their persistence and extensive presence in ecosystems. Although comprehensive studies exist on their individual behavior, their synergistic interactions remain unexplored, necessitating in-depth investigation to understand their impacts on environmental compartments. This review investigates the combined sources of MPs and PFASs, including commonly used daily products of human and wastewater treatment plant effluents, which release approximately 7.2 billion microplastics daily into aquatic environments and PFAS concentrations ranging from 8.1 to 24 µg/person/day. The review also discusses the mechanisms and environmental parameters that govern PFAS sorption over MPs. Studies indicate that the efficiency of PFAS retention increases with smaller, aged, or biofilm covered MPs due to larger surface areas, with adsorption rates varying from 20% to 85% depending on the type of MP and environmental conditions. Furthermore, the review explores the trophic transfer and combined toxicity of these contaminants, demonstrating that MPs act as carriers for PFAS, affecting their distribution, accumulation, and impact within ecosystems. These interactions can severely affect aquatic species, causing intestinal damage, oxidative stress, and disrupted reproductive systems in fish and other organisms. Despite these findings, significant knowledge gaps remain in understanding their interactions in complex ecosystems, particularly in terrestrial environments. Addressing these gaps requires developing standardized detection methods and conducting studies under realistic environmental conditions. Finally, this review suggests that future research should focus on developing combined removal strategies and source abatement measures to effectively manage the associated environmental and health risks.

1. Introduction

The production rate of plastic has seen exponential growth since the 1970s. The world now generates 400 million tons of plastic trash annually and the global primary plastic production is expected to exceed 1100 million tons by 2050, if current growth rates persist ([UN Environment Programme: Visual Feature, n.d.](#)). Plastic waste is ubiquitous and has become a fundamental thing of human daily life. The large plastic particles undergo aging and fragmentation through various physicochemical processes, leading to the formation of microplastics

(less than 5 mm) ([Murphy et al., 2016](#)). MPs can be found in various environment, including air, soil and water, and their widespread pervasiveness are a serious concern due to rising impact on the ecosystems ([L. Yang et al., 2021](#)). The co-occurrence of MPs and PFAS in different ecosystems has been reported, with concentrations ranging from 0 to 7 particles/m³ in air, 1–4712 particles/kg in soil, and 1–26 particles/L in aquatic matrices for MPs, and < 0.0011 to 95.378 ng/m³ in air, 6.90 to 294,000 ng/kg in soil, and 4 to 268 ng/L in aquatic environments for PFAS ([Parashar et al., 2023](#)). Microplastics can adsorb a wide range of contaminants in aquatic systems, such as antibiotics,

* Corresponding author at: Department of Civil and Environmental Engineering, Temple University, USA.

E-mail address: gangadhar@temple.edu (G. Andaluri).

PFAS, 6PPD, PCBs, PAHs and heavy metals (Enyoh et al., 2024; Syraniou and Kalogerakis, 2022). Hydrophobic organic contaminants exhibit a higher attraction for plastics compared to water, leading to their adsorption onto the microplastic particles (Fu et al., 2021). Furthermore, microplastics experience weathering through various biological and physiochemical mechanisms, such as biofilm attachment, and ultraviolet (UV) radiation (Huang et al., 2022). The interaction between these aged and weathered microplastics and other contaminants have become increasingly complex. Therefore, knowledge of these interaction mechanisms among emerging contaminants is required to mitigate the possible toxicity to the ecosystem (Huang et al., 2022).

PFASs are a group of approximately 5000 synthetic fluorinated compounds, have gathered significant interest from the scientific community because they are one of the persistent organic contaminants (Sonne et al., 2021). PFAS are used extensively in textiles, cleaning products, packaging materials, semiconductors, hydraulic fluids, insecticides, electroplating and lithography industry because of their high biochemical stability and surface activity (Rahman et al., 2014). Recent studies have identified the presence of PFAS throughout various environments, such as drinking water, groundwater, stormwater, freshwater and seas (Elgarahy et al., 2024b). Although there are not many direct studies on the impact of PFAS on the health of humans, there have been a few studies on the toxic impact of PFAS on aquatic ecosystem (Du et al., 2023).

Emerging contaminants such as PFAS and MPs exhibit identical characteristics, like ubiquity, biofouling potential, persistence, and diversity (Coffin et al., 2023). Many products can release both PFAS and MPs into the environment and MPs can adsorb PFAS due to their numerous properties, such as hydrophobicity and wide surface area (Barhoumi et al., 2022). MPs and adsorbed PFAS can be ingested, entering the food chain and causing severe impacts on human health as well as on aquatic organisms. Significantly, MPs and PFAS interaction characteristics have not received adequate attention from the researchers. A few researchers have investigated the synergy between PFAS and microplastics, but the understanding of combined trophic transfer and toxicity to the ecosystem is still unclear (Mejías et al., 2022). For instance, the toxicity of PFAS and microplastics varies depending on their distribution in aquatic species, and further research is required to identify the risks associated with their combined ingestion. Furthermore, the interaction processes between MPs and PFAS are complex due to their co-existence with other contaminants in environmental compartments.

There are a few reviews on the interaction between the emerging contaminants, but most of the studies focus on individual contaminant sources, trophic transfer, toxicity, and removal technologies rather than revealing the combined effect of MPs and PFAS and their interaction. At present, no well-established studies are available for the combined removal of MPs and PFAS. However, best available technologies, such as adsorption, ion exchange, nanofiltration, sono-hybrid processes, advanced oxidation processes, destructive technologies, and supercritical water oxidation, can be considered for future feasibility studies addressing the removal of combined MP and PFAS contamination (Elgarahy et al., 2024a). In addition, emerging materials like geopolymers can also be considered for future studies on the combined removal of these emerging contaminants, as they address a wide range of contaminants, including heavy metals and organic pollutants, offering potential for innovative remediation strategies (Elgarahy et al., 2023a). Although these physical and chemical treatments show promising results, bioremediation also represents a viable treatment technology. Bioremediation of PFAS through anaerobic digestion with carbon adsorbent such as activated carbon increases methane production and reduces the toxicity of PFAS (Silva et al., 2022). However, biological treatment of PFAS in soils remains challenging due to existing knowledge gap on degradation mechanisms. Advanced microbial ecology techniques, including metagenomics and metabolomics, may help to identify and optimize PFAS biodegradation pathways (Shahsavari et al.,

2021). A multidisciplinary approach that incorporates technological advancements with a reevaluation of recycling and upcycling practices, strengthened policies and regulations, and life-cycle assessment is required to achieve highly efficient recycling and upcycling of these contaminants for a sustainable future (Elgarahy et al., 2023b).

To address the gaps in understanding the interactions between MPs and PFAS, the aim of this systematic review is to investigate the inherent interaction characteristics between these contaminants, including their co-sources, sorption mechanisms, and the factors influencing these interactions, identify the combined trophic transfer, and assess the combined toxicity of these emerging contaminants. In summary, this critical review is anticipated to represent a turning point toward a more comprehensive understanding of microplastics and PFASs combined toxicity, providing a detailed insight of these forever contaminants by considering their intrinsic features of the interactions. This study will also assist in exploring appropriate removal technologies for these interacting emerging contaminants to mitigate their harmful effect on the ecosystem.

The study hypothesizes that smaller, aged, or biofilm-covered MPs exhibit greater PFAS adsorption due to increased surface area and enhanced hydrophobic interactions. It further suggests that MPs serve as carriers for PFAS, facilitating their trophic transfer and exacerbating their ecological and health impacts. Moreover, it is hypothesized that combined exposure to MPs and PFAS results in more severe toxicity effects on aquatic and terrestrial organisms than exposure to either contaminant alone. By addressing these questions and testing these hypotheses, this study aims to provide a comprehensive understanding of the co-existence and interactions between MPs and PFAS, enabling the development of effective mitigation strategies.

2. Research trends on MPs and PFAS interaction

A thorough review of the literature was conducted from January 2024 to October 2024 to identify publications related to the synergy of PFAS and MPs, their combined toxicity, influencing factors, and trophic transfer. Over the past two decades, a bibliography of studies on microplastics, PFAS, and research addressing both was compiled. A keyword analysis was undertaken to explore publications focusing on both microplastics and PFAS, facilitating the analysis of emerging research trends. The literature was searched in Google Scholar, Web of Science, and ScienceDirect using key terms like "microplastics", "per- and poly-fluoroalkyl substances", as well as terms such as PFAS, PFOA, PFOS, GenX, F-53B, and phrases like "co-sources", "interaction", "adsorption", "influencing factors", "marine environment", "freshwater", "environment on land", "transfer through trophic levels", "combined toxicity", and "ecological toxicology".

To refine the results, specific inclusion and exclusion criteria were applied. The inclusion criteria focused on studies addressing both MPs and PFAS, either individually or in combination, with an emphasis on interaction mechanisms, co-sources, sorption behavior, trophic transfer, or combined toxicity. Only peer-reviewed research papers and review articles were considered, with a particular focus on recent advancements. Exclusion criteria included articles focusing solely on MPs or PFAS without addressing their interactions, editorials, and non-peer-reviewed publications. Irrelevant studies outside the scope of environmental science and toxicology were also excluded. This systematic process initially yielded 173 studies, comprising both review and research manuscripts. Each study was carefully reviewed, and irrelevant or duplicate articles were removed. Additionally, review articles that did not provide original data or synthesis relevant to the topic were excluded. Finally, 69 research papers were included in the study, with the majority being published in recent years, highlighting the growing academic interest in this emerging area of research.

As illustrated in Fig. 1, the number publications on microplastics were observed to gradually increase after 2010, with a more pronounced surge between 2020 and 2023. Similarly, research on PFAS has shown a

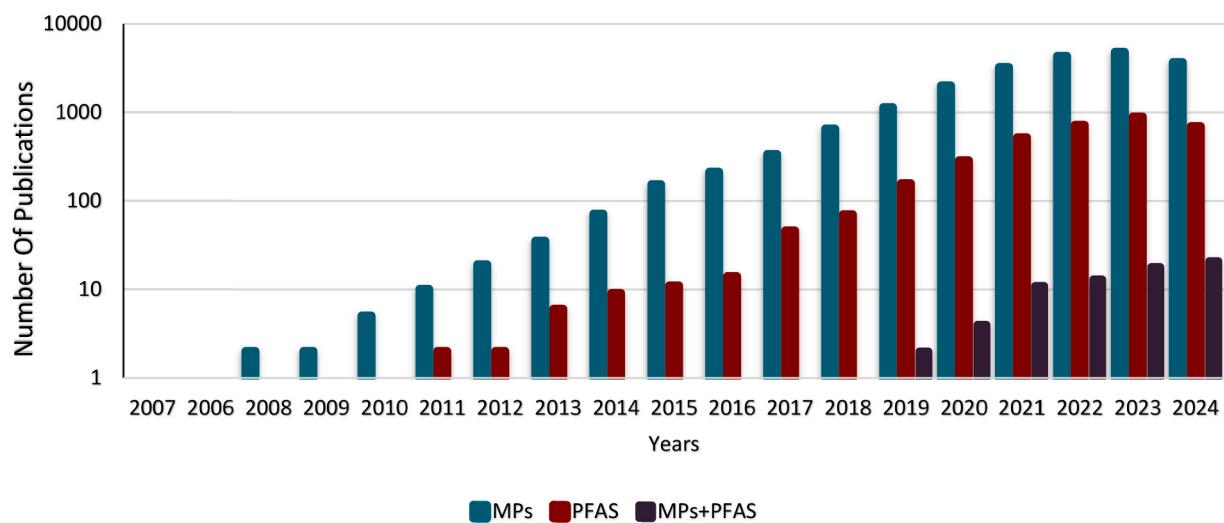


Fig. 1. The number of publications related to MPs and PFAS from 2007 to September 2024.

steady upward trend over the past two decades, but the increase observed during 2019–2023 was also greater than ever before, like microplastics. This growth can be attributed to the heightened academic interest in emerging pollutants, which has led to increased focus on both microplastics and PFAS. Although these fields have gained significant attention as research hotspots, the trend is anticipated to decelerate due to the saturation of existing studies, with future research likely shifting towards innovative directions, such as the integrated investigation of microplastics and PFAS.

The first research addressing the synergy between PFAS and MPs appeared in 2019. Despite the recent increase in publications, the overall volume of studies remains limited, with significant knowledge gaps, indicating substantial potential for further exploration into the

trophic transfer, combined toxicity, and co-occurrence of these contaminants.

The research trends analysis was conducted using VOSviewer software, a powerful tool for bibliometric analysis and visualization of large volumes of scholarly data. The findings reveal that at the beginning of MPs and PFAS studies, research primarily focused on their occurrence and source in the ecosystem (Fig. 2). As research progressed, investigations began to address the mechanisms and interactions between MPs and various associated contaminants, including PFAS, antibiotics, and heavy metals.

The Sankey diagram illustrates the literature analysis on key research areas, particularly focusing on the number of research exploring the sorption behavior and the combined toxicity of PFAS and

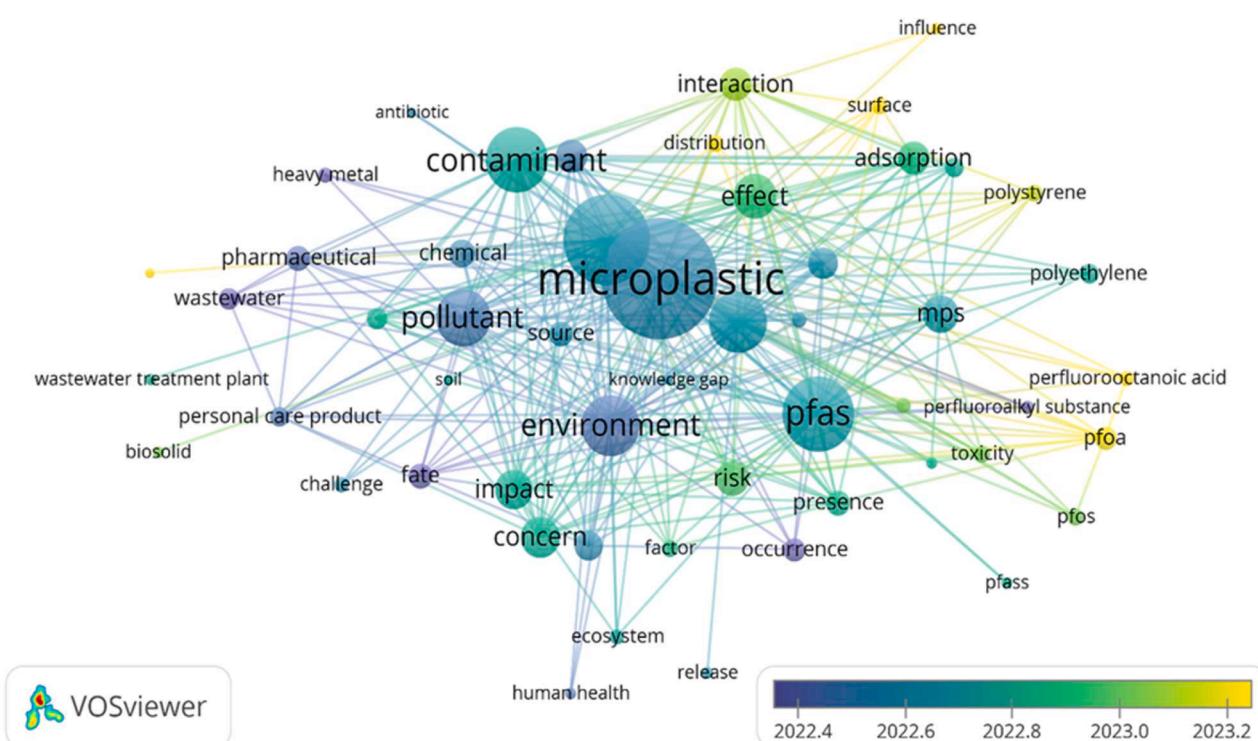


Fig. 2. Overlay visualization network map of frequent keywords for microplastic and PFAS research. (This network map illustrates the connections between frequently used keywords in microplastic and PFAS research, created using VOSviewer. Node size represents keyword frequency, and line thickness indicates co-occurrence strength.).

MPs. The diagram also highlights the geographic distribution and quantity of studies related to microplastics (MPs) and PFAS (Fig. 3).

3. Co-sources of PFAS and MPs and factors influencing their interactions

3.1. Co-sources of PFAS and MPs

The common sources of MPs and PFASs are products (functional polymeric fabrics, food-contact materials, fluoropolymers) that have widespread application in human daily life (Barhoumi et al., 2022) (Fig. 4). Plastics and PFASs are applied in the same products to improve their stability and durability, and these products release both contaminants into the environment through their manufacturing process, uses and disposal (Gaines, 2023; Weis and Alava, 2023). Functional textile fabrics-Polyamide (PA) designed for personal protective equipment and outdoor activities are subjected to weathering and physical stress may lead to considerable release of polymeric PFASs into the environment (Peaslee et al., 2020; Radley-Gardner et al., 2016; Schellenberger et al., 2022). Some plastics food contact materials are generally coated with PFASs due to its functional properties to repel oil, grease and water (Curtzwiler et al., 2021). These food contact materials can release and transfer MPs and PFASs into the food chain and cause serious impact to health of human as well as on the environment (Perkins, 2021). For instance, MPs and PFASs were detected in food and bottled water due to migration of these emerging contaminants from its plastic containers (Akhbarizadeh et al., 2020; He et al., 2021). Fluoropolymers based non-stick cookware, kitchenware and food processing machinery might leach Teflon MPs and PFASs while cooking (Parashar et al., 2023). Hence, there is a crucial requirement to investigate the potential human health risk and ecological risk for these contaminants in the food chain.

The effluent from wastewater treatment plants (WWTPs) are considered as a major source of MPs and PFAS contaminants to the ecosystem (W. Liu et al., 2021; Nguyen et al., 2022). Most urbanized cities with large population densities release higher concentrations of MPs and PFASs through municipal drain which is generated from human daily life (Cheng et al., 2021; Karim et al., 2024). Another study investigated that 8.1–24 µg/person/day of the total twelve PFAS was released to Australian WWTPs (Nguyen et al., 2022). Most of the conventional WWTPs could not efficiently remove PFASs and sometimes higher concentrations of PFAS have been found in effluent than influent due to the formation from polyfluorinated precursors during treatment process (E. Houtz et al., 2018; E. F. Houtz et al., 2016). Prada et al., 2024 also

found that PFAS may be removed through conventional WWTPs, but not to the same degree as MPs. Another review reported that WWTPs release about 7.2 billion microplastics per day into the river, accounting for 2% of total MPs in the influent (W. Liu et al., 2021; Ziajahromi et al., 2021). Instead, agricultural operations use the sludge of WWTPs containing the majority of PFASs and microplastics (Nguyen et al., 2022; Ziajahromi et al., 2021). The removed PFASs and microplastics in different treatment processes of WWTPs are transported to Landfills (Nguyen et al., 2022).

Landfills receive significant amount of MPs and PFASs from WWTPs; however numerous used products and materials containing these contaminants are improperly discarded, allowing their release into the environment (Coffin et al., 2023; Lohmann et al., 2020). Kabir et al. (2023) observed the MPs concentration in landfill leachate ranged from 0 to 382 items L⁻¹. In a study, Zhang et al. (2023a) found that PFASs were also present in landfill leachate and C4-C7 PFCAs are dominant. This Landfill based leachate is the source of MPs and PFASs contamination of soil, groundwater and surface water (J. Li et al., 2023; Sekar and Sundaram, 2023). The co-existence and synergy of Microplastics and PFASs may lead to serious toxic effects to the environment (Dai et al., 2022).

3.2. Factors influencing the interaction between microplastics and PFAS

The interaction between microplastics and PFAS depends on many factors including chemical and physical characteristics of microplastics and PFAS, characteristics of the medium, etc. The influencing factors of this sorption are described below and shown in Fig. 5.

3.2.1. Characteristics of microplastics

The physicochemical properties of MPs in aquatic ecosystems vary significantly and they are quite diverse. Polymer types, size, shape and concentrations of microplastics significantly influence their sorption properties, trophic transfer and combined toxicity. The size of microplastics is a critical physical property, as the surface area fluctuates with size, and the sorption of PFAS depends on this surface area. The number of active sites for PFAS adsorption can be increased by smaller microplastics since they have a higher surface area to volume ratio (J. Wang et al., 2019). This is because hydrogen bonds, hydrophobic interactions, and pore filling all affect the sorption process. An experiment conducted by Cormier et al. (2022) that lasted more than six months showed a linear increase in the amounts of PFOS absorbed by microplastics (PE) with size of the particle dropped. Similarly, Mejias et al. (2022) found

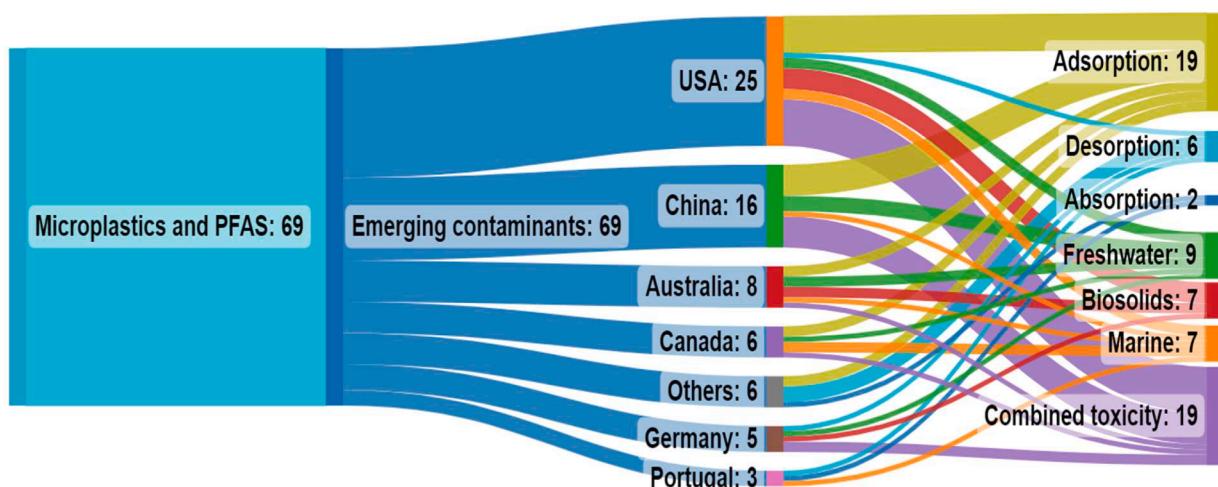


Fig. 3. The number and regions of MPs and PFAS studies and their corresponding sorption behavior. (This Sankey diagram illustrates the geographic contributions to microplastics and PFAS research and their thematic focus, including adsorption, desorption, freshwater systems, biosolids, marine environments, and combined toxicity. The width of the flows indicates the relative contribution to each theme, highlighting global research trends and priorities.).



Fig. 4. The co-sources of Microplastics and PFASs.

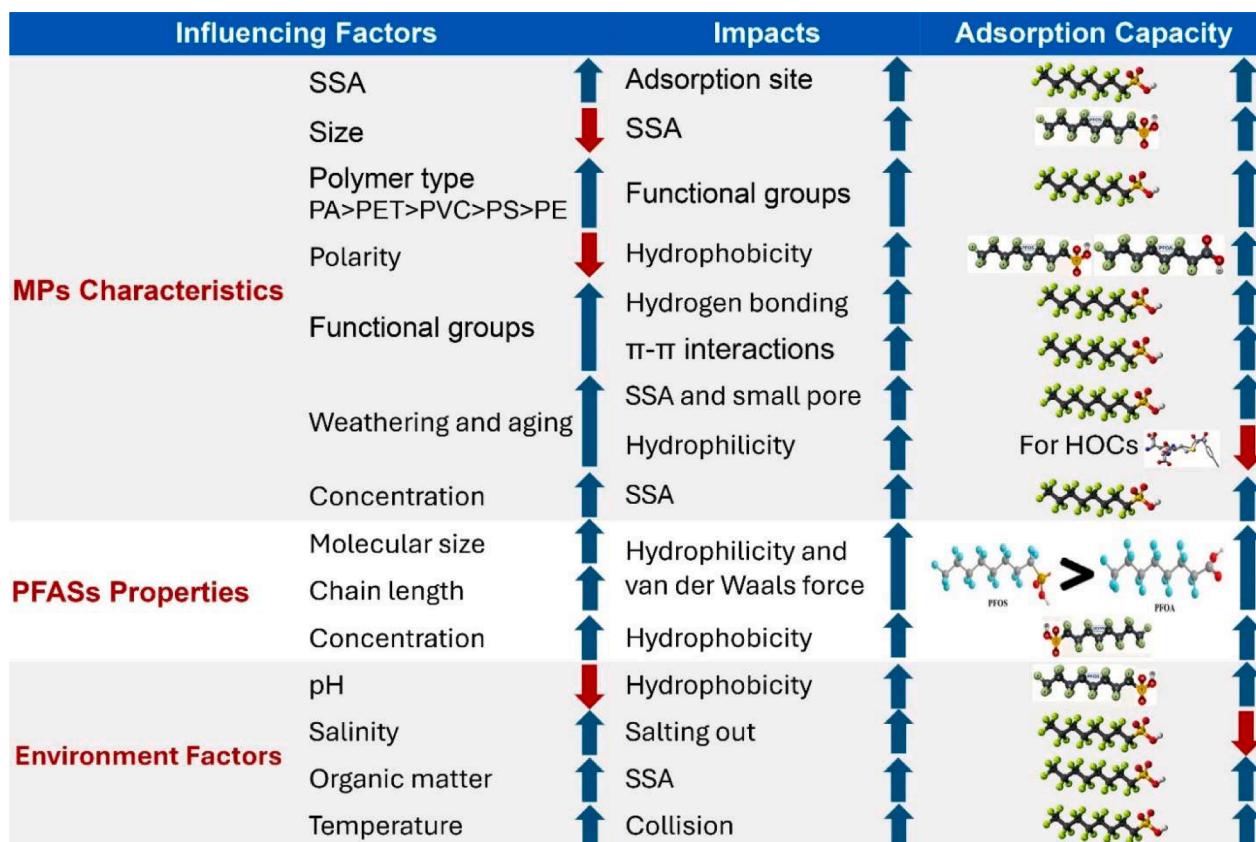


Fig. 5. Factors influencing the interaction between microplastics and PFAS. Note: Upward blue sign indicates increased and downward red sign indicates decreased.

that smaller MPs (50 µm) particles adsorbed 99.9% of PFASs, whereas larger MPs (3000 µm) exhibited significantly lower adsorption, at only 19.6%. Adsorption increases when surface area and particle size decrease, despite the varied polymer content. Furthermore, PFAS

sorption capability is also greatly impacted by the shape of MPs particles. For instance, HDPE microplastics showed the lowest sorption affinity for PFAS because of their granular structure (Llorca et al., 2018). However, the aforementioned features related impacts are minor

because they may be overridden by many factors such as biofilm formation, weathering and NOM (N. Islam et al., 2021).

The polymer types of MPs are key factors in their adsorption process of contaminants, where MP polarity being the primary characteristic to assess. Polymers that are not polar have covalent bond between carbon and hydrogen atoms, which can produce great structural strength and chemical resistance. However, polarity can be introduced into the polymer through the incorporation of various functional groups (F. Liu et al., 2019a). Among the most common types of microplastics, the sequence of polarity is as follows: PP < PE < PS < PVC < PET < PA. For instance, F. Wang et al. (2015) demonstrated that PFOSA and PFOS adsorption by PVC, PS and PE depends on their polarity in addition to other factors. PE is absorbed by non-polar PFOSA due to its highest distributivity, while polar PFOS also shows higher distributivity to PE and PVC compared to PS (F. Wang et al., 2015). This is because PS creates less space due to its unique resistance, which hinders molecules from adhering to it. Islam et al. (2021) indicated that PFOS and PFOA more readily absorbed by PP, whereas PE might exhibit a lower efficiency in this regard. Furthermore, the distributivity of PS and PS-COOH is higher to PFAS than in HDPE (Llorca et al., 2018). The concentration of MPs is also a key factor that impacts synergy with contaminants. The higher concentration of MPs increased the SSA and considerably increased the percentage of adoption to PFAS (Mejías et al., 2022).

Original physical and chemical characteristics of MPs vary significantly with microplastic weathering and aging (C. Wang et al., 2020a). Microplastics undergo weathering because of temperature, water (corrosion), and UV radiation, which increases their surface area and adsorption capacity (H. Zhang et al., 2018). The specific surface area (SSA) of PS increased as a result of the formation of numerous small pores due to weathering (Y. Sun et al., 2020). Additionally, C—C and C—H bonds in MPs are oxidized due to weathering. The resulting functional groups that contain oxygen make MPs more hydrophilic or strengthen the hydrogen bonds that attach them to organic pollutants, which enhances their ability to adsorb hydrophilic PFAS (G. Liu et al., 2019b).

3.2.2. Physical and chemical properties of PFASs

The adsorption and hydrophobicity of PFAS on microplastics are influenced by functional group and chain length. PFOS is more hydrophobic than PFOA due to its greater molecular size and higher chain length. For instance, PFOS exhibited a higher adsorption capacity of 0.873 mg/g compared to PFOA's 0.235 mg/g, primarily due to hydrophobic interactions (Mejías et al., 2022). The main interaction mechanism of PFOSA and PFOS on PVC, PE, and PS is attributed to hydrophobic attraction (F. Wang et al., 2015). Conversely, PFOA had low dissociation constant values and negligible affinity for PE and PVC (Bakir et al., 2014). Furthermore, there is a higher possibility for adsorption of PFOS at higher concentrations on polyethylene compared to lower concentrations of PFOS (Cormier et al., 2022).

Short-chain PFAS or non-fluorinated chemicals have started to replace long-chain PFAS because of their benefits for waterproof, anti-fouling, safety reasons and grease-proof requirements, although there is existence of both short and long chain molecular structures of PFAS in the earth. The greater solubility values of shorter-chain PFASs indicate that they are more hydrophilic and water-soluble than long-chain PFASs. Arvaniti and Stasinakis (2015) investigated that short-chain PFASs exhibit a reduced tendency for sorption, resulting in increased mobility within natural aquatic ecosystems. PFAS adsorption on a variety of adsorbent materials has also been thoroughly investigated and the results of these studies demonstrated that the PFAS sorption increased as the length of the perfluorocarbon chain increased (Gagliano et al., 2020). For example, S. B. Kang et al. (2023b) investigated that the polyethylenimine-polyvinyl chloride electrospun nanofiber exhibited an adsorption capacity of 326.39 mg/g for PFOS (a long-chain PFAS), which is higher than the adsorption capacities for the short-chain PFAS, PFBS (214.37 mg/g) and PFBA (84.26 mg/g). F. Wang et al. (2015)

found that the sorption of PFASs onto MPs varied among functional groups, following the order: carboxylic < sulphonamide < sulphonates groups. Therefore, it is imperative to consider functional groups and chain length to comprehend the impact of PFAS physicochemical features on adsorption.

3.2.3. Environmental factors

The properties of environmental media, alongside MPs and PFAS, can notably influence the interactions between these substances. A prior investigation found that at lower pH the interaction of PFOS on microplastics (PS and PE) was favored, while PFOSA exhibited adsorption on microplastics across a range of pH conditions (F. Wang et al., 2015). Likewise, the variations in PFAS adsorption by PA across various pH conditions was explored by Mejías et al., 2022. The study revealed that adsorption between PFBuA and Polyamide decreased from 19 % to 11 %, while PFOS reduced from 99 % to 57 % as the pH increased from 4 to 7, with initial PFAS concentrations of 500 ng/mL. This is due to the water's increased pH reducing the amount of exposure time required for PFAS and MPs to achieve equilibrium (Llorca et al., 2018). In terms of salinity, the affinity of PFOS on PS and PE microplastics polymers were observed to rise with higher concentrations of CaCl₂ and NaCl (F. Wang et al., 2015). For instance, the adsorption of PFOS increased by a factor of 6 with the increase of salinity from 0.005 to 0.5 mol/L at pH 8, whereas at pH 7, the sorption of PFOS increased by a factor of 3 (You et al., 2010). Moreover, another study conducted by Salawu et al. (2024) revealed that PFBA adsorption capacity at equilibrium increased significantly ($p = 0.01$) as ionic strength increased, from $7.6 \pm 0.9 \mu\text{g/g}$ at 0 mM to $23.7 \pm 7.6 \mu\text{g/g}$ at 100 mM, whereas the adsorption capacity for PFOS also increased (but not significantly; $p = 0.11$) from $38.6 \pm 4.8 \mu\text{g/g}$ at 0 mM to $58.2 \pm 8.9 \mu\text{g/g}$ at 100 mM. However, another study indicated that the existence of salts could reduce the synergy of PFAS on Microplastics (Llorca et al., 2018).

The sorption of microplastics and per- and polyfluoroalkyl substances can influence the existence of NOM in aquatic ecosystem through various mechanisms. Organic matter may cover all microplastics or adhere to their surfaces, influencing the electrostatic characteristics and site resistance. However, NOM compete against PFAS for interaction on MPs or may attach with PFAS for co-existence (Zhuang and Wang, 2023). Scott et al. (2021) investigated that microplastics exposed to NOM exhibited enhanced adsorption of PFOA and PFOS. Thus, the presence of NOM can enhance the sorption of PFASs by rearranging connecting forces, which creates more adsorption sites through increased dispersion.

Furthermore, it is essential to consider the temperature of the aquatic media during consideration of the adsorption process. The sorption of PFOS and PFOA on PE and PP notably enhanced with the rise of temperature, although excessive temperatures can affect the contaminants properties and subsequently influence their adsorption (Khumalo et al., 2022). For instance, the adsorption capacity of PFAS on MPs increased significantly with the increase of temperature from 25 °C to 50 °C (Salawu et al., 2024). The occurrence of MPs biofilm is a widespread phenomenon observed in the aquatic system. Bhagwat et al. (2021) found that microplastics polymer covered with biofilms exhibited larger surface areas, indicating higher PFOS adsorption capability than pure samples. In summary, the above findings indicate that existing laboratory investigations on the sorption mechanism of PFAS by pure microplastics underestimate the real scenarios because they overlook the presence of NOM and biofilm formation. Factors influencing the interaction between microplastics and PFAS are shown in Fig. 5.

4. Sorption of PFAS on microplastics (Studies under laboratory settings and field environment)

The sorption behavior strongly indicates the connection between MPs and PFASs. Sorption refers to the transfer of molecules to the solid phase from the fluid, consisting of both absorption and adsorption

process (Hanun et al., 2021). Adsorption is the adherence of molecules at the interface between a solid and a liquid, while absorption is the penetration and incorporation of molecules into the solid matrix (Vieira et al., 2021). The process of adsorption plays a crucial part in the sorption mechanisms of most research on MPs. Nevertheless, the processes of adsorption and absorption often progress too closely to be differentiated, hence this review will not attempt to do so. Although MPs have been found to be carriers for PFASs, there has been little research conducted on the systematic evaluation of PFASs sorption onto MPs. Thus, a summary of sorption of PFAS onto microplastics surface and the variables that influence their sorption have been provided in Table 1.

An analysis of the sorption of PFAS onto microplastics with the influence of pH, natural organic matter (NOM), ionic strength, and temperature was studied by Salawu et al. (2024). A thermodynamically spontaneous adsorption of PFAS to the microplastics occurred at 25 °C, empirical equilibrium was achieved in adsorption within 7–9 h. The presence of NOM reduced the ability of PET to absorb PFAS by electrostatic repulsion. Conversely, increasing ionic strength enhanced the sorption of PFAS by reducing electrostatic separation. Higher pH levels resulted in greater electrostatic repulsion, therefore nullifying the adsorption of PFAS. However, another research investigated on freshwater, Ateia et al. (2020) found that preloaded MPs containing natural organic matter (NOM) exhibited enhanced absorption of micro-pollutants by either creating a complex with NOM or by co-sorption. Adsorption of PFAS on fourteen well-defined microplastics in surface water of Lake Hartwell, USA was shown to follow the sequence of PFOS>PFOA>GenX. Bhagwat et al. (2021) observed that the abundance of adsorbed PFOS was greater in biofilm-covered and aged microplastics compared to virgin microplastics, with variations ranging from 20% to 85% depending on the polymer type. This phenomenon can be attributed to the enhanced surface areas of the treated microplastics, which arise from the accumulation of biomass.

A higher amount (67–730 ng/kg) of PFAS was found to be attached to microplastics that had been floating around in Muskegon Lake, Michigan, USA for one to three months. Similarly, the adsorption capacity of PFOSA by PS was observed to be the highest, and PS exhibited the greatest adsorption capacity in the presence of PFOA (Scott et al., 2021). Adsorption of PFAS occurred on MPs (PE > PES > PP) and obtained the greatest concentrations of PFOA, which were 24 to 259 times higher than the natural background levels. Similarly, the adsorption capacity of PFOSA by PS was observed to be the highest and PS exhibited the greatest adsorption capacity in the presence of PFOA (Meng et al., 2023). Another study looked at how PFOS attached to polyethylene microplastics of different sizes (4–500 µm) and found that smaller particles had a higher PFOS adsorption capability (Cormier et al., 2022). This effect can be explained by the fact that intraparticle diffusion is less limited in smaller particles, there is a more surface area compared to volume, and film diffusion expedites because the boundary layer is thinner.

The studies conducted by Llorca et al. (2018) under marine conditions examined the capacity of three microplastics (PS-COOH, PS and HDPE) to adsorb eighteen PFASs from seawater environments. The findings from the batch sorption investigation indicated that the various types of PFASs exhibit differing affinities for adsorption onto MPs. Nevertheless, the predominant PFASs reached their peak adsorption onto MPs after a duration of seven days, after which a gradual desorption process commenced. The overall adsorption capacity of the materials was observed to follow the order: PS > PS-COOH > HDPE. The rise of conductivity and pH levels resulted in improved adsorption of PFAS, whereas the PFAS adsorption capacity decreased due to rise of salinity. PFOA adsorption characteristics on 200–250 µm sized PE and PVC microplastics was observed under conditions of rotational agitation at 220 rpm over a duration ranging from 24 to 360 h, in the absence of light at a temperature of 18 °C in a seawater medium (Bakir et al., 2014). Although PVC and PE demonstrated the capacity to sorb PFOA, a decrease in adsorption was observed after a specific duration (50 to 100

mins) due to low K_d values. Wang et al. (2015) demonstrated that as the concentrations of CaCl₂ and NaCl increased, the absorption of PFOS by PE and PS also raised. Nevertheless, the adsorption of PFOSA and PFOS on PVC microplastics remained unchanged despite variations in the concentrations of NaCl and CaCl₂. This observation suggests that electrostatic interactions act as a crucial factor in the sorption mechanism involved.

A study conducted by Sun et al. (2024) investigated the effect of polyamide microplastics (PAMP) on the adsorption dynamics of four perfluoroalkyl substances (PFAS) within soil matrices. The findings indicate that PAMP markedly increases the PFAS adsorption. The investigation revealed that the presence of soil particles and biofilms on the surface of PAMP diminishes its capacity to adsorb PFAS effectively. However, the presence of MPs in the soil significantly increases (20–56 times) the adsorption capacity of PFAS in comparison to the soil alone.

In contrast to research conducted in controlled laboratory environments, there are a few field studies that have emphasized the co-occurrence and interaction of microplastic and per- and poly-fluoroalkyl substances in natural settings. Cheng et al. (2021) investigated and collected samples from 8 rivers that flow into the Estuary of Pearl River. The higher levels of PFASs on microplastics (ranging from 105 to 9.07×10^3 ng/g) were detected in drain outlets of highly urbanized areas than the MPs ($10.3\text{--}227.8$ ng/g) were detected in the drainage outlets that primarily received wastewater from forested and agricultural regions. Similarly, significant levels of PFOS (0.21 ± 0.06 ng/L) and PFOA (0.31 ± 0.04 ng/L) were detected in ten-year-old HDPE plastics obtained from the estuary of Port Stephens in Australia Bhagwat et al., 2021. Another study also found the occurrence of 21 distinct perfluoroalkyl substances (PFASs) in the litter of marine plastic from central Chile (Gómez et al., 2021). The findings indicate that long-chain PFASs, especially MeFOSE, were the most abundant, with Coliumo beach exhibiting the highest concentrations of PFASs.

Synthetic materials like functional textiles and artificial turfs (AT) release PFAS into the ecosystem. For instance, the emission of PFAS from functional textiles throughout their usage and exposure to environmental conditions were examined by Schellenberger et al. (2022). Outdoor aging experiments demonstrated that textile fragments containing PFAS and low molecular weight PFAS diminish over time due to weathering. These aging and washing processes of fabrics through fluorinated polymers may lead to an elevated concentration and generation of perfluoroalkyl acids (PFAAs). Washing functional textiles leads to the release of microplastic fibers that contain fluorinated polymers, which may subsequently convert into short-chain PFAAs in the environment. Additionally, Per- and polyfluoroalkyl substances (PFAS) are commonly found in artificial turf fields, with total fluorine identified in all samples from a study conducted in Stockholm (Lauria et al., 2022). Although the fluorine in AT seems to exist mainly in non-extractable, polymeric forms, there are ongoing concerns regarding production and end-of-life challenges. Although AT fields are utilized extensively around the world, there remains an inconsistency in regulations that tackle potential health and environmental risks (Zuccaro et al., 2022). The historical application of aqueous film forming foams (AFFFs) at military airports has resulted in considerable PFAS contamination in adjacent environments, such as groundwater, surface water, and fish (Filipovic et al., 2015).

Microplastics (MPs) also act as carriers for various emerging contaminants including heavy metals, microcystins and antibiotics, causing ecological risks in aquatic systems (Elgarahy et al., 2021; Shi et al., 2023). A study conducted by Almeida et al. (2020) found that heavy metals such as lead (Pb), zinc (Zn), and copper (Cu) adsorbed on the surface of MPs at concentrations of approximately 0.1 µg/g, 270 µg/g, and 3000 µg/g, respectively, in marine environments (Almeida et al., 2020). This sorption capacity depends on the physicochemical properties of microplastics, including surface charge, surface area, and functional groups, with aged MPs exhibiting increased sorption due to surface oxidation (Gonçalves et al., 2019). Similarly, antibiotics such as

Table 1

Studies investigating PFAS sorption onto MPs under laboratory settings and field environment.

Types of water and location	Adsorbate (PFAS)	Adsorbent (MPs) characteristics	Experimental setup				Remarks	References	
			Compound and Concentration	Polymer type, size and concentration	pH	Temp (°C)	Rotary agitation (rpm)	Duration (days)	
Milli-Q	PFOS, PFOA, PFBA, GenX, PFBS; 200 µg/L	PET (39–493 µm); 2 mg/mL	3–11	25–50	–	–	–	The sorption of PFAS on microplastics occurred instinctively at 25 °C. The equilibrium condition reached within 7–9 h.	(Salawu et al., 2024)
Milli-Q	PFOSA, PFOA; 50–500 µg/L	PE, PP, PVC, PS, PTFE; 5 mg/L	5–9	25	500	7	The highest concentration of PFOSA were adsorbed by PS than other polymers. Microplastics act as PFAS concentrators. PFOA showed negligible photodegradation in the presence of MPs.	(Meng et al., 2023)	
Ultrapure water	UFHA/C8 PFAS	PS; 10 g/L	4.0 ± 0.2	80	–	1	UFHA was absorbed by MP. The aggregation on MP particles were rapid with neutral particles.	(Bere et al., 2023)	
MilliQ	PFOS; 0.01 to 600 mg/L	PE (4–6 µm, 11–13 µm, 20–25 µm, and 125–500 µm); 2.5 g/L	6.7/4	25	20	180	The concentration of PFOS sorbed by PE were increased with the decreased of microplastic size.	(Cormier et al., 2022)	
Muskegon Lake, USA	PFOA, PFHxA, PFHpA; 5 µg/L	Incubated LDPE, PP, and PET (2–4 mm); 42 g	6.7/4	Room	90	30–90	The existence of organic as well as inorganic substance significantly influenced the PFAS adsorption onto MPs.	(Scott et al., 2021)	
Seawater	PFOS; 20 µg/L	Virgin and biofilm-covered PE, PP, PES, PA (2–3 mm); 10 g/L	7.9	22	150	7	Hydrophobic and weak van der Waals interaction. PFOS adsorption: PA>PES>PE>P. 20–85% higher concentration of PFOS were adsorbed by aged microplastic than virgin microplastic.	(Bhagwat et al., 2021)	
Surface water, Hartwell Lake, USA	GenX, PFOA, PFOS; 5 µg/L	Pure and real PE, PP, PA66, PMMA, PLA; (<500 µm); 50 µg/L	6.5 ± 0.2	25	150	14	High adsorption by PLA. High adsorption: GenX < PFOA < PFOS. Real MPs with natural organic matter had higher adsorption than pure polymers.	(Ateia et al., 2020)	
Freshwater, Ebro River, Spain	18 PFASs; 10 µg/L	Pure HDPE (3–16 µm, 5 mg/L), PS-COOH (10 µm, 2 mg/L), PS (10 µm, 2 mg/L)	–	22	120	4–50	The adsorption rate of PFASs by PS and PS-COOH were higher than HDPE. Hydrophobic, Van der Waals and electrostatic interactions. High pH and conductivity of water increases the adsorption capacity.	(Llorca et al., 2018)	
Deionized water	PFOS 0.02 µg/L	LDPE; 11 to 13 µm; 5 mg/L	–	Room	20	7	PFOS adsorption on microplastics were 70.22 ± 12.41 µg/g.	(O'Donovan et al., 2018)	
Seawater	PFOS, PFOSA	PVC (230 µm), PE (150 µm), PS (250 µm); 5 mg/mL	7.0 ± 0.2	25	150	7	PFOSA adsorption on microplastics is not affected by pH and salts. PFOS adsorption on microplastics were increased with low level pH and high salt concentration.	(F. Wang et al., 2015)	
Seawater with surfactant	PFOA; 0.2–2.1 µg/L	Pure PE, PVC; (200–250 µm); 0.4 g/L	4	18	220	1–15	Desorption rates were higher with gut surfactant than in seawater alone.	(Bakir et al., 2014)	
Soil	PFOA, FTSA, PFHxS, GenX; 20 mg/L	Polyamide (36.7 µm); 0.1 g in 2 g soil with 20 mL PFAS	–	25	200	1–5	The presence of MP in the soil significantly increases (20–56 times), the adsorption capacity of PFAS in comparison of the soil alone.	(Sun et al., 2024)	
Freshwater Pearl River Estuary, China (Field study)	Σ21 PFAS 5–50 µg/L	MPs	N/A	N/A	N/A	N/A	Higher concentration of PFAS on MPs were found in the dry season in comparison to the wet season. The concentration of PFAS on MPs ranged from 105 to 9.07 × 103 ng/g (drain of urbanized area) to 10.3–227.8 ng/g (drain of agricultural land).	(Cheng et al., 2021)	
Seawater, Beaches of central Chile (Field study)	Σ6PFAS 279–1211 pg/g	Macro plastic (PP) >2.5 cm	N/A	N/A	N/A	N/A	PFAS were detected on PP.	(Gómez et al., 2021)	
Artificial Turfs, Stockholm, Sweden (Field study)	PFAS	Plastics	N/A	N/A	N/A	N/A	PFAS were observed in less than 42% of all sample.	(Lauria et al., 2022)	

(continued on next page)

Table 1 (continued)

Types of water and location	Adsorbate (PFAS)	Adsorbent (MPs) characteristics	Experimental setup				Remarks	References
			Compound and Concentration	Polymer type, size and concentration	pH	Temp (°C)	Rotary agitation (rpm)	
Functional textiles, Sydney, Australia (Field study)	SFPs	Polyamide textile fabrics	N/A	N/A	N/A	N/A	Textile fabrics emitted perfluoroalkyl acids (PFAAs) due to weathering.	(Schellenberger et al., 2022)

Acronyms: Polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), Polyvinyl chloride (PVC), Polyethersulfone (PES), Polytetrafluoroethylene (PTFE), Perfluorohexanoic Acid (PFHxA), low density polyethylene (LDPE), high density polyethylene (HDPE), polylactic acid (PLA), polymethyl methacrylate (PMMA), perfluorooctane sulfonic acid (PFOS), perfluoroheptanoic acid (PFHpA), perfluoroctanoic acid (PFOA), side-chain fluorinated polymers (SFPs), Polyamide (PA), Perfluorooctanesulfonamide (PFOSA), Perfluoroalkyl carboxylic acids (PFCAs).

tetracycline and ciprofloxacin absorb MPs like polyamide (PA) through hydrogen bonding and porous structures, with environmental factors such as pH further refine these interactions (Elgarahy et al., 2021; Ninwiwek et al., 2019). This dual role of MPs as contaminants and vectors underscores their significant ecological impact and the need for effective mitigation measures. As discussed above, the sorption of these contaminants onto MPs is a very prevalent phenomenon, but it can be affected by numerous factors. Although several studies investigated this phenomenon, there is limited information available in real environments, indicating a need for further research due to its combined toxicity.

5. Interaction mechanisms of PFAS on MPs

Relevant studies examined not only the adsorption of PFASs on microplastics but also investigated the factors and mechanisms that affect PFAS sorption onto MPs. The various sorption mechanisms, such as electrostatic interactions, hydrophobic interactions, Van der Waals forces, hydrogen bonding, etc. frequently work together during the sorption process in addition to the physicochemical characteristics and types of microplastics and PFASs and environmental factors (P. Kang et al., 2023a; Mejías et al., 2022). Schematic representation of the interaction mechanisms of PFAS on MPs are shown in Fig. 6.

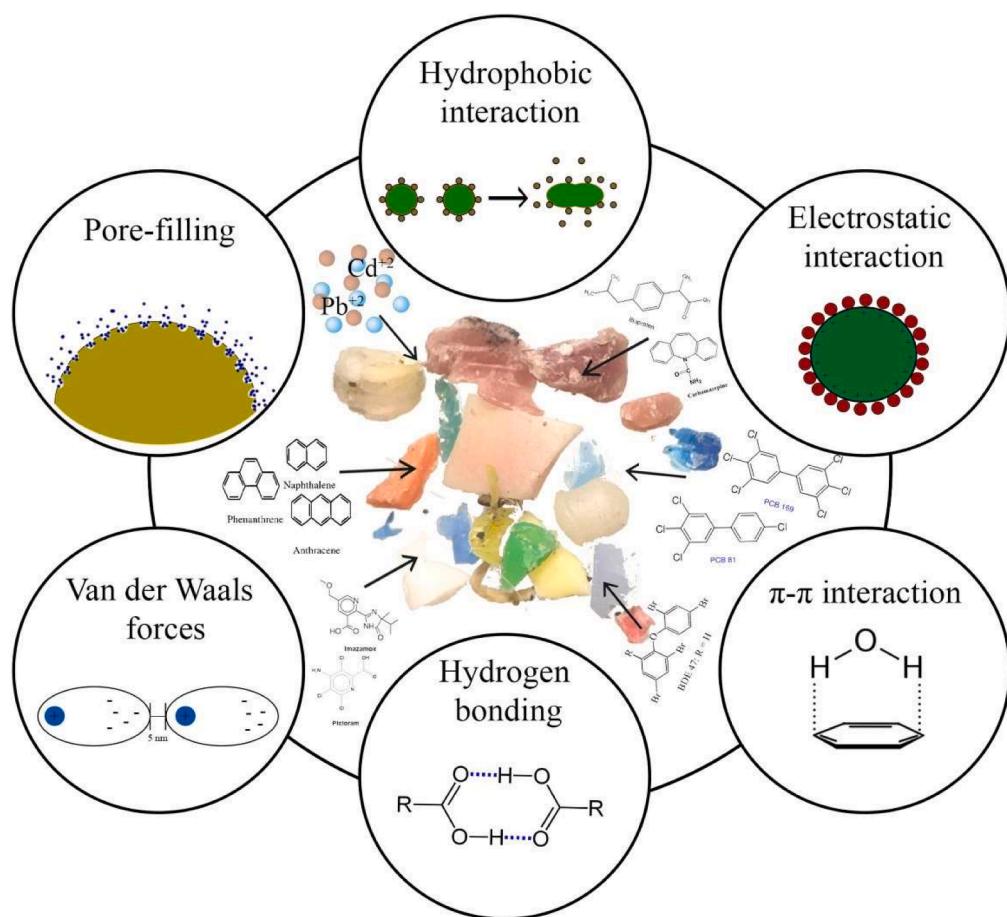


Fig. 6. Schematic representation of the interaction mechanisms of PFAS on microplastics. Reprinted from (Torres et al., 2021). Elsevier License Number: 5892850953332.

5.1. Electrostatic interaction

Electrostatic interaction is a process wherein PFASs and microplastics with opposing charges are typically adsorbed electrostatically, however, those with identical charges repel each other. The pH of the solution, distinct molecule structures, functional groups, and environmental factors can all affect the charge of the contaminant and their electrostatic interaction. The quantity of charged particles on the microplastics surface varies with pH, which influences electrostatic sorption. For instance, compared to PVC, PTFE, and PE MPs, polystyrene (PS) MPs had a greater adsorption ability for PFOA since MPs (PS) have a zeta potential (positive) within a pH range of 5 to 6 (Meng et al., 2023). Furthermore, ionic strength may also have an impact on electrostatic sorption. For example, F. Wang et al. (2015) investigated that the sorption capacity of PFOS on PE and PS was increased by adding higher concentrations of NaCl and CaCl₂ in the systems. However, the ionic strength was unaffected for PFOSA and PFOS adsorption on PVC as hydrophobicity influences in this process.

5.2. Hydrophobic interactions

Hydrophobic interactions are important adsorption mechanisms between MPs and PFAS, since most microplastics in the ecosystem are hydrophobic (Torres et al., 2021). The enhanced microplastics hydrophobicity increases adsorption capacity. For instance, the increased PFOSA adsorption on PE compared to PS and PVC is because PE is more hydrophobic than PVC and PS plastics (Min, 2020). Furthermore, the properties of PFASs are one of the many factors that can influence hydrophobic interaction. In general, the long-chain PFASs show a tendency for adsorption and greater hydrophobicity than short-chain PFASs (Llorca et al., 2018). Scott et al. (2021) investigated that the longer chain (PFOA) adsorbed more than the shorter chain (PFHx). Functional groups also influence hydrophobicity of PFASs in addition to the length of the chain. The sorption of PFASs with identical carbon chain lengths but varying functional groups onto microplastics has been demonstrated to increase in the following order: carboxylic groups, sulphonate groups, and sulphonamide groups (Llorca et al., 2018). For instance, a higher adsorption on MPs (PS) exhibited by sulphonamide groups (PFOSA) than those with carboxylate groups (PFOA), although both have same length of carbon chain (Llorca et al., 2018). Moreover, the hydrophobic properties of MPs generally reduce with aging. For instance, a study conducted by H. Yang et al. (2020) indicated a reduction in the hydrophobicity of PS, as the contact angle of water reduced from 127.75° to 99.81° after 9 days of exposure to Fenton's solution.

5.3. π - π interactions and van der Waals forces

Although hydrophobic and electrostatic interaction were identified predominant adsorption processes, Van der Waals forces, π - π interactions, Hydrogen bonding and Pore-filling mechanism could also have a substantial impact on the synergy between microplastics and PFAS. The synergy of MPs and PFAS is combined effect of many mechanisms including the influence of Van der Waals forces. However, the impact of van der Waals forces is insignificant due to low polarizability and small molecular sizes of PFASs. Most of the π - π interactions were found in aromatic compounds. PFASs and PS MPs with benzene rings may generate π - π interactions through π - π electron coupling (Dai et al., 2022). Cation π interactions primarily occur between aromatic and cationic molecules. MPs with benzene rings and cationic/zwitterionic PFASs have the potential to create cation- π linkages (Dai et al., 2022). Further comprehensive studies are required to understand the influence of π - π interactions and Van der Waals forces coupling of these processes, addressing the existing knowledge gaps in real-world scenarios while considering the complexities of natural ecosystems.

5.4. Hydrogen bonding

Hydrogen bonding between MPs and PFAS C-F chains is challenging due to their hydrophobic properties. Nevertheless, the carboxylate groups of PFAS established hydrogen bonds with the carboxyl group in the solute (X. Li et al., 2013). X. Wang et al. (2020c) investigated that, the oxygen-containing aged MPs groups formed hydrogen with carboxylate groups containing PFOA. Hence, aged MP exhibits a higher possibility of forming hydrogen bond due to the presence of oxygen containing groups compared to the pure particle. However, PFOS demonstrated a greater adsorption capacity on the amid group of polyamide microplastics compared to polyethylene and polypropylene, attributable to the formation of hydrogen bonds between hydrogen donor chemicals and polyamide microplastics (Endo et al., 2011).

5.5. Pore-filling adsorption

Pore-filling is an adsorption-like interaction between pollutants and microplastics within their nano and micropores (Q. Wang et al., 2020b). Hüffer and Hofmann (2016) found evidence of the pore filling adsorption mechanism in glassy microplastic polymers (PS, PVC, PA), a process similar to the adsorption mechanisms observed in materials like bentonite, where isomorphous substitution generates constant negative charges that enhance sorption efficiency (El-Korashy et al., 2016). The contaminant size and pore size of microplastics determine the diffusion rate from the surface of polymers to the pores. The molecular diffusion rate of contaminant decreases with the pore size of the microplastics (Atugoda et al., 2021). Scanning Electron Microscopy (SEM) analysis of microplastic particles conducted by Mejías et al. (2022) found that the surface pore of the plastic was filled with large amounts of PFAS. Furthermore, MPs and PFAS possible interaction mechanisms need to be explored vigorously to reduce this knowledge gap.

6. Trophic transfer of combined MPs and PFAS

The widespread use of plastics and PFASs has led to their unavoidable presence in the environment worldwide, with numerous reports highlighting that various water bodies, including oceans, are considered their ultimate sinks. MP occurrence and movement may have some impact on PFAS fate due to their coexistence in both organisms and environment. MP transportation also involves the combined transfer of PFASs that have been absorbed but remained unidentified. Hence, it is essential to investigate the trophic transfer of these contaminants due to their interaction, where knowledge remains inadequate.

The usual transportation media for MPs and PFASs include the water, soil, and air. MPs and PFASs have similar transportation patterns from different ecosystems to water and their co-existence significantly changes their individual trophic transfer and fate. The primary focus is on the trophic transfer of MPs within aquatic environments since MPs act as a carrier of contaminants due to their larger size compared to PFAS. The contamination of MPs and PFASs is directly correlated with the proximity of human activities and the density of the population since pollutants are generated from human daily life activities (Dai et al., 2022). The major contributor to human intake of MPs is air inhalation, which can cause serious health risks, including lung inflammation, cancer, and immune responses (Elgarahy et al., 2021). Although studies on the accumulation and air-water interaction of MPs and PFAS are very limited, further comprehensive research is needed to identify the extent of their potential toxicity in air (Y. Wang and Good, 2024). MPs in water and soil may come from atmospheric fallout and transfer. High density MPs tend to go inside of soil and enter deeper strata through a variety of mechanisms, including earthworm biological activity (Wu et al., 2019). However, low density MPs are more susceptible to surface runoff and wind before entering the water bodies (Zylstra, 2013). In addition to this, degradation of microplastics (MPs) in the environment is significantly influenced by their intrinsic properties, including density,

hydrophobicity, and susceptibility to hydrolysis (L. Liu et al., 2022a). High-density MPs tend to sink, leading to sediment accumulation, while low-density MPs remain buoyant, affecting their exposure to environmental degradation factors such as UV radiation and microbial activity (Van Melkebeke et al., 2020). Hydrophobic MPs interact differently with organic pollutants and biofilms, potentially altering their degradation pathways (Fu et al., 2021). Moreover, the chemical composition of MPs determines their hydrolyzation rates, with certain polymers being more prone to hydrolytic degradation under specific environmental conditions (Andrade, 2017). Hence, the identification of these MP properties is crucial to assess the ecological risks associated with MP pollution (Md. S. Islam et al., 2023). MPs and PFAS are transported to the oceans from developed areas through rivers and estuaries. Marine animals often ingest these contaminants, mistaking them for food, leading to gastrointestinal blockages and growth disruptions (Elgarahy et al., 2021).

MPs and PFAS are generated from terrestrial activities and released into the environment by sewage and freshwater system. These contaminants can accumulate in freshwater systems (estuaries, wetlands and lakes) due to their low flow velocity and stagnant condition. Microplastics typically float at the surface of the water and are transported through river due to strong currents (Schwarz et al., 2019). However, vertical movement instead of surface transport might take place in an instance of a weaker current of ocean. MP density is the major factor influencing the fate and transport of these contaminants as well as their adsorbed PFAS. Higher density MPs typically accumulate at higher water depths. For instance, the percentage of acrylics and polyesters reduced to 5% on the sea surface, while reaching up to 77% in the deep-water column of sea. Similarly, the abundance PP and PE were higher in water surface than in the deeper water column due to their low density (Erni-Cassola et al., 2019). However, low-density MPs with their adsorbed PFAS also tend to transfer vertically in water column because of their altered size and shape, aggregate formation and biofouling (Kane and Clare, 2019). For instance, high abundance of PE and PP were found in sediment, although water has a higher density than their density (Koelmans et al., 2017). Hence, sediment is considered the final sink for these contaminants instead of open water surface and water column. Although, these contaminants can easily float again from sediment due to ocean currents (Wu et al., 2019).

The adoption and trophic transfer of contaminants on microplastics is increased due to natural organic matter accumulation and biofilm formation on the surface. Compared to pure MPs, aged microplastics with natural organic matter can adsorb 20–85% more PFOS (Bhagwat et al., 2021). However, Bhagat et al. (2021) found that specific surface area of microplastics may reduce due to biofilm formation and negatively affect the sorption of PFAS on microplastics. The adsorbed PFOSA of MPs is transferred through microplastics and PFOSA half-life may be extended due to their interaction with MPs (Meng et al., 2023). Furthermore, a higher abundance of PFAS with long chain is typically found in sediment, whereas water predominantly holds short-chain variants of these contaminants.

PFASs are ubiquitous in aquatic environments, although MPs can only absorb a small portion of them. Other contaminants and biota except microplastics may also adsorb PFAS in the aquatic environment. Microplastic can also affect the trophic transfer of PFAS with other contaminants in addition to their combined movement in the aquatic system. In summary, the trophic transfer as well as adsorption of PFAS on microplastics or other contaminants in the real-world environment is more complicated due to various influencing factors and remain unrevealed. Therefore, comprehensive research is required to address the knowledge gap regarding the combined trophic transfer of these contaminants.

7. Combined toxicity of PFAS and MPs

PFASs and microplastics are increasingly detected in a diverse array of creatures across many trophic levels in ecosystems, including food

particles and zooplankton (Stapleton et al., 2023). The specific characteristics and distribution of these contaminants affect trophic transfer and bioavailability in aquatic environments. For instance, it is evident that fish have substantially varied MP or PFAS distributions and locations. MPs were primarily concentrated in fish intestines and gills, whereas PFASs were found in fish muscle, reproductive organs, liver, and blood, although both PFASs and MPs have combined toxicity consequences. The size, shape, color, polymer toxicity and dose of microplastics significantly influence their potential toxicity. For instance, Hermabessiere et al. (2017) demonstrated that due to their tiny size and widespread distribution, MPs are consumed by aquatic species such as fish, worms, and zooplankton, along with the organic pollutants they have adsorbed, and sharp microplastics can harm their intestines or gills (Saud et al., 2023). Besides, PFAS released into the environment exhibit minimal decomposition and remain persistent in both aquatic and terrestrial ecosystems. Shi et al. (2018) found that the existence of functional groups and chain lengths significantly impacted distribution, accumulation and toxicity of PFAS. For example, N. Wang et al. (2023) explored that PFAS with short chain are less toxic than long-chain PFAS.

MPs or PFASs have quite varied distribution and harmful effects. MPs and PFASs can cause combined toxicity, including harmful effects on growth, organs, tissues, the nervous system, and the immune system. Compared to PFASs, MPs have distinct effects on the intestinal microbial community and digestive system, while PFAS exposure primarily affects the reproductive system and sex ratio (Fig. 7). Thus, it is speculated that the combined toxicity of PFAS and MPs is more severe than exposure to PFAS and MPs alone. Most of the investigations found that the combined toxicity of PFASs and microplastics on aquatic species are higher than exposure alone, although there are a few studies that investigated the combined toxicity (Chen et al., 2020). Rainieri et al. (2018) revealed that zebrafish homeostasis was considerably impacted due to combined exposure to MPs and PFAS, while the consumption of MPs alone by themselves did not have any impact.

Some fish are useful model organisms for investigating different illnesses because of physiological, anatomical, and genetic similarities to humans (Angom and Nakka, 2024). Hence, various studies have been conducted on fish species for preliminary understanding of the impact of emerging contaminants on the human body. A study on freshwater fish revealed that coexistence of PS microplastic and PFOA at the level of genes can increase the carcinogenicity of Persistent Organic Pollutants (POPs) (S. Liu et al., 2022b). The toxicity of various fish species in the presence of PFOS and PE microplastic was investigated by different researchers. According to the study conducted by Le Bihanic et al. (2020), consuming PFOS combined with MPs had effects that were either lower than or identical to those of PFOS or MPs alone. The studies conducted on zebrafish and medaka fish found that co-exposure to pollutants decreased the fish bioaccumulation, oxidative stress and bioavailability in comparison with separate exposure, although the mechanism was different (Le Bihanic et al., 2020; H. Yang et al., 2020). Energy availability may be decreased by the subsequent intestinal obstruction and the reduced action of digestive enzymes in zebrafish and yellow croaker due to the ingestion of contaminants (Gu et al., 2020).

The toxicity in aquatic plants, algae, and shellfish due to co-exposure to MPs and PFAS has been investigated by only a few researchers. Studies conducted by Islam et al. (2021) revealed that the accumulation of PFAS and microplastics onto shellfish was dependent to MP size and simultaneously developed neurotoxicity. Moreover, exposure to PFOA and PVC raised the synthesis of microcystin-LR (MC-LR), decreased the growth of algae, and posed an adverse impact on Malondialdehyde (MDA) content and Catalase (CAT) activity (W. Zhang et al., 2023b). PFOA and PS can adsorb on to algal cells inducing shade and prevent photosynthesis, which can result in cytotoxicity (Zhao et al., 2023). Furthermore, through modeling, the potential risks posed by MPs and PFAS to humans have also been examined, in addition to their toxicity to aquatic species. The molecular modeling showed that PFAS with various plastic additives may affect the reproductive system of women and the

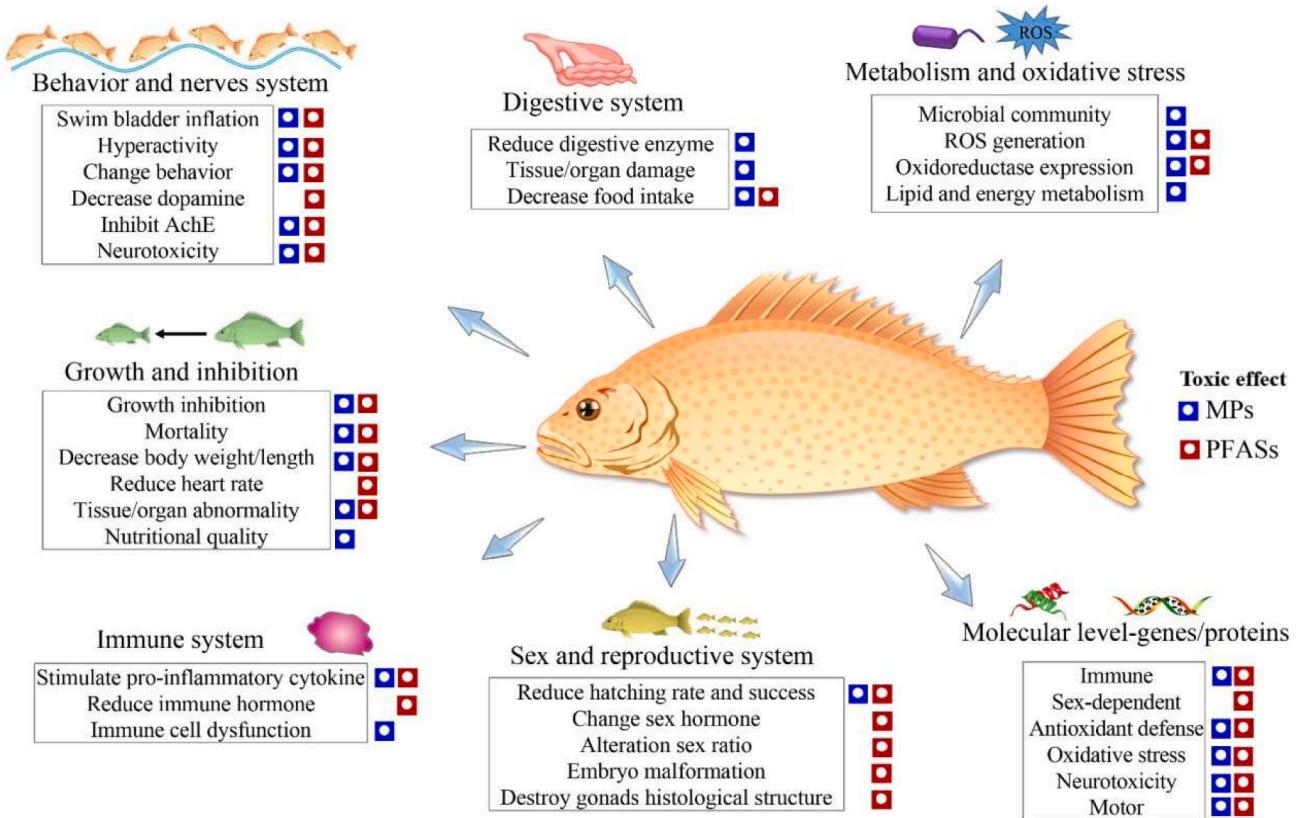


Fig. 7. Combined toxicity of PFASs and microplastics to fish. Reprinted from Dai et al. (2022).

presence of PFAS and MPs in breast milk might be detrimental to babies who are breastfed (Du et al., 2023; Enyoh et al., 2023). In summary, only a few studies have explored the combined toxicity of microplastics and PFAS. Therefore, further comprehensive investigation is essential to unravel the numerous interaction mechanisms between these emerging contaminants and to understand their combined effects on aquatic species as well as humans.

8. Research gaps and future research perspectives

The presence of microplastics and PFAS in the ecosystem has emerged as a critical worldwide concern. There is a deep emphasis on the need to understand their interactions within aquatic systems to safeguard ecological and public health. The review of existing literature reveals several knowledge gaps in current research and potential areas that require further exploration. The development of standardized protocols is required to ensure consistency, reproducibility, and comparability in the study of MPs and PFAS synergy in complex matrices. Sampling methods should address contamination risks and consider diverse environmental matrices, including water, soil, and biota. Rigorous extraction procedures, such as density separation for MPs and solid-phase extraction for PFAS, should be established to maintain the integrity of these contaminants during analysis. Analytical techniques such as Fourier-transform infrared (FTIR) and Raman spectroscopy for MPs, and liquid chromatography-mass spectrometry (LC-MS/MS) for PFAS, require optimization for higher sensitivity and precision, especially when addressing their coexistence in environmental matrices. Emerging technologies like pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS) can be used for integrated analysis.

There are limitations in current detection and analytical methods due to a lack of standardized and universally accepted methods for MPs and PFAS in complex matrices. Significant challenges of current methodologies include differentiating MPs from organic materials and

identifying PFAS at low concentrations. Matrix effects, such as the presence of salinity and organic matter further complicate detection accuracy and impact the effectiveness of remediation strategies, requiring site-specific adaptations for real-world applications. Moreover, inconsistencies in particle size classification, polymer identification, and PFAS quantification across various studies hinder data comparability and analysis. Additionally, inconsistent regulations, policies, and the lack of standardized monitoring protocol hinder comprehensive remediation efforts.

To address these challenges requires not only standardized protocols but also the development of innovative and advanced techniques to overcome matrix interferences. Collaborative efforts among researchers, policymakers, and industry stakeholders are crucial to develop standardized methodologies by incorporating advanced technologies into routine analyses. This comprehensive effort may enable a consistent understanding of MPs-PFAS interactions and their implications for ecosystem health and remediation strategies. Although some studies have explored the synergy between PFAS and MPs and their combined negative impacts, still many aspects remain insufficiently understood. Further exploration is needed to identify their interaction mechanisms, factors influencing these interactions, co-existence in complex environmental compartment, impact on trophic levels, adverse outcome pathways, and combined removal strategies. The following sections outline the key research gaps and future directions:

- More emphasis should be placed on investigating the dynamics between MPs and PFAS in sediments and soil, along with their impact on terrestrial systems. Terrestrial organisms may experience increased exposure to these contaminants due to prolonged and higher exposure of MPs and PFAS.
- Incorporation of environmental factors such as temperature, pH, competitive sorption, and biofilm formation to better simulate real

- world conditions and provide more accurate assessment of the combined effects of MPs and PFASs.
- Development of consistent methods to better understand MPs-PFAS interactions when nano-plastics are present in the matrix including their transport, dispersion and biological interactions.
 - More studies need to explore the neurotoxic, histopathological, behavioral and transgenerational impacts of combined toxicity effects, especially terrestrial ecosystems.
 - Comprehensive investigations are required to develop combined treatment techniques for effectively eliminating MPs and PFAS from the environment.

9. Conclusion

This review is a consolidation of current knowledge on the co-existence, interactions, and combined effects of microplastics and PFAS across different ecosystems, emphasizing key mechanisms and influencing factors. The majority of studies conducted around the globe have explored adsorption mechanisms such as hydrophobic and electrostatic interactions as well as the emerging role of surface complexation. However, much of the research is focused on aquatic systems, leaving terrestrial food chains and alternate types of PFAS underexplored. The interactions, distribution, and toxicity of microplastics and PFAS are significantly influenced by their physiochemical properties and environmental parameters like organic matter, pH, and salinity. The combined effects of MPs and PFAS show varied outcomes, including DNA damage, neurotoxicity, oxidative stress, immune responses, gut microbial changes, and behavioral changes in organisms. Still, further research is necessary to illuminate the combined impact of MPs-PFAS on trophic levels, adsorption processes, and adverse outcome pathways in complex environmental matrices. Even though wastewater treatment plants (WWTPs) can remove some MPs, smaller particles and PFAS often pass through, entering water bodies and threatening aquatic life. The combined toxicity of MPs and PFAS remains poorly understood, as studies have reported inconsistent effects. Considering the coexistence and cumulative impact of these pollutants, advancing co-removal technologies is essential for effective mitigation. Finally, source control, involving collaboration among governments, industry stakeholders, and the public, is crucial to reduce the existence of Microplastics and PFAS in the environmental system.

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

Data availability

Data will be made available on request.

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