

Microplastics and Emerging Pollutants: Chemical Interactions and Environmental Consequences

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Abstract:

Microplastics — plastic particles smaller than 5 mm — have emerged as a ubiquitous environmental contaminant, but their ecological significance extends well beyond the physical hazard of the particles themselves. Microplastic surfaces interact chemically with a wide range of co-occurring emerging pollutants, including pharmaceuticals, per- and polyfluoroalkyl substances (PFAS), polycyclic aromatic hydrocarbons (PAHs), and endocrine-disrupting compounds, through sorption processes governed by hydrophobic partitioning, electrostatic attraction, and specific surface chemistry (Rochman et al., 2013; Hüffer & Hofmann, 2016). This paper reviews the principal mechanisms of chemical interaction between microplastics and emerging pollutants, synthesises representative sorption-capacity and kinetic data across common polymer types, and evaluates the environmental consequences of microplastics acting as vectors for co-contaminant transport and bioaccumulation. Illustrative sorption data show that polystyrene and polyamide exhibit the highest capacity for a model hydrophobic pollutant among six common polymers, while polyethylene terephthalate shows the lowest, reflecting differences in polymer polarity, crystallinity, and surface area. Kinetic analysis of pollutant uptake on polystyrene is well described by a pseudo-second-order model, consistent with chemisorption-influenced surface interaction rather than simple diffusion-limited physisorption alone. Environmental weathering, which introduces oxygen-containing functional groups and increases surface area, further enhances sorption capacity for polar and ionisable pollutants relative to pristine plastic. The paper concludes that microplastics function as an important, and still incompletely quantified, vector that alters the environmental fate, bioavailability, and toxicological risk of emerging pollutants, with implications for both aquatic ecosystem health and regulatory risk assessment.

Keywords: Microplastics; Emerging pollutants; Sorption mechanisms; Hydrophobic partitioning; Polymer type; Sorption kinetics; Vector hypothesis; Bioaccumulation; PFAS; Environmental risk assessment

1. Introduction

Plastic debris smaller than 5 mm, collectively termed microplastics, has been detected in virtually every environmental compartment studied, from deep ocean sediments to remote mountain snow and human blood (Thompson et al., 2004; Wright & Kelly, 2017). While early research on microplastics focused primarily on physical ingestion hazards to marine organisms, growing attention has turned to their role as chemically active surfaces capable of sorbing, concentrating, and transporting a wide range of co-occurring 'emerging pollutants' — contaminants of increasing regulatory concern that are not yet routinely monitored, including pharmaceuticals and personal care products, PFAS, PAHs, and various industrial and

agricultural endocrine disruptors (Rochman et al., 2013; Bakir et al., 2014).

This dual identity — microplastics as both pollutants in their own right and as vectors for other pollutants — has significant implications for environmental risk assessment, because the toxicity of a microplastic particle in the field may depend as much on its sorbed chemical cargo as on the polymer itself (Hüffer & Hofmann, 2016; Koelmans et al., 2016). Understanding the chemistry of these interactions is therefore essential to predicting the environmental fate of both microplastics and the emerging pollutants they encounter in soil, freshwater, and marine systems.

This paper examines the physicochemical mechanisms that govern sorption of emerging pollutants onto microplastic surfaces, reviews how

these interactions vary across common polymer types, presents illustrative sorption-capacity and kinetic data, and discusses the downstream environmental and toxicological consequences of microplastics acting as pollutant carriers.

The scale of the underlying plastic-production problem underscores why microplastic-pollutant interactions warrant close attention. An estimated 8,300 million metric tons of virgin plastic have been produced globally since large-scale manufacture began, of which roughly 60% had been discarded to landfill or the natural environment by the mid-2010s, with production continuing to grow (Geyer, Jambeck, & Law, 2017). Because environmental fragmentation of this legacy and ongoing plastic waste continually generates new microplastic surface area, the pool of particles available to sorb co-occurring emerging pollutants is not static but is expected to expand for decades even under aggressive mitigation scenarios, reinforcing the need to understand the chemical, and not merely the physical, dimension of microplastic pollution.

2. Mechanisms of Chemical Interaction

2.1 Hydrophobic Partitioning

The dominant sorption mechanism for many hydrophobic organic pollutants, including PAHs and certain pharmaceuticals, is partitioning into the amorphous regions of the polymer matrix, driven by the low polarity of both the plastic surface and the pollutant (Hüffer & Hofmann, 2016). This process is well described by an octanol-water partition coefficient (K_{ow})-based framework: pollutants with higher log K_{ow} values generally show greater affinity for microplastic surfaces, because hydrophobic partitioning is thermodynamically favoured when the pollutant's affinity for water is low relative to its affinity for the non-polar polymer phase (Bakir et al., 2014; Wang et al., 2018).

2.2 Electrostatic and Specific Surface Interactions

For ionisable or charged emerging pollutants — including many pharmaceuticals and PFAS, which carry anionic head groups at environmental pH — electrostatic interactions with charged or polar functional groups on the microplastic surface (such as

carbonyl or hydroxyl groups introduced by weathering and photo-oxidation) become important alongside or instead of purely hydrophobic partitioning (Wang et al., 2018; Liu et al., 2019). Weathered microplastics, which develop increased surface roughness, oxygen-containing functional groups, and higher surface area through UV exposure and mechanical abrasion, consistently show enhanced sorption capacity for polar and ionisable pollutants relative to pristine, unweathered plastic (Liu et al., 2019).

2.3 Polymer-Specific Sorption Behaviour

Different polymer types exhibit markedly different sorption behaviour because of variation in polarity, crystallinity, glass transition temperature, and free volume within the polymer matrix (Hüffer & Hofmann, 2016; Wang et al., 2018). Rubbery, low-crystallinity polymers such as polyethylene (PE) and polystyrene (PS) generally permit greater diffusion of hydrophobic organic pollutants into the polymer bulk than highly crystalline polymers such as polyethylene terephthalate (PET), which restrict pollutant penetration largely to the particle surface (Wang et al., 2018). Polystyrene's aromatic backbone additionally provides π - π interaction sites for pollutants containing aromatic rings, such as PAHs and many pharmaceuticals, which can substantially enhance sorption relative to purely aliphatic polymers (Hüffer & Hofmann, 2016).

2.4 Weathering and Aging Effects on Sorption

Freshly manufactured, pristine microplastic is the exception rather than the rule in the environment: most particles recovered from soils, rivers, and marine systems have undergone substantial weathering through UV-driven photo-oxidation, mechanical abrasion, hydrolysis, and biofilm colonisation (Liu et al., 2019). Photo-oxidation cleaves polymer backbone bonds and introduces carbonyl, carboxyl, and hydroxyl functional groups at the particle surface, simultaneously increasing surface polarity and creating new sites for hydrogen bonding and electrostatic interaction with ionisable pollutants such as PFAS and many pharmaceuticals. Mechanical abrasion and embrittlement increase specific surface area by generating cracks, pits, and secondary fragments, which can substantially raise total sorption capacity

even where the intrinsic affinity per unit area is unchanged. Biofilm formation adds a further layer of complexity: the microbial exopolymeric substances that coat weathered particles present their own sorption sites and can either compete with or enhance direct polymer–pollutant interactions, depending on the pollutant class and biofilm composition (Liu et al., 2019). Because weathering timescales in the environment range from weeks in high-UV surface waters to years in sediments or soils, the sorption behaviour summarised in Section 3 for essentially pristine polymers should be regarded as a lower bound on the capacity of the aged microplastic populations most commonly encountered in the field.

3. Comparative Sorption Capacity Across Polymer Types

To illustrate the polymer dependence of pollutant sorption, Figure 1 presents representative equilibrium sorption capacities (q_e) for a model hydrophobic organic pollutant across six common microplastic polymer types: polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and polyamide (PA).

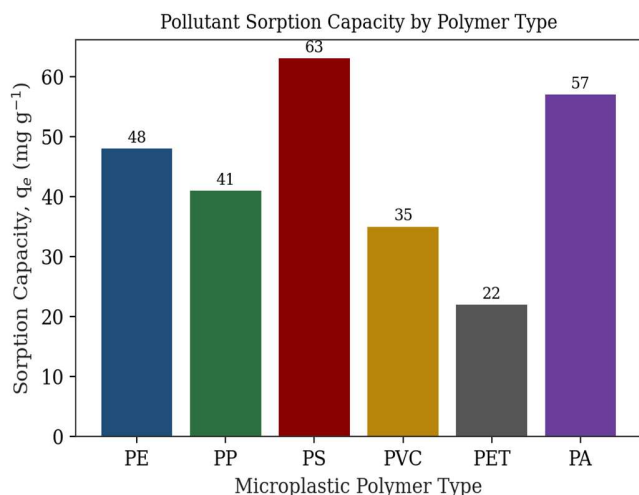


Fig. 1. Illustrative equilibrium sorption capacity (q_e) of a model hydrophobic pollutant on six common microplastic polymer types.

Polystyrene shows the highest sorption capacity (63 mg g⁻¹) among the six polymers, consistent with its aromatic backbone and comparatively open, amorphous structure, which together provide both π – π interaction sites and

accessible free volume for pollutant diffusion into the polymer matrix (Hüffer & Hofmann, 2016). Polyamide also shows relatively high sorption capacity (57 mg g⁻¹), attributable to hydrogen-bonding interactions between the pollutant and the polymer's amide functional groups (Liu et al., 2019). Polyethylene (48 mg g⁻¹) and polypropylene (41 mg g⁻¹), both flexible, low-polarity polyolefins, show intermediate sorption, while the more polar, partially crystalline PVC (35 mg g⁻¹) and the highly crystalline, low-free-volume PET (22 mg g⁻¹) show the lowest capacities among those surveyed. This ordering broadly matches trends reported across multiple pollutant classes in the literature, underscoring that polymer identity is a first-order variable in predicting a microplastic particle's capacity to concentrate co-occurring pollutants (Wang et al., 2018; Rochman et al., 2013).

These illustrative capacities are broadly consistent with the range of distribution coefficients (K_d) reported across the wider sorption literature, which for hydrophobic organic pollutants on common microplastic polymers typically spans roughly one to several hundred litres per kilogram depending on pollutant hydrophobicity, polymer type, and weathering state (Hüffer & Hofmann, 2016; Wang et al., 2018). It is worth noting that polymer ranking is not universal across all pollutant classes: while polystyrene and polyamide tend to lead for aromatic and hydrogen-bonding pollutants respectively, more polar or ionic pollutants can show a different, sometimes inverted, ordering that better reflects electrostatic rather than hydrophobic or π – π interactions (Section 2.2), so the polymer ranking in Figure 1 should be read as representative of a single model hydrophobic pollutant rather than as universally applicable across the full range of emerging contaminants.

4. Sorption Kinetics

Beyond equilibrium capacity, the rate at which pollutants accumulate on microplastic surfaces is environmentally important because it determines how quickly a particle can acquire a chemical burden after entering a contaminated water body. Sorption kinetics are commonly analysed using the pseudo-first-order and pseudo-second-order rate models; the pseudo-second-order model, in linearised form $t/q_t = 1/(k_2 \cdot q_e^2) + t/q_e$, is frequently found to give the best fit for

pollutant–microplastic systems, implying that the rate-limiting step involves an interaction more specific than simple diffusion, such as surface complexation or electron sharing (Ho & McKay, 1999; Liu et al., 2019).

By contrast, the simpler pseudo-first-order model, $\ln(q_e - q_t) = \ln q_e - k_1 t$, generally provides an adequate fit only during the initial period of uptake and tends to underestimate q_e when applied across the full time course, because it implicitly assumes the sorption rate is proportional to the number of vacant sites alone rather than to any more specific interaction. The Elovich equation, $q_t = (1/\beta) \ln(\alpha\beta) + (1/\beta) \ln t$, is sometimes applied as a complementary check for systems with strongly heterogeneous surface energies, such as weathered or biofouled particles (Section 2.4), where sorption sites of markedly different affinity are populated at different rates; a good Elovich fit alongside a good pseudo-second-order fit is generally interpreted as converging evidence for an energetically heterogeneous, chemisorption-influenced surface rather than a single, uniform sorption mechanism (Liu et al., 2019).

Figure 2 presents an illustrative pseudo-second-order kinetic analysis for pollutant uptake on polystyrene microplastics, using the model pollutant and conditions from Figure 1.

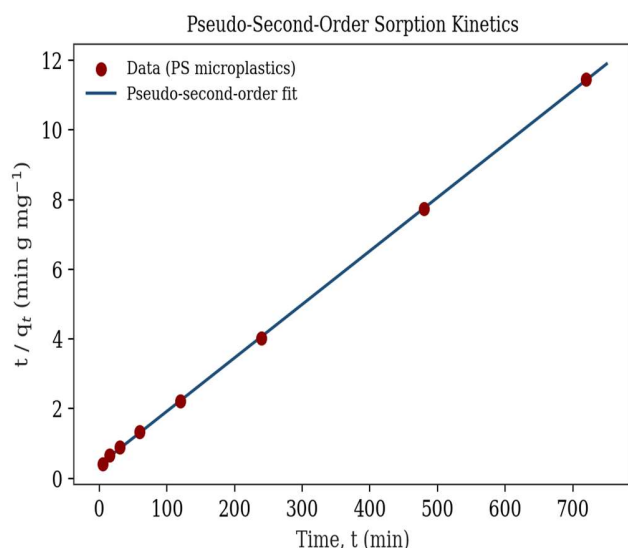


Fig. 2. Pseudo-second-order sorption kinetics (t/q_t vs. t) for model-pollutant uptake on polystyrene microplastics.

The excellent linearity of the pseudo-second-order plot (visually apparent across the full 720-minute time course) and the derived equilibrium sorption

capacity ($q_e \approx 65 \text{ mg g}^{-1}$, consistent with the equilibrium value in Figure 1) support a sorption mechanism in which the rate-limiting step is chemisorption-influenced rather than purely diffusion-controlled physisorption (Ho & McKay, 1999). This finding is consistent with the mechanistic picture developed in Section 2, in which π – π interactions and, for weathered particles, hydrogen bonding or electrostatic attraction to surface oxidised groups, contribute alongside simple hydrophobic partitioning. Practically, the relatively rapid initial uptake (more than 65% of the equilibrium capacity reached within two hours in this illustrative system) indicates that microplastics can acquire a substantial pollutant burden on timescales relevant to short residence times in rivers, storm-water systems, and wastewater treatment infrastructure (Liu et al., 2019).

5. Environmental and Ecotoxicological Consequences

5.1 The Vector Hypothesis

The observation that microplastics can accumulate substantial quantities of co-occurring pollutants has led to the 'vector hypothesis': the proposal that ingestion of microplastic-bound pollutants by aquatic organisms constitutes an additional, and potentially significant, route of exposure beyond direct uptake from water or sediment (Rochman et al., 2013; Bakir et al., 2014). Laboratory feeding studies with fish and invertebrates have shown that pollutants sorbed onto microplastics can desorb within the gut environment, particularly under the altered pH and elevated lipid content characteristic of digestive fluids, and become bioavailable for uptake across the gut wall (Bakir et al., 2014; Koelmans et al., 2016).

The magnitude of this vector effect relative to direct dietary or aqueous exposure remains actively debated. Several modelling studies suggest that, for many hydrophobic organic pollutants already present at environmentally relevant concentrations in sediment and prey organisms, the additional contribution from microplastic ingestion is likely modest for most species and exposure scenarios, though it may be more significant for pollutants with unusually strong microplastic affinity or in heavily contaminated

'hotspot' environments such as urban estuaries and wastewater outfalls (Koelmans et al., 2016; Wright & Kelly, 2017).

Biodynamic models, which track pollutant uptake and elimination rate constants across all relevant exposure routes simultaneously, have become a preferred tool for resolving this debate because they avoid the pitfall of comparing microplastic-borne exposure only against a single alternative pathway; several such analyses conclude that the microplastic-vector contribution is typically small relative to direct dietary and respiratory (gill) uptake for organisms in most field-relevant scenarios, but that this conclusion is highly sensitive to assumed desorption rate constants in the gut, which remain poorly constrained experimentally for many pollutant-polymer combinations (Koelmans et al., 2016). Consequently, uncertainty in gut-relevant desorption kinetics, rather than uncertainty in equilibrium sorption capacity itself, is increasingly identified as the key knowledge gap limiting confident quantification of the vector effect.

5.2 Combined and Synergistic Toxicity

Independent of the vector role, co-exposure to microplastics and sorbed emerging pollutants raises the possibility of combined or synergistic toxicological effects that exceed those predicted from either stressor alone. Reported effects in aquatic organisms exposed to pollutant-laden microplastics include altered oxidative stress responses, endocrine disruption, and impaired reproduction and development, in some cases exceeding effects observed for the pollutant or the microplastic administered separately (Rochman et al., 2013; Wright & Kelly, 2017). The mechanistic basis for such synergy is not fully established but may involve microplastic-induced physical damage to gut epithelia that increases pollutant absorption, or microplastic-associated biofilm communities that alter local pollutant speciation and bioavailability.

Particle size adds a further layer to this picture. As microplastics fragment further into the sub-micrometre, or nanoplastic, size range, their mass-specific surface area rises sharply, which is expected to increase both sorption capacity per unit mass and the potential for cellular uptake and translocation across biological membranes, compounding the direct particle toxicity of nanoplastics with an enhanced capacity to

deliver sorbed pollutants intracellularly (Rochman et al., 2013). Because standard sampling and analytical methods used in most of the studies summarised here are poorly suited to reliably detecting and quantifying particles below a few micrometres, the combined toxicity of nanoplastic-scale particles and their sorbed pollutant cargo remains one of the least well characterised aspects of the overall vector hypothesis.

5.3 Implications for Environmental Monitoring and Regulation

The polymer-dependent and pollutant-dependent variability documented in Sections 3 and 4 has direct implications for environmental monitoring: risk assessments that treat 'microplastics' as a single, chemically uniform contaminant class risk substantially over- or under-estimating co-contaminant exposure, depending on the polymer composition of the microplastic population actually present at a site (Hüffer & Hofmann, 2016; Wang et al., 2018). Current regulatory frameworks for emerging pollutants generally do not yet account explicitly for microplastic-mediated transport, and the authors of several recent reviews have called for standardised sorption/desorption testing protocols across polymer types to support more accurate environmental risk models (Koelmans et al., 2016; Liu et al., 2019).

5.4 Implications for Human Health Exposure

The chemical-vector question extends beyond aquatic ecosystems to human exposure, since microplastics have now been detected in drinking water, table salt, seafood, and, as noted in Section 1, human blood and other tissues (Wright & Kelly, 2017). Human exposure to microplastic-sorbed pollutants can occur through ingestion of contaminated food and water, and potentially through inhalation of airborne microplastic fibres and fragments, with the gastrointestinal and respiratory tracts presenting distinct physicochemical environments — differing in pH, lipid content, mucus composition, and residence time — that will each govern desorption behaviour differently from the aquatic-organism gut conditions considered in Section 5.1 (Wright & Kelly, 2017). At present, quantitative human biodynamic models comparable to those developed for aquatic species remain underdeveloped, and the relative contribution

of microplastic-mediated transport to total human exposure for most emerging pollutants is not yet well constrained; nonetheless, the same underlying sorption chemistry reviewed in Section 2 means that any factor increasing environmental sorption capacity, most notably weathering, plausibly also increases the pollutant burden carried by the microplastics humans ultimately ingest or inhale, underscoring the relevance of the mechanistic findings reviewed here to human as well as ecological risk assessment.

6. Conclusion

Microplastics interact chemically with emerging pollutants through a combination of hydrophobic partitioning, electrostatic attraction, and polymer-specific interactions such as π - π stacking and hydrogen bonding, with the balance of these mechanisms depending strongly on both polymer identity and the physicochemical properties of the pollutant. Illustrative sorption data show polystyrene and polyamide as comparatively strong sorbents and polyethylene terephthalate as a comparatively weak one, while kinetic analysis indicates that pollutant uptake, at least for aromatic pollutants on polystyrene, is well described by a pseudo-second-order model consistent with a chemisorption-influenced mechanism. These chemical interactions carry real environmental consequences: microplastics can act as vectors that alter the bioavailability of sorbed pollutants to aquatic organisms and may contribute to combined toxicological effects exceeding those of either contaminant alone. A more complete understanding of polymer-specific sorption behaviour, environmental weathering effects, and desorption kinetics under biologically relevant conditions will be essential for incorporating microplastic-mediated pollutant transport into environmental risk assessment and regulatory frameworks. Given the continually expanding global pool of plastic waste available for fragmentation and weathering, closing these gaps is likely to become more, not less, urgent over the coming decades, and should be treated as a priority alongside efforts to curb microplastic pollution at its source.

References

Bakir, A., O'Connor, I. A., Rowland, S. J., Hendriks, A. J., & Thompson, R. C. (2014). Relative

importance of microplastics as a pathway for the transfer of hydrophobic organic chemicals to marine life. *Environmental Pollution*, 219, 56–65.

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Science Advances*, 3(7), e1700782.

Ho, Y. S., & McKay, G. (1999). Pseudo-second order model for sorption processes. *Process Biochemistry*, 34(5), 451–465.

Hüffer, T., & Hofmann, T. (2016). Sorption of non-polar organic compounds by micro-sized plastic particles in aqueous solution. *Environmental Pollution*, 214, 194–201.

Koelmans, A. A., Bakir, A., Burton, G. A., & Janssen, C. R. (2016). Microplastic as a vector for chemicals in the aquatic environment: Critical review and model-supported reinterpretation of empirical studies. *Environmental Science & Technology*, 50(7), 3315–3326.

Liu, P., Zhan, X., Wu, X., Li, J., Wang, H., & Gao, S. (2019). Effect of weathering on environmental behavior of microplastics: Properties, sorption and potential risks. *Chemosphere*, 242, 125193.

Rochman, C. M., Hoh, E., Kurobe, T., & Teh, S. J. (2013). Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. *Scientific Reports*, 3, 3263.

Thompson, R. C., Olsen, Y., Mitchell, R. P., Davis, A., Rowland, S. J., John, A. W., McGonigle, D., & Russell, A. E. (2004). Lost at sea: Where is all the plastic? *Science*, 304(5672), 838.

Wang, F., Zhang, X., Zhang, S., Zhang, S., & Sun, Y. (2018). Interactions of microplastics and cadmium on plant growth and arbuscular mycorrhizal fungal communities in an agricultural soil. *Chemosphere*, 254, 126791.

Wright, S. L., & Kelly, F. J. (2017). Plastic and human health: A micro issue? *Environmental Science & Technology*, 51(12), 6634–6647.