

Heavy metal adsorption by pristine and aged microplastics: A focused evidence synthesis

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Abstract. This focused evidence synthesis comparatively examined how aging alters heavy-metal adsorption by pristine and aged microplastic based on quantitative results reported in published studies. Across the selected evidence base, aging generally increased the adsorption capacities of polypropylene, polyethylene, polystyrene, and poly(butylene adipate-co-terephthalate), although the extent of enhancement varies with polymer type, metal species, and aging conditions. For example, the adsorption capacities of aged polyethylene for Pb and Cu showed a significantly increased, rising from 1.913 to 5.807 mg/g and from 1.960 to 4.299 mg/g, respectively, whereas UV-aged polypropylene and polystyrene also exhibited consistent enhancement. Evidence from ultraviolet aging in different media shows that the enhancement ratio followed air > seawater > pure water for multiple metals, indicating strong pathway dependence. The enhanced adsorption of aged microplastics was mainly associated with the formation of oxygen-containing functional groups, larger specific surface area, greater surface roughness, and altered hydrophilicity. These findings suggest that environmentally aged microplastics should be explicitly considered when assessing heavy-metal ecological risk.

1 Introduction

Microplastics (MPs) have been widely detected in freshwater, estuarine, marine, and terrestrial environments^[1-3]. They are widely recognized as persistent carriers of coexisting contaminants in aquatic and terrestrial environments, thereby affect the transport and exposure of coexisting chemicals. MPs can serve as mobile sorbents and transport vectors for heavy metals (HMs) in aquatic and terrestrial environments. Their surfaces provide adsorption sites through electrostatic attraction, surface complexation, pore-filling and, in some cases, cation- π or donor-acceptor interactions. HMs such as Pb, Cd, Cu, Cr, Zn, Ni, Mn, and As are among the most concerning co-contaminants because they are persistent and toxic^[4]. HMs adsorbed onto MPs can alter their mobility, bioavailability, and toxicological pathways, thereby complicating environmental risk assessment and pollution control.

One of the central questions in current research is whether MPs function as effective vectors for HMs under environmentally realistic conditions. The answer depends not only on the polymer identity, particle size, surface chemistry, metal speciation, and solution conditions, but also on how strongly the particles have aged^[5]. During environmental exposure, MPs undergo processes such as ultraviolet (UV) irradiation, oxidation, hydrolysis, mechanical abrasion, and environmental weathering.

These processes can introduce oxygen-containing functional groups, alter surface charge, increase roughness and specific surface area, and may ultimately enhance HMs adsorption capacity^[6, 7].

Recent studies have advanced from qualitative observation to quantitative analysis using meta-analysis, machine learning, field exposure experiments, and mechanistic adsorption studies^[8, 9]. However, the literature remains heterogeneous in terms of particle sources, aging pathways, and metals. A synthesis that integrates mechanistic experiments and field evidence is therefore needed to elucidate how aging MPs modifies HMs adsorption behavior and its implications for environmental risk.

Accordingly, this study aims to comparatively evaluate HMs adsorption by pristine and aged MPs. Specifically, it seeks to elucidate the specific adsorption characteristics of HMs on MPs, compare the adsorption behaviors of pristine and aged particles, and examine the adsorption effects of MPs aged in different media. The findings are expected to advance the understanding of aging-induced changes in adsorption behavior and their implications for HMs transport and ecological risk.

2 Materials and Methods

This study was designed as a focused evidence synthesis rather than a formal systematic review or full meta-analysis. The literature basis was established from the SCI

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papers compiled for this study and screened against publications indexed in major journal databases, including Web of Science and Scopus. Search terms used during screening included combinations of "microplastic", "aged microplastic", and "heavy metal", and the names of representative metals such as Pb, Cu, Cd, and Zn.

Studies were retained for the core comparison when they (i) examined the adsorption of HMs by pristine and/or aged MPs, (ii) reported directly comparable quantitative adsorption data or explicit aging-related adsorption trends, and (iii) clearly described the polymer type, metal species, and aging condition. During the literature screening process, priority was given to studies that directly compared the adsorption capacity of pristine versus aged MPs or explicitly quantified the enhancing effect of the aging process on adsorption capacity.

This study integrates and analyzes data across five dimensions: polymer type, HM species, aging pathway, environmental medium, and adsorption response. Adsorption response metrics primarily encompass maximum adsorption capacity, adsorption enhancement ratio, and other quantitatively comparable descriptors from the original research. Numerical values used in the tables and figures were extracted from directly comparable results reported in the selected studies. If the literature only provided mechanistic or trend-level evidence, these results were used for qualitatively to support interpretation rather than treated as equivalent quantitative data points.

The natural logarithm of the ratio between adsorption by aged and pristine MPs was calculated using Formula 1 to derive the aging effect ratio (ER). This metric was used only when paired pristine and aged values were available from the same study under comparable conditions. Combined with mechanistic analysis and field investigation results, the enhanced effect of the aging process on heavy metal adsorption and its potential environmental significance are further revealed.

$$ER = \ln \left(\frac{q_{aged}}{q_{pristine}} \right) \quad (1)$$

Where q_{aged} and $q_{pristine}$ are the adsorption capacity of aged and pristine MPs, respectively. This metric was used to quantify whether aging enhanced or reduced metal adsorption relative to pristine particles. Specifically, $ER > 0$ indicates that aging increased adsorption capacity, $ER = 0$ indicates no measurable change, and $ER < 0$ indicates that aging reduced adsorption capacity.

3 Results and Discussion

3.1 Analysis of Controlling Factors for Adsorption Variability

Extensive research indicates that the adsorption behavior of microplastics toward heavy metals is jointly regulated by multiple factors rather than dominated by a single factor. A machine learning-based meta-analysis indicated that adsorption strength is jointly determined by environmental conditions, HM characteristics, and MP properties, with results shown in Figure 1^[8, 9]. Environmental conditions exert the greatest influence on

adsorption capacity (63.0%), followed by MP physicochemical properties (27.4), whereas the HM chemical properties contributed comparatively less (9.6%). Further machine learning research in 2025 confirmed that adsorption outcomes result from the synergistic interaction of particle chemistry, solution chemistry, and metal properties^[9]. These results indicate that adsorption should be regarded as an interfacial process dependent on environmental conditions rather than an inherent property of the particles themselves. For the same polymer-metal combination, adsorption behavior may exhibit significant variations when pH, salinity, natural organic matter content, oxidation state, or aging time changes occur. Therefore, studies comparing pristine and aged MPs hold particular value. Such research effectively isolates aging—the most environmentally variable key factor—thereby revealing its independent contribution.

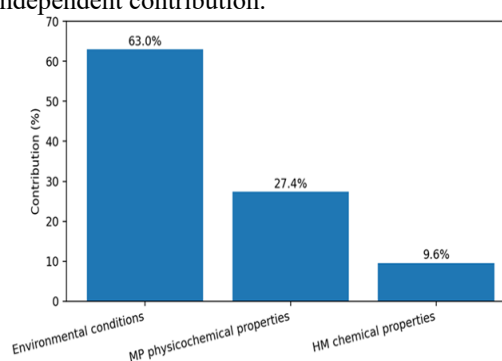


Fig. 1. Relative contributions of environmental conditions, MPs physicochemical properties, and HMs chemical properties to adsorption variability.

3.2 Comparison of Heavy Metal Adsorption by Pristine and Aged Microplastics

The aging process can enhance the adsorption capacity of various polymers for HMs. Table 1 lists the adsorption of HMs for pristine and aged-MP^[10-12]. Compared to pristine MPs, aged-MPs exhibit significantly enhanced adsorption capacity for HMs, with an increase ranging from 1.01 to 3.17 times. The adsorption capacities of polyethylene (PE) for Pb and Cu increased from 1.913 and 1.960 mg/g in the pristine state to 5.807 and 4.299 mg/g, respectively. Similarly, the adsorption capacities of aged polypropylene (PP) and polystyrene (PS) for Pb and Cu also showed a significant enhancement trend. These results indicate that aged MPs exhibit higher adsorption capacities for heavy metals than their original samples. Additionally, after weathering or oxidation treatment, PS, poly(butylene adipate-co-terephthalate) (PBAT), and other environmentally relevant polymers also exhibit similar adsorption enhancement effects^[11]. The above comparisons indicate that surface changes during aging does not yield a universal adsorption enhancement coefficient. Instead, the adsorption enhancement depends on the polymer backbone structure, degree of oxidation, and the affinity of the target metal for the newly generated surface groups. This also explains why both polymer type and aging state must be considered simultaneously when evaluating the adsorption behavior of MPs toward HMs.

Table 1. Representative comparable adsorption capacities for pristine and aged MPs reported in studies.

Polymer	Metal	Pristine q_{max} (mg/g)	Aged q_{max} (mg/g)	Fold change
PBAT	Cu (II)	0.367	0.453	1.23
	Pb (II)	0.454	0.564	1.24
PA		0.731	0.736	1.01
PE	Cr(VI)	0.076	0.137	1.80
PS		0.146	0.319	2.19
PE	Cu (II)	1.960	4.299	2.19
	Pb (II)	1.913	5.807	3.04
PP	Cu (II)	1.365	3.421	2.51
	Pb (II)	1.449	4.590	3.17
PS	Cu (II)	3.547	5.387	1.52
	Pb (II)	5.392	7.643	1.42

3.3 Effect of Environmental Media on Aging-Enhanced Adsorption

The impact of aging on HMs adsorption is influenced by the environmental medium. Figure 2 illustrates the effect of aged PS on HMs adsorption under three different media conditions. Results indicate that ER increased from pure water to seawater and then to air for all HMs^[1]. This demonstrates that adsorption efficiency progressively increases with the intensity of UV aging. Zn exhibited the highest ER values, followed by Ni and Cd, whereas Pb and Cu showed relatively lower responses. These results demonstrate that UV-aging enhancement was both medium-dependent and metal-dependent.

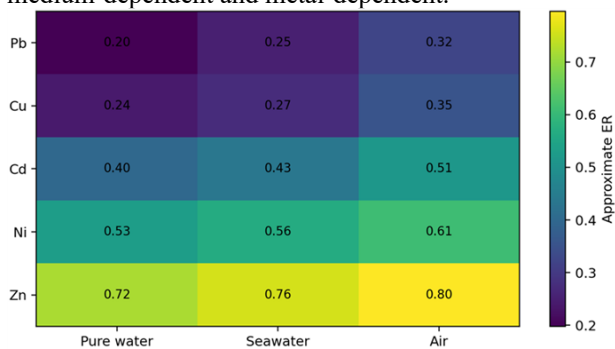


Fig. 2. Semi-quantitative ER values for HMs under pure water, seawater, and air UV-aging conditions.

The gradual increase in ER can be attributed to differences in aging severity and the resulting surface modification of MPs. More intensive aging likely generated a greater abundance of oxygen-containing functional groups and a rougher surface morphology, thereby increasing the number and affinity of adsorption sites. Air aging generally produced stronger photo-oxidation and more oxygen-containing functional groups, thereby favoring HMs adsorption^[1]. In seawater, ionic competition may weaken this effect, while pure-water aging was relatively limited. Therefore, the adsorption behavior of the same polymer can vary across weathering environments. The stronger response observed for Zn and Ni further indicates that specific metal properties, such as ionic radius, hydration behavior, and complexation tendency, may interact with aging-altered surface characteristics to determine the final adsorption enhancement. These findings are environmentally

relevant because microplastics are continuously transported across freshwater, estuarine, and marine compartments^[2, 13].

3.4 Polymer-specific contrasts and biodegradable MPs

Adsorption behavior differed strongly among polymers and cannot be inferred from aging alone. Figure 3 showed that UV aging increased the adsorption of selected particle types^[11, 14]. The ER values were positive for all cases, indicating that aging enhanced heavy-metal adsorption. However, the magnitude of enhancement varied markedly. The increase was limited for PBAT, but was much more pronounced for TWP and PP, especially for Pb and Cd. This difference was likely related to material-specific changes in surface chemistry and adsorption-site after UV aging. A plausible explanation is that PBAT already contains oxygen-bearing ester groups in its original structure, so UV aging may generate a smaller relative increase in new adsorption sites. By contrast, PP is initially dominated by hydrocarbon chains, and UV-induced chain scission and oxidation may create more new terminal radicals and oxygen-containing functional groups, resulting in a larger increase in metal binding.

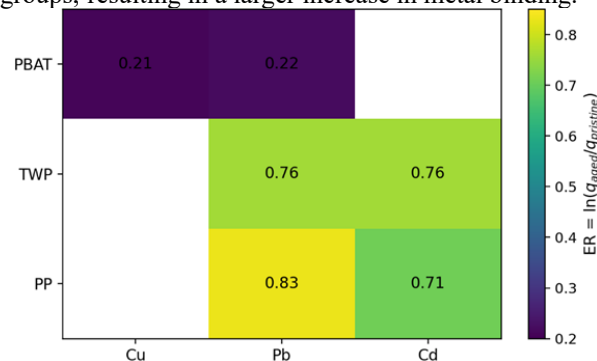


Fig. 3. Aging effect ratios calculated from values for representative particle-metal systems.

Figure 4 compared Cu adsorption capacities of MPs derived from selected commercial plastic products. PLA-derived MPs, especially PLA-egg and PLA-spoon, showed substantially higher Cu adsorption than PE-, PET-, and PS-derived particles. The results indicate that biodegradable materials exhibit stronger adsorption properties compared to conventional polymers. Previous studies analyzing conventional and biodegradable commercial plastics also revealed pronounced metal-specific differences among particle types^[15]. This finding is environmentally relevant because biodegradable plastics are increasingly used as substitutes for conventional polymers. However, this contrast should not be interpreted as a simple biodegradable-versus-conventional polymer effect. The higher adsorption observed for PLA-derived MPs may also reflect source-specific additives, processing residues, or hydrolysis-related surface changes associated with the original products. Therefore, product-derived biodegradable MPs should be regarded as an important source of uncertainty and a knowledge gap that requires more controlled studies separating polymer identity from product-source effects.

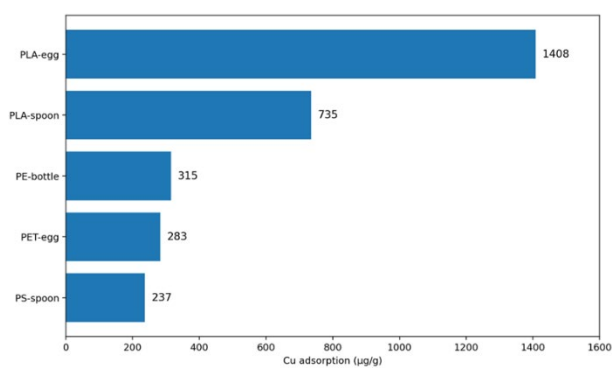


Fig. 4. Comparison of Cu adsorption among MPs derived from different commercial plastic products.

3.5 Practical implications and limitations

From the perspective of aquatic environments, the key implication is that aged MPs are more relevant than pristine particles for risk assessment. Monitoring or treatment studies that rely only on pristine commercial MPs may underestimate the capacity of environmental plastics to scavenge and transport toxic HMs. This study also has clear limitations. The literature corpus is heterogeneous, and the extracted numerical dataset does not cover every MPs, HMs, or aging pathway. Some studies report q_{max} , whereas others report removal efficiency or qualitative trends only. Therefore, the present quantitative synthesis should be interpreted as a focused evidence-based comparison rather than a formal meta-analysis.

4 Conclusions

This study showed that HMs adsorption by MPs is jointly controlled by environmental conditions, MPs physicochemical properties, and HMs chemical properties, among which environmental conditions play the dominant role. Aging generally enhanced the adsorption capacity of MPs, but the magnitude of enhancement depended on polymer type, metal species, and aging medium. Adsorption varies significantly among different polymers, with biodegradable derived MPs exhibiting stronger adsorption capacity than conventional plastics. These findings indicate that aged MPs are more environmentally relevant than pristine particles in evaluating the transport and risk of HMs.

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