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Evaluation of the Spreading Dynamics and Interactions of Lead-Carrier Microplastics Affected by Biofilm: A Mini-Review

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Abstract The toxic effect of microplastics (MPs) on living organisms is caused by the plastics and other pollutants attached to their surface. The interaction of MPs with hazardous toxic pollutants such as lead (Pb) is possible due to the large surface area of MPs and the high adsorption capacity of heavy metals such as Pb. When combined with toxic heavy metals, the interaction of MPs with aquatic environments and living organisms leads to environmental and biological problems. When MPs enter water, they form a biofilm under the influence of organic and inorganic substances, significantly altering the adsorption–desorption properties of the heavy metal. The current study aims to understand the effect of Pb-MP interaction on MPs by investigating biofilm formation in MPs. By reviewing the studies in the existing literature, the study analyses how biofilm formation affects the adsorption behavior of Pb heavy metal on the surface of MPs. Furthermore, future perspectives highlight potential research directions aiming to fill the knowledge gaps in this field. Addressing the challenges, it also highlights the need for a multidisciplinary approach to understanding microplastic and heavy metal interactions in aquatic ecosystems and to assess the long-term effects of these interactions on ecology and health.

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1 Introduction

Environmental pollution, especially the spread of microplastics (MPs) in natural ecosystems and their capacity to adsorb various pollutants, is becoming an increasing threat to global environmental health and natural ecosystems (Jiang et al., 2020; Prokić et al., 2019; Wu et al., 2019). In this context, understanding the environmental impacts and propagation dynamics of Pb carried on microplastic (MP) surfaces has become a crucial research area for sustainable environmental management. MPs are prevalent in the environment, spreading through the atmosphere (Adebiyi & Kok, 2020), water (Alvim et al., 2020), sediment (Brandon et al., 2019), and soil (Alengebawy et al., 2021), negatively impacting the health of organisms in ecosystems (Cao et al., 2021). MPs can adsorb various harmful substances such as organochlorine pesticides, persistent organic pollutants, endocrine disruptors, toxic organic chemicals, and heavy metals onto their surfaces (Sajid et al., 2016), leading to the potential transfer of these substances to living organisms, resulting in bioaccumulation and biomagnification (Akhbarizadeh et al., 2019), which can cause disruptions in metabolic (Wang et al., 2023), neurological (Viana et al., 2020), reproductive (Afreen et al., 2023), and immune systems.

(Sharifinia et al., 2020). MPs, vectors for toxic elements, can keep heavy metals such as Cd, Co, Cr, Cu, Ni, Pb and Zn on their surfaces (Godoy et al., 2019).

The adsorption of organic pollutants onto the MPs' surface is a multifaceted and complex process that depends on the characteristics of both the pollutants and the MPs, as well as the conditions of the solution and the environment (Wang et al., 2020). In this process, numerous factors, such as hydrophobic interactions, chemical interactions, surface properties, time and temperature, play crucial roles in specifying the type and degree of adsorption mechanisms (Munoz et al., 2021). Among the adsorption mechanisms are physical adsorption, chemical adsorption, ion exchange, complex formation, surface reaction, and pore filling (Abbas et al., 2018), which influence the attachment strength and pollutants' reversibility to the MP surface (Tourinho et al., 2019). Additionally, inorganic contaminants like metal ions can be adsorbed on MPs' surface (Fu et al., 2021a, 2021b). In such cases, different mechanisms can come into play, including surface oxidation, surface complexation, co-precipitation, and electrostatic interactions (Nagoya et al., 2019). Tang et al., (2021) conducted a study examining the adsorption capacities of nylon-MPs for Cu, Ni, and Zn. The study finding revealed that the sequence of ions adsorbed by MPs was Cu, Zn, and Ni. The results indicated that the primary mechanism governing adsorption is surface complexation. Environmental factors such as air humidity, pH, salinity, organic matter abundance, attached biofilms, and redox potential influence pollutants adsorbed on the MP surface (Tang et al., 2021). Lin et al., (2021) explored the sorption kinetics and mechanisms of Pb on polyvinyl chloride (PVC), polyethylene (PE), and polystyrene (PS)-MPs, which brought to light that the sorption capacities of MPs were subject to factors like pH, ionic strength, and MP type. The predominant factors influencing this phenomenon were primarily intraparticle diffusion and the ultimate equilibrium process. The highest sorption capacities recorded were 483.1 µg/g for PVC, 416.7 µg/g for PE, and 128.5 µg/g for PS, respectively. Advanced analyses using Fourier transform infrared spectroscopy (FTIR) and X-ray photoelectron spectroscopy (XPS) revealed no formation of new bonds Pb-MP, emphasizing physisorption as the primary force driving Pb sorption (Lin et al., 2021). According to Gu et al., (2018), Pb exhibits significant biotoxicity and proves resistant to biodegradation, exerting adverse effects on organisms even at lower concentrations (Gu et al., 2018).

Pb-MP interaction adversely affects soil, plants, water, and human health (Kumar et al., 2022). Pb can be disseminated from various sources that pose harm to the environment and human health (Karbalaei et al., 2018). Sources contributing to the accumulation of Pb on the surface of MPs include industrial activities releasing Pb into the environment, wastewater, agricultural pesticides, waste batteries, lead-based paints, toys, Pb pellets from ammunition, leaded-gasoline, cosmetic products (Hettiarachchi et al., 2024). Also, its sources are associated with landfills, leachates, mines, petrochemical industry and agricultural runoff (Obeng-Gyasi, 2019). These sources release Pb into water, soil, and air, allowing it to adsorb onto or penetrate the surface of MPs (Adji et al., 2022; Sharma et al., 2021). By carrying Pb along the food chain, MPs adversely affect living organisms' health (Kumar et al., 2020). Pb exposure is associated with severe health problems (Obasi & Akudinobi, 2020; Tong et al., 2000; Wang et al., 2009). Pb can access the body through inhaling, swallowing, or contact with the skin, amassing in the bloodstream, skeletal structure, cerebral region, renal system, hepatic tissue, neural system, and additional bodily structures (Collin et al., 2022; Pandey & Madhuri, 2014). This accumulation can result in damage to brain functions, DNA, and chromosomes, leading to allergic reactions, fatigue, headaches, and adverse reproductive effects (Bhargava et al., 2017; Engwa et al., 2019; Jaishankar et al., 2014; Singh et al., 2018).

Several investigations have highlighted the prevalent association of MPs with Pb in freshwater environments. Investigating the adsorption of Pb on MPs and their synergistic impacts is crucial for comprehending the coexistence of MPs with various pollutants. Therefore, this study focuses on Pb as a representative contaminant. This study aims to evaluate Pb-MP interactions deposited on the surface of MPs to understand the propagation dynamics and environmental exposure of these interactions. This study also helps to grasp the current limitations of Pb-MP interactions and highlights important perspectives and challenges for future studies.

2 Influence of Biofilm Formation on the Adsorption of Heavy Metals in MPs

The biofilm can readily establish its presence on the surface of MPs (He et al., 2022). Following immersion in aqueous settings, a layer composed of organic and inorganic substances termed the conditioning membrane (Rummel et al., 2017) occurs on the MPs' surface, playing an important role in contributing to the subsequent development of the biofilm (Guan et al., 2020) (Fig. 1).

As seen in Fig. 1, biofilm is a cluster of microorganisms where cells adhere to each other or to the surface they are on (Qiang et al., 2021), which arises from the conditioning membrane formed on the surface of MPs after they enter the aquatic environment, composed of inorganic and organic substances (Feng et al., 2020). This layer facilitates microorganisms' attachment to MPs and biofilm formation (Tu et al., 2020a, 2020b). Weak bonds are formed between microorganisms and MPs through physical forces (van der Waals force, electrostatic forces, and hydrophobic interactions), which can be fragile or strengthened depending on environmental conditions (Fu et al., 2021a, 2021b; Prajapati et al., 2022). However, strong bonds can also form between microorganisms and MPs through chemical forces (hydrogen bond, ionic bond, and covalent bond), which are independent of environmental conditions and allow microorganisms to adhere permanently to the surface of MPs (Moyal et al., 2023).

The secretion of extracellular polymeric substance (EPS) is a crucial step in the process of microorganisms adhering to MPs' surface (Deng et al., 2021). This process begins with the initial attachment of pioneer microorganisms to the surface of MPs (Debroy et al., 2022). Attachment to MPs typically occurs in reversible and irreversible stages (Dennehy & Abedon, 2021). On the surface they adhere to, microorganisms release extracellular polysaccharides, referred to as EPS (Liu et al., 2021a, 2021b), containing polysaccharides, proteins, nucleic acids, and lipids (Izadi et al., 2021), which facilitates a tighter binding of microorganisms to the surface of MPs (Stabnikova et al., 2022). The role of EPS is to create an adhesive matrix covering the surface of MPs,

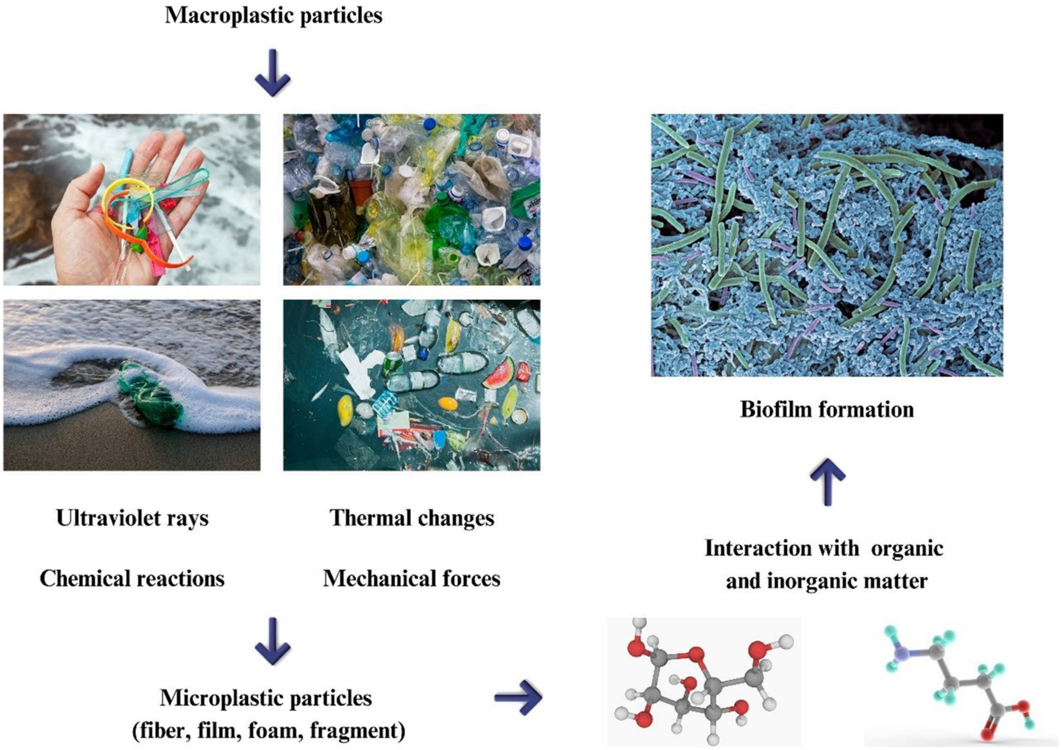

Fig. 1 Interaction of MPs with biofilm

thereby enhancing the resilience of microorganisms and facilitating the formation of a biofilm (Tu et al., 2020a, 2020b). This process is a significant ecological phenomenon, influencing the interaction of microorganisms with MPs and enhancing the resistance of MPs to environmental conditions (Deng et al., 2021).

Microbial proliferation represents the final stage of biofilm formation, a process that encompasses the development of a dynamic microbial community on the surface of MPs (Sooriyakumar et al., 2022). In the concluding phase of biofilm formation, additional microorganisms continuously settle on the surface of MPs. This occurs through the proliferation of previously attached microorganisms in earlier stages and the arrival of new microorganisms (Battulga et al., 2022). Alongside the proliferation of microorganisms, organic substances, cell residues, and other biological remnants generated during biofilm formation accumulate on the surface of MPs (Hale et al., 2020). Simultaneously, depending on environmental conditions, inorganic residues may also become part of this biofilm matrix (Flemming et al., 2023), initiating a process of accumulation and diversification within the biofilm. The biofilm on the surface of MPs becomes increasingly enriched and diversified through the proliferation of microorganisms and the combination of organic/inorganic residues, supporting intricate interactions among microorganisms (Arias-Andres et al., 2019). Factors such as relationships between different species, competition, and cooperation play an important role in this phase of the microbial community (Ghoul & Mitri, 2016; Gralka et al., 2020). In the final stage of microbial proliferation and biofilm formation, a complex and dynamic microbial ecosystem emerges on the surface of MPs, which shape biological interactions in the MP environment, influencing resistance against environmental factors (Sooriyakumar et al., 2022). Li et al., (2022a, 2022b) examined how Pb behaves in terms of adsorption on biodegradable poly(butylene succinate) (PBS) MPs during the process of biodegradation. The study findings suggest that the amount of Pb adsorbed by biofilm-colonized, biodegraded PBS-MPs is approximately 10 times greater than that observed with pristine PBS (647.09 µg/g compared to 64.13 µg/g). This notable increase is attributed to both the presence of biofilm colonization and the degradation of PBS (Li et al., 2022a, 2022b). Ahamed et al., (2020) noted a significant increase in the adsorption of Pb on low-density polyethylene (LDPE) surfaces in the presence of biofilm. This led to a 13-fold rise in the equilibrium adsorption capacity, reaching 1602 g/m^2, compared to the absence of biofilm, which was only 124 g/m^2 (Ahamed et al., 2020). The investigation conducted by Fan et al., (2021) revealed notable differences in the adsorption capacities of polypropylene (PP)-MPs for various heavy metals. Notably, the adsorption capacities for Pb and Cu were notably higher when compared to those for Cd and Zn (Fan et al., 2021). This suggests that Pb exhibits the highest adsorption capability across diverse MP particles, with physisorption onto the MPs identified as the primary sorption mechanism (Lin et al., 2021).

3 Selecting the Impact of Pb on the MPs

Heavy metals may be of natural origin or occur due to human activities (Vareda et al., 2019). Numerous compounds containing heavy metals exhibit high solubility in aqueous environments (Cánovas et al., 2023; Mariana et al., 2021). Heavy metal concentrations can vary due to the impact of human activities, and their discharge into the receiving environment is rapidly increasing (Hembrom et al., 2020). Heavy metal substances, which originate from the wastewater of different industries, may mix with the receiving environment due to human influence and natural factors (Vardhan et al., 2019). If heavy metals are discharged into the aquatic environment without adequate treatment, it can lead to severe problems for both the environment and living organisms (Mishra et al., 2019) (Fig. 2). Heavy metals are transported through complex processes such as dissolution, precipitation, complex formation, adsorption, and bioaccumulation in aquatic environments (Liu et al., 2022a, 2022b, 2022c), altering the physicochemical properties of water (Qiu et al., 2021), which disrupt vital functions in living organisms (Fu & Xi, 2020), including growth (Witkowska et al., 2021), development (Bharti & Sharma, 2022), reproduction (Massányi et al., 2020), respiration (Nowicka, 2022), photosynthesis (Souri et al., 2019), enzyme activity (Witkowska et al., 2021), protein synthesis (Engwa et al., 2019), and the structure of DNA and RNA (Bharti & Sharma, 2022), which can adversely affect human health.

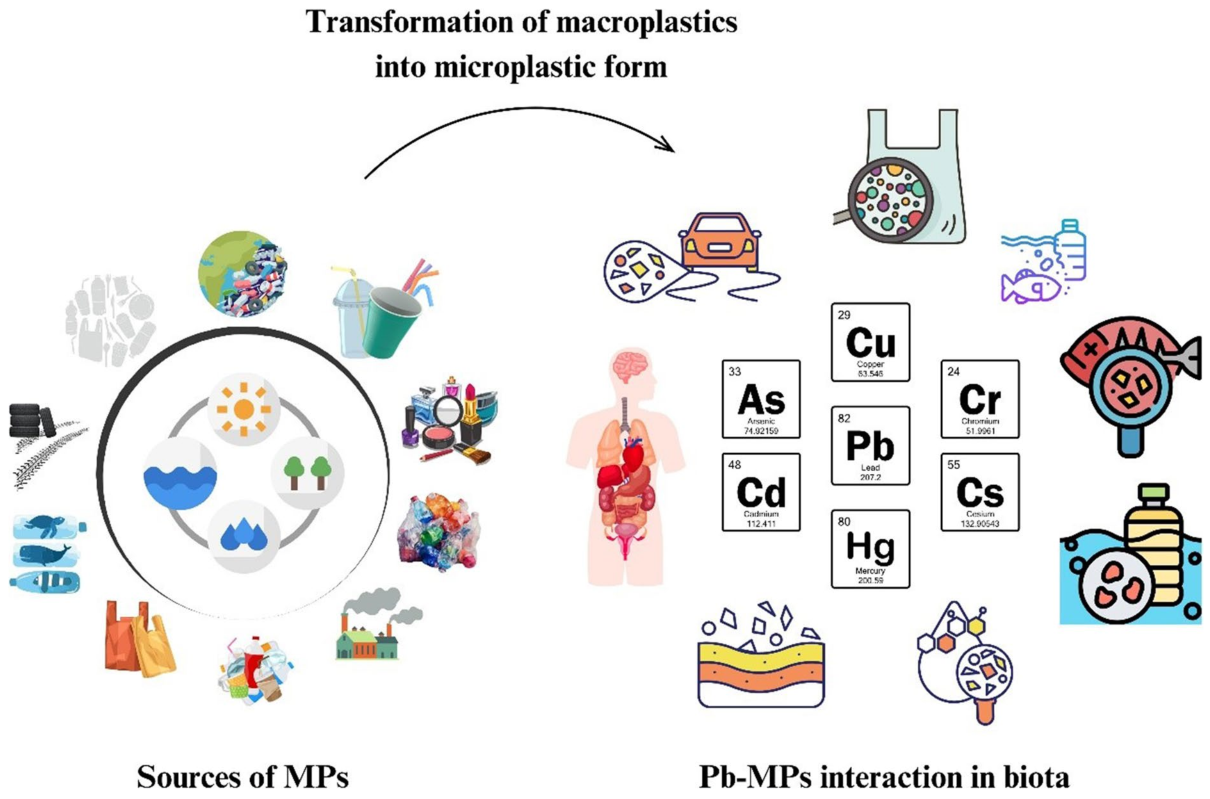

Fig. 2 Schematic representation of the interactions between MP and heavy metals

Heavy metals cause long-term environmental pollution, and recent research has revealed the interaction between MP and heavy metals (Cao et al., 2021; Liu et al., 2022a, 2022b, 2022c; Zhang et al., 2022). Pb can be incorporated into the polymer matrix as a heavy metal, increasing the toxicity of the polymer. Pb might exist in the polymer matrix of MPs as functional additives or residues from recycling or reactions (Nguyen et al., 2023). Functional additives are substances used to modify polymers' processing and performance properties (Campanale et al., 2020). Recycling or reaction residues, on the other hand, are waste or leftover materials generated during the production, processing, or use of polymers (Khoo et al., 2021; Moumakwa, 2023). These materials can mix with the polymer matrix in unwanted or unknown ways, affecting the polymer's physical, chemical, or biological properties (Inamdar, 2022). The primary source of Pb is the smoke from vehicle exhaust (Heal et al., 2005; Negahban & Mokarram, 2021; Sassykova et al., 2019). Soils along roadsides are places where Pb accumulates heavily. MPs in the environment can adsorb Pb onto their surfaces, increasing their toxicity. MPs, widespread in aquatic and terrestrial ecosystems, can lead to the biological accumulation of Pb on their surfaces (Elgarahy et al., 2021), allowing Pb to be transported through atmospheric processes such as wind, rain, hail, and snow, facilitating the biological breakdown of MPs and their entry into the food chain (Özgenç et al., 2023). This can negatively impact organisms' growth, reproduction, behavior, and health (Padha et al., 2022). The tendency of Pb to bioaccumulate in the body and be stored in bone tissue is also concerning, leading to toxic effects in cases of long-term exposure (Collin et al., 2022). It can induce genetic disorders and developmental problems by affecting genetic material. Biomedical interactions can occur due to various toxicity mechanisms inside and outside cells (Paz-Sabillón et al., 2023). In contrast to other environmental materials, MP particles display heavy metal concentrations 10–100 times higher, primarily attributable to their smaller particle size and an increased surface area-to-volume ratio (Acosta-Coley et al., 2019).

In this context, Pb-MP interaction enhances bioaccumulation, which is important in transferring environmental pollutants to organisms. The adsorption of Pb on MP surfaces contributes to the accumulation of these tiny particles in organisms in both aquatic and terrestrial environments. This creates a scenario where environmental toxins can ascend the food chain, presenting a potential threat and causing harm to ecosystems. Therefore, the Pb-MP interaction represents a significant research area for comprehending and managing environmental impacts.

4 Pb-MP Interactions in the Receiving Environment

The contamination of aquatic environments with heavy metals is a substantial global concern, given its persistence and enduring impact on ecosystems (Lin et al., 2016). When ingested from the environment, MPs can also bind to heavy metals, accumulating in organisms' bodies and potentially causing biological issues. Digestion of MPs allows heavy metals to be transported into organisms (Zhu et al., 2018). Heavy metals endanger human health when they enter the food chain. MPs bind heavy metals to their surfaces, harming living organisms in the sea, freshwater and land (Wen et al., 2018). As seen in Table 1, some laboratory experiments have proved how MPs affect heavy metals, which factors influence adsorption or desorption and how MPs transport heavy metals (Table 1). Similarly, recent investigations have indicated that MPs may be crucial carriers of toxic heavy metals (Godoy et al., 2019). A study conducted by Massos and Turner (2017) revealed that the analysis of the MP sample ($n = 924$) from two beaches showed the presence of Cd in 6.9% and Pb in 7.5% of all MPs, respectively. The concentration of both metals exceeded 1 mg/g. Maršić-Lučić et al., (2018) detected the presence of some metal ions in MP samples from beach sediments on the Croatian island of Vis. Compared to samples from the nearby ocean, the study showed that MPs had higher levels of trace metals such as Fe, Cr, Mn, Cu, Ni, Zn, Pb and Cd, confirming that MPs enrich the marine ecosystem in metals. In the study conducted by Lin et al., (2021), the adsorption characteristics of Pb ions were examined using PVC, PE, and PS. It was found that PVC exhibited the highest maximum adsorption capacity, reaching 483.1 µg/g for Pb ions. Davranche et al., (2019) revealed that 97% of lead Pb was detected on nanoparticles isolated from MPs gathered from the North Atlantic region. The research illustrates the ability of nanoparticles to bind with both organic pollutants and heavy metals, affirming that organic and inorganic origin pollutants exhibit an affinity for plastic. Similarly, the study by Fu et al., (2021a, 2021b) confirmed that naturally aged MPs exhibit a heightened adsorption capacity for Pb, with the primary mechanism of this process likely determined by the electrostatic force between the oxygen-containing functional groups present in MPs and Pb. The diffusivity of MPs allows Pb to diffuse into MPs over a larger area, leading to environmental contamination affecting a larger area, which means that Pb contamination in water sources can be widespread. This process affects the environmental behavior, bioavailability and toxicity of both MPs and Pb. Thus, Pb contamination in water bodies can affect a specific region where MPs are present and a large area where MPs are transported or dispersed.

As seen in Table 1, research on the Pb-MP interaction covers an important area for an in-depth understanding of the role of MPs in environmental systems (Cao et al., 2021). The Pb-MP interaction has many consequences in the aquatic environment, highlighting significant effects on microbial communities and biofilm formation. The diversity of MP species is an important factor in determining the absorption of Pb ions (Wang et al., 2022). Studies reveal that different MP types have different absorption properties and that Pb ions exhibit a high affinity for MP surfaces (Liu et al., 2021a, 2021b). High Pb concentrations in water systems and oxygen-containing functional groups increase Pb adsorption to the surface of MPs, contributing to a more efficient transfer of the heavy metal through MPs into water systems (Shen et al., 2021). It was also observed that the degree of oxidation, MP type and environmental conditions (pH, ion strength, dissolved organic matter (DOM)) affect Pb adsorption, and various factors regulate the Pb-MP interaction. In particular, the degree of oxidation determines the surface properties of MPs (Liu et al., 2022a, 2022b, 2022c). This reveals that Pb adsorption is enhanced with the increase of oxygen-containing groups on the MP surface (Zhou et al., 2020). The Pb-MP interaction is mostly characterized by physical adsorption, which is characterized by a direct process

Table 1 Researches on Pb-MP interaction in the aquatic environment

Environmental compartment/Location	MP type	Size and/or density	Pb concentration on MPs	Target	Analytical methods and/or experimental studies	Response	References
China	PS-MPs	50 µm	The concentration of interfering Pb ranged from 0.01 – 0.1 mmol/L	Aquatic ecosystems organisms	Adsorption isotherms, Adsorption isotherms, scanning electron microscopy (SEM), X-ray diffraction (XRD)	The adsorption of Pb had a more pronounced impact on the microbial community and biofilm-affected with MPs	(Qiongjie et al., 2022)
China coastline	PVC, PP, PE, polyamide (PA), polyoxymethylene (POM)	4 mm	0.823 ± 0.019 µg/L in seawater, 0.441 µg/L on MPs	Marine environment	Adsorption experiments at different time intervals	The different types of MPs demonstrated varying adsorbability to different heavy metals in correlation with ion concentration, adsorption time, and particle size	(Gao et al., 2019)
China	PVC (1.35 g/cm^3), PS(1.05 g/cm^3), PE (0.97 g/cm^3)	PVC (5.72 nm), PS(7.03 nm), PE (9.23 nm)	The maximum sorption in 0.01 M NaCl solution was 483.1 µg/g for PVC, 128.5 µg/g (PS) and 416.7 µg/g for PE	The study mainly focused on the aquatic ecosystem	SEM, FTIR, BET, dithizone method, adsorption experiments	Pb has exhibited a higher affinity for PVC compared to PS and PE	(Lin et al., 2021)

Table 1 (continued)

Environmental compartment/Location	MP type	Size and/or density	Pb concentration on MPs	Target	Analytical methods and/or experimental studies	Response	References
Seawater, urban wastewater and irrigation water/ Granada (Spain)	PE, polyethylene terephthalate (PET), PP, PS, PVC	The ratio of MPs to water ranged from 1:10 in fragment and pellet forms	< 5,553 mg/g	Different aquatic environments	BET, FTIR, SEM, adsorption experiments in two different initial concentrations ($C_i = 4$ mg/L and $C_i = 8$ mg /L)	Greater quantities of Pb were adsorbed in PET, PP, and PS. Pb was the metal adsorbed in the highest quantity in both Milli-Q and natural waters. The results indicated increased metal adsorption in waters characterized by high chemical and biological oxygen demands, such as urban wastewater and irrigation water	(Godoy et al., 2019)

Table 1 (continued)

Environmental compartment/Location	MP type	Size and/or density	Pb concentration on MPs	Target	Analytical methods and/or experimental studies	Response	References
China	PE, biodegradable MPs (PLA, polylactic acid), aged PE (APE), aged PLA (APLA)	PE: 150 µm, PLA: ranged from 180–270 µm	The maximum adsorption capacities in descending order were PLA > aged PE > original PLA > original PE, with values of 0.98 mg/g, 0.83 mg/g, 0.67 mg/g, and 0.54 mg/g, respectively	Natural environments	UV/O_3 oxidation, SEM, FTIR, X-ray photoelectron spectroscopy (XPS), atomic absorption spectroscopy, adsorption experiments	The research revealed that oxidation treatment substantially elevated the presence of oxygen-containing functional groups and the hydrophilicity of MPs, consequently enhancing their capacity to adsorb heavy metals. Oxidation degree, type, and environmental conditions influence Pb adsorption on MPs, including pH, ionic strength, and dissolved organic matter (DOM)	(Liu et al., 2022a, 2022b, 2022c)
Sandy beaches in south-west England	PE, PP, PS, PVC	Minimum primary particle diameter of approximately 1 mm in red and yellow pellets	Pb was identified in 7.5% of the plastic samples, reaching a maximum concentration of 5330 µg/g	Beach environments/Assessing the bioaccessibility of Pb to avian	FTIR, field-portable-x-ray fluorescence (FP-XRF) spectrometry, physiologically-based extraction test (PBET), cell-ICP-MS	Although the bioaccessibility of Pb in MPs by birds is low, accessible Pb concentrations in brightly colored fragments can exceed the corresponding concentrations in the seabird diet by 4 times	(Massos & Turner, 2017)

Table 1 (continued)

Environmental compartment/Location	MP type	Size and/or density	Pb concentration on MPs	Target	Analytical methods and/or experimental studies	Response	References
The Chao Phraya River in the Tha Pra Chan area of Bangkok, Thailand	PP, PE, PS, PVC, Polyester	In fragments, fibers and pellets, mostly white, with sizes ranging from 0.05 to 1 mm, the density is 80 ± 65 items/m^3 and 53.3 ± 58.4 mg/m^3	17.61 ± 18.26 µg/g	River water and sediment/assess potential risks to humans and biota	FTIR, optical microscope, micro-FTIR, optical emission spectroscopy (ICP-OES)	Significant concentrations of heavy metals, mostly Pb, were observed adsorbed on MPs	(Ta & Babel, 2020)
Musi River, South Sumatera Province, Indonesia	PP, PE, Polyethersulfone (PES), PVC, nylon	PP: 36.36% PE: 27.27% PES: 18.18% PVC: 9.09% Nylon: 9.09%	0,152–2,218 mg/kg	River water/Differential effects of environmental factors on heavy metals in MPs	FTIR spectrometer, adsorption isotherms model, one-way ANOVA (significant level 0.05) and the Tukey test	Heavy metals in water have a pronounced impact on the metal content within MPs. The Pb-MP interaction is attributed to physisorption, characterized by a straightforward process and weak bonding	(Purwiyanto et al., 2020)
China	Low-density polyethylene (LPE), chlorinated polyethylene (CPE), PVC, high-density polyethylene (HPE)	LPE: 150 µm CPE: 250 µm PVC: ranging from 0.18 to 1 µm HPE: 27–45 µm	The adsorption of Pb onto PVC, HPE, and LPE varied within the range of 240 ml/g to 1841 ml/g	Aqueous environment/Evaluation of MPs as heavy metal vectors	SEM, FTIR, ESEM electron microscope, XPS, Freundlich and Langmuir models	The sorption of metals onto MPs was influenced by factors such as pH and ionic strength. Electrostatic interactions emerged as a significant factor in the sorption process of Pb onto MPs	(Zou et al., 2020)

Table 1 (continued)

Environmental compartment/Location	MP type	Size and/or density	Pb concentration on MPs	Target	Analytical methods and/or experimental studies	Response	References
Castillogrande and Cabrero-Marbella beaches/Cartagena, a Caribbean city	PE, PP	4.60±0.08 mm, in pellet form	Pellet: 0.07–0.61 µg/g Secondary MP: 1.55–43.68 µg/g	Ocean beaches/Surface degradation features	FTIR, Mercury analysis- direct mercury analyzer, inductively coupled plasma mass spectrometry (ICP/MS)	The majority of MPs consisted of new-white polyethylene pellets and secondary MPs. Pb, among various other elements, accumulated particularly in degraded pellets	(Acosta-Coley et al., 2019)

and weak binding (Li et al., 2022a, 2022b). In this context, Pb ions are physically adsorbed on the MP surface, meaning weak bonds bind them and can be released (Fu et al., 2021a, 2021b).

Overall, Pb-MP interaction is a complex process that can increase the environmental impacts of MPs and extend the pollution spread of the heavy metal in aquatic systems, which means that it can lead to long-term environmental contamination of Pb. Based on this information, it is clear that Pb-MP interaction is a severe problem in the aquatic environment. To solve this problem, taking measures such as reducing the sources of MPs and Pb, removing MPs and Pb from the aquatic environment, and monitoring the toxic effects of Pb-MP interaction can be an effective factor in the success of long-term solutions to environmental problems.

5 Future Perspectives and Challenges

Future research on heavy metal adsorption–desorption properties of biofilm-affected MPs should cover both fundamental and applied aspects. Fundamental aspects should aim to understand better biofilm's effects on heavy metal adsorption–desorption capacity, kinetics, isotherms, thermodynamics, and mechanisms of MPs. It should also systematically investigate the factors affecting the heavy metal adsorption–desorption properties of biofilm on MPs, such as biofilm thickness, structure, composition, age, type, shape, size, surface area, degree of contamination, concentration of heavy metal ions, pH, temperature, salinity, redox potential, etc. Studying them under long-term and realistic conditions to improve fundamental knowledge and applied solutions is important to better understand how heavy metal adsorption–desorption properties change with time. The applied aspects should aim to develop new methods and materials to modify biofilm-affected MPs' heavy metal adsorption–desorption properties and design new technologies and strategies to remove or recover them from the environment.

The current studies focusing on metal ions are generally concentrated on Pb and Cu. However, other metal ions should also be considered to understand biofilms' impact on the heavy metal adsorption mechanism by plastic residues. Particularly, as plastic pollution is increasing in aquatic environments, there is a need for further research in this area. Although the studies are mostly carried out in the laboratory, they should be simultaneously combined with in situ experiments to reveal the biofilm-enhanced adsorption mechanisms of metals. This biofilm may reflect realistic environmental factors that affect MPs' heavy metal adsorption–desorption properties. Additionally, while studies have mainly focused on adsorption isotherms and spectroscopic methods, there is a highlighted necessity for more work on mathematical modeling and dynamic analysis confirming the contribution of environmental conditions and biofilms to metal adsorption. Nevertheless, there still exists a knowledge gap in the current research literature:

(1) The hydraulic parameters influencing the movement, accumulation, and resuspension of different MP particles in freshwater environments have not yet been sufficiently investigated. These parameters are important in transporting, settling, and remixing MPs in receiving environments. Therefore, it is important to examine the hydrodynamic behaviors of MPs and the factors influencing them to understand their fate and transport in freshwater environments.
(2) Data on the age, degradation levels, and biofilm accumulation of MPs detected in the studied aquatic environment is limited. The age of MPs can help determine their sources and pathways of entry. The degradation levels of MPs vary depending on plastic types, environmental conditions, and microbial activity. The biofilm accumulation on MPs influences their density, hydrophobicity, toxicity, and biological interactions. Therefore, determining the age, degradation levels, and biofilm accumulations of MPs is necessary to understand the characteristics and impacts of MPs in freshwater environments.
(3) The clear impact of biofilm accumulation on different MP density changes has not yet been fully understood. Biofilm accumulation can either decrease or increase the density of MPs, thereby affecting the probability of floating, which can influence MPs' transport, accumulation, and resuspension. Additionally, biofilm accumulation can alter the chemical composition, surface properties, and the release or absorption of toxic substances in MPs, affecting MPs' environmental risk and toxicology. Therefore, investigating the open effect of biofilm accumulation on different MP density changes is important to understand the behavior and outcomes of MPs in freshwater environments.
(4) Quantitatively determining the dominant process, such as release or absorption, for MPs with different characteristics is challenging. MPs exhibit diversity in terms of plastic types, shapes, sizes, surface properties, and biofilm accumulations, affecting MPs' release or absorption capacity and rate. MPs can release or absorb toxic substances in their environment, determining their and other organisms' toxic effects. Therefore, quantitatively determining the dominant process for MPs with different characteristics, such as release or absorption, is necessary to understand the toxicology of MPs in freshwater environments.

Challenges related to heavy metal adsorption–desorption properties of MPs exist at both experimental and theoretical levels. At the experimental level, there is a lack of standardized, sensitive, and reliable methods to measure heavy metal adsorption–desorption properties of biofilm-affected MPs. At the theoretical level, there is the complexity and diversity of numerous factors influencing the heavy metal adsorption–desorption properties of MPs. Furthermore, the lack of sufficient data and models to assess the environmental impacts and health risks of heavy metal adsorption–desorption properties of MPs is also a challenge. There are also technical challenges to improving or utilizing MPs' heavy metal adsorption–desorption properties, such as high cost, low efficiency, and low selectivity. Combating these challenges requires experimental and theoretical method development, data, model and technical improvements, and multidisciplinary collaboration, which can help better understand MP's heavy metal adsorption–desorption properties and is important for environmental risk assessment and waste management.

6 Conclusion

This study provides valuable insights into the complex relationships between the dynamic interactions of biofilm formation on MPs and Pb adsorption. Biofilm formation was found to be an important influence on the adsorption of heavy metals on

MPs. Biofilms act as dynamic interfaces, altering MPs' surface properties and significantly changing heavy metals' adsorption–desorption capacity, adding a new dimension to MP pollution's environmental and biological problems. Selected effects on Pb-MP interactions have also been studied, revealing that these interactions are physical coupling and involve specific mechanisms based on factors such as surface chemistry, particle size and environmental conditions. The study of Pb-MP interactions in receiving environments has revealed a complex interaction influenced by various environmental factors. Therefore, dynamic interactions between environmental compartments play a critical role in understanding the interactions of MPs with potentially toxic elements, allowing for more effective environmental policies and, management strategies and interventions to minimize environmental risks.

Specific regulations, standards, and protocols are required to understand and effectively manage MPs' environmental impacts fully. These regulations should include a comprehensive approach across the various stages of MP production, transportation, use, disposal, and biotoxicity. At this point, future research and regulations are expected to contribute to environmental sustainability goals by establishing an effective framework to combat MP pollution. Scientific research can shed light on a better understanding of environmental impacts and the development of more effective strategies to address this problem. At the same time, establishing regulations on MPs at national and international levels can encourage various sectors and societies to take responsibility for this issue. By understanding these dynamics, researchers and policymakers can make informed decisions to reduce the environmental impacts of MPs and heavy metals in aquatic ecosystems. Future studies can further investigate the long-term effects of these interactions and develop targeted interventions and strategies to minimize ecological consequences.

Authors Contributions Enes Özgenç planned and designed all stages of this study, collected and compiled the data, and wrote and edited the manuscript.

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Declarations

Ethical Approval The author has read, understood, and has complied as applicable with the statement on "Ethical Responsibilities of Authors" as found in the Instructions for Authors.

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Consent to Publication The author confirms that this paper has not been published before, that it is not under consideration for publication elsewhere, and that its publication has been approved by Enes Özgenç.

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