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REVIEW ARTICLE

Interplay between microplastics and natural organic matter in association with environmental processes

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Abstract
Microplastics (MP) have obtained remarkable attention from the scientific community owing to the potential damage they can cause to the environment. Several research works conducted towards consequences of MP in soil and aquatic systems reveal that there is significant interaction between various MP particles and natural organic matter (NOM). This results in changes in physicochemical properties, transport behaviours, and bioavailability of MP. Conversely, properties of NOM can be affected by the interaction with polymer microparticles. Consequently, MP-NOM interaction is crucial for environmental processes such as C sequestration, nutrient cycling, and microbial activity. Therefore, this critical review assesses the possibility of the existence of 'MP-NOM association', by analysing the currently available research results. It could even be presumed that MP enter into various environmental compartments through the respective organic matter regimes. This would, then, lead to the scenario that knowledge on MP-NOM associations acts as the key to understanding how MP operate within the environment. Therefore, this review also analyses the challenges and limitations while addressing MP-NOM associations. This work brings in the concept of 'MP-NOM Association' and helps researchers to identify knowledge gaps and challenges so that ideas and experiments can be devised to investigate the fundamental aspects of microplastic pollution in soil and water.

Keywords Microplastics · Natural organic matter · MP-NOM association · Adsorption · Polymer microparticles · Organic contaminant

Introduction

Background on microplastics and their environmental consequences

Microplastics (MP) are minute plastic particles of size smaller than 5 mm (Wagner et al. 2014) and have become a major environmental concern because of their potential to harm the ecosystem and human health (S. Xu et al. 2020a, b). These particles come from a variety of sources, including cosmetics, textiles, and degraded plastic waste. MP are persistent in the environment and can accumulate in soil, sediment, water bodies, and biota, where they can cause physical harm and release toxic chemicals (Chaukura et al. 2021).

Microbeads in personal care products are examples of primary MP that are generated on purpose, whereas secondary MP are created when bigger plastic waste undergoes mechanical breakdown. Owing to their small size and light weight, they can spread easily and penetrate various environmental compartments. This makes them ubiquitous, irrespective of the source. Although oceans are the ultimate sink for MP, as with any pollutant, soils hold them for a long period before they reach the ocean. Therefore, it is equally crucial to address the consequences in soil, as it is for the oceans, to perceive the ecological effects of MP. Wastewater solids (Conley et al. 2019; Corradini et al. 2019), plastic applications in farming like greenhouses, mulch, or silage films (Piehl et al. 2018), and plastic-containing fertilisers (Conley et al. 2019), tyre deterioration (Jan Kole et al. 2017), municipal sewage (Chae & An 2018), landfills (Su

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et al., 2019), etc., are the major sources of soil-invading MP particles (Weithmann et al. 2018). Several researchers have unravelled the consequences of MP in terms of soil physicochemical properties (e.g. bulk density (De Souza MacHado et al. 2018), water holding capacity (Huerta Lwanga et al. 2016), and contaminant sorption (Horton et al. 2017)), microbial (Yi et al. 2021), and plant growth (Sun et al. 2020). Recent reviews discuss various aspects of MP pollution in marine and terrestrial systems, of which the most addressed themes are listed in the following.

Sources and types: Possible sources and types of MP include microfibers from clothing, microbeads in personal care products, and microfragments (C. Wang et al. 2020a, b), which are the degradation (mechanical/physical) products of large plastic materials (S. Xu et al. 2020a, b; D. He et al. 2018). Effluents of wastewater treatment plants and washing machines are identified as very large sources of MP in the environment (Conley et al. 2019; Browne et al. 2011).

Detection and measurement: Detecting, determining, and identifying MP are challenging because of their size, heterogenous distribution, and complexity of the observed environmental matrix. Intensive research is being undertaken to advance the current methods and instrumental techniques, such as FTIR, Raman and its microanalysis, and thermo-analytical methods (Y. Zhang et al. 2020; Radford et al. 2021).

Environmental impact: MP particles can affect the quality of aquatic and terrestrial systems, with adverse effects on various physical, chemical, and biological processes as well as on the health of organisms, including humans (Dhevagi et al. 2022; S. W. Kim et al. 2021). Such observations are briefly discussed in the next section.

Mitigation strategies: The observed harmful effects of MP on the biota point to the demand for developing mitigation strategies. Reducing the production and use of plastics and MP, improving waste management practices, and developing technologies to remove MP from the environment are among the few expert suggestions (Chaukura et al. 2021; Gerdes et al. 2018).

Policy and regulation: Identifying the emergency, there is a call to formulate local and global policies and regulations. Different policies and regulatory approaches are reviewed by many authors (Shahul Hamid et al. 2018; Karbalaei et al. 2018).

Environmental impact of MP

Researchers have unravelled the consequences of MP on soil physicochemical properties (e.g. bulk density (De Souza MacHado et al. 2018), water holding capacity (Huerta Lwanga et al. 2016), contaminant sorption (Horton et al. 2017)) and growth and development of soil organisms (e.g. microbes (Yi et al. 2021), plants (Sun et al. 2020), earthworms (S. Guo et al. 2023a, b)). A detailed review of research works shows that MP induce both unfavourable and favourable effects within aquatic and terrestrial ecosystems, although evidence for the latter is limited.

Effects on soil physical properties

Polyamide (PA) beads, which are often used in personal care products and industrial applications, were found to contaminate soil, potentially affecting soil structure, water holding capacity, and plant-root interactions (Nizzetto et al. 2016). Polythene (PE) fragments commonly derived from plastic bags and packaging materials can persist in soil, leading to reduced water infiltration, altered nutrient cycling, and changes in microbial communities (Sun et al. 2020). Different polymer types with respect to the chemical structure can have varying degrees of persistence and potential to interact with soil components (Koelmans et al. 2017).

Effects on soil chemical properties

MP of all kinds, including polyester (PS) fibres, PA beads, and PE fragments, were found to disturb the soil's natural equilibrium in agroecosystems (Chae et al. 2018). For example, PS fibres can accumulate in soil, causing nutrient immobilisation and hence reducing nutrient availability to plants and other soil organisms (Horton et al. 2017). At the same time, MP particles could interfere with mineralisation and decomposition of soil organic carbon (SOC), leading to a reduction in microbial greenhouse gas emissions (Yu et al. 2021). Rillig et al. (2021) suggested that delayed decay of leaf litter caused by the presence of MP particles might diminish carbon sequestration in soil organic matter (SOM) (Rillig et al. 2021). On the contrary, degradation of biodegradable MP can trigger the priming effect, wherein the release of bioavailable carbon resources during MP degradation enhances the decomposition of SOM (J. Zhou et al. 2021). In addition to this, MP might modify the biogeochemical cycles of nitrogen, phosphorous, and potassium (Wijesooriya et al. 2023). Interaction and holding of water within the soil matrix were also found to be affected by the presence of MP, as observed in terms of changes in water preservation and permeability (Sajjad et al. 2022). This result is complemented by a study conducted by Guo et al. (2022), who demonstrated that varying particle size and concentration of polypropylene (PP) microparticles have resulted in a reduction of saturated hydraulic conductivity (Z. Guo et al. 2022).

Effect on mobilisation of heavy metals and small organic compounds

Sorptive properties of MP particles towards heavy metals and small organic contaminant molecules have been widely studied, since the micro-sized polymer particles are good sorbents, owing to their surface characteristics. There is evidence suggesting that heavy metals and hydrophobic organic compounds can sorb onto MP surfaces in aquatic systems (Brennecke et al. 2016; Davranche et al. 2019; Hodson et al. 2017; Holmes et al. 2014). In comparison to the latter, heavy metals exhibit considerably lower sorption coefficients within a similar initial concentration range (F. fei Liu et al. 2019a). Further, the effect of polymer aging on sorption capacity was explored: aged MP exhibited stronger affinity for heavy metals than for hydrophilic organic compounds (B. Xu et al. 2020a, b). In short, MP can serve as a carrier of both of these species. This would help these contaminants access environmental regimes that are not otherwise accessible and enhance their transport and mobility. Thus, MP may cause an added effect—of itself and of the carried species.

Studies on the influence of MP on heavy metal toxicity posed mixed results. PE particles showed no effect on the toxicity of Cu to marine microalgae (Davarpanah & Guilhermino 2015), but were found to enhance the toxicity of hexavalent Cr to early juveniles of the common goby fish. Kim et al. (2017) observed that Ni alone is less harmful to Daphnia magna than Ni in the presence of PS, due to the increased intake of Ni when present along with PS (D. Kim et al. 2017). They have also found that the chemical structure of MP is decisive for the enhancement in Ni assimilation. Similar results were obtained with Ag-PE (Manuscript 2017) and Cd-PS systems (Lu et al. 2018) in the case of the zebrafish.

Effects on biota

MP can be carried through the soil by earthworms and are known to impact negatively on seed germination, plant development, and bacterial populations (Sajjad et al. 2022; Rillig et al. 2021, 2017; Cao et al. 2017; Qi et al. 2018). The particles enter plant roots and leaves directly from the soil and the air and reach the entire plant body (Luo et al. 2020; Hollóczki & Gehrke 2019; Lin et al. 2020). Even the microparticles from biodegradable plastic mulches are dangerous to soil bacterial populations and to seed germination (Boots et al. 2019). This suggests that physical interactions caused by MP, owing to their size and shape, are already sufficient to impart adverse effects. MP can move through the food chain (Y. L. Wang et al. 2020a, b) and have a significant impact on the health of higher-level organisms at the subcellular and molecular levels (L. Li et al. 2020a, b).

Influence of polymer properties on environmental effects

The size and shape of MP can influence their mobility, transport, and distribution in the soil environment, affecting their accessibility to soil organisms, potential for contaminant binding, and turnover of soil carbon and nutrients (Huerta Lwanga et al. 2016; Wijesooriya et al. 2023). For example, PS beads were found to affect soil properties and plant photosynthetic parameters by changing microbial metabolism and correlations among microbes (Ren et al. 2021). On the other hand, polymer fibres alter soil aggregate formation and stabilisation, whereas other particle shapes affect organic matter (OM) loss (Lehmann et al. 2021). Surface properties of MP, such as hydrophobicity and the presence of adsorbed chemicals, can influence their interactions with soil particles and microbial communities (Horton et al. 2017). Biodegradable MP exhibit stronger inhibitory effects on plant growth compared with non-biodegradable ones (Inubushi et al. 2022).

Favourable effects of MP

Although very few in number, studies have reported certain beneficial effects of MP on agroecosystems by enhancing soil structure, aeration (J. Zhou et al. 2021), and soil enzyme activity (H. Liu et al. 2017). Presence of MP, in an atmosphere with the right temperature and moisture level, can boost plant root exudation and promote root growth (Y. P. Wang et al. 2016). Additionally, these pollutants prevent water from evaporating, which raises soil moisture levels (Qin et al. 2015). MP increase carbon sequestration, decreasing greenhouse gas emissions (Sajjad et al. 2022; Yu et al. 2021). PS fibres were found to increase microbial communities of the mycorrhizal coil and to trigger greater root health (De Souza MacHado et al. 2019). It was suggested that microorganisms can interact with MP particles by adhering to their surface, perhaps utilising them as growth substrates, altering their properties, or even biodegrading them (Lin et al. 2020; Stabnikova et al. 2021). Altogether, the direction and intensity of the effect vary depending on several factors, which are yet to be examined in detail.

From the above discussion, it can be deduced that MP induces changes mainly within the OM regime of both water and soil systems: changes in microbial population, plant growth, nutrient cycling, C sequestration, and water holding capacity are mostly operated through SOM and dissolved/particulate organic matter in terrestrial and aquatic systems, respectively. Therefore, it could be deduced that MP enter into considerable interactions with natural organic matter (NOM). Recent studies have demonstrated that NOM significantly influences the environmental behaviour and impacts of MP. MP adsorb NOM molecules, forming a surface 'eco-corona' that alters their physicochemical characteristics such as surface charge, hydrophobicity, and aggregation propensity (W. Chen et al. 2018; Abdurahman et al. 2020). This interaction modulates the fate of MP by enhancing dispersion in aquatic and terrestrial environments, increasing microbial colonisation on MP surfaces, and affecting their bioavailability and toxicity (Yi et al. 2021; Qiao et al. 2019Enfrin et al., 2019). Consequently, MP-NOM associations influence environmental processes including nutrient cycling, microbial community structure, and contaminant transport dynamics in ways that differ markedly from MP alone (Ali et al. 2022a; Q. Wang et al. 2023). Therefore, consideration of MP-NOM associations is essential to fully understand and predict the ecological effects of MP pollution. Further, a number of studies suggest that MP behave differently in the presence and absence of NOM, as will be discussed further below. It is in this context that this review focuses on the interaction of MP with NOM. In order to make the discussion easier, a brief outline of the relevant physicochemical features of NOM is given below.

Background on natural organic matter (NOM) and its environmental significance

NOM is a diverse and intricate blend of organic compounds that exhibits complexity and heterogeneity resulting from various interactions between the hydrological cycle, biosphere, and geosphere (Matilainen & Sillanpää, 2010). It is a significant source of carbon and nutrients for aquatic microorganisms, playing an important role in microbial food webs and biogeochemical cycling (Hamid et al. 2025). The composition of NOM varies widely depending on the source, environmental conditions, transformation pathway, and age. Macromolecules, small molecules including water, ions, etc. are held together by supramolecular interactions (Schaumann 2005; Simpson et al. 2002). This provides a high degree of dynamicity as well as complexity to the matrix. It is very reactive due to the presence of many functional groups (Philippe & Schaumann 2014). Protonation/deprotonation status of the acidic functional groups (carboxylates, phenols, amines, and thiols mainly) varies with respect to environmental conditions like pH and is decisive for several interactions (Schaumann et al. 2013). Presence of NOM in environments like soils and water bodies influences key ecological processes through its role in carbon cycling, nutrient dynamics, and pollutant interactions (Hamid et al. 2025). NOM adsorption alters MP surfaces by forming eco-coronas, which modify charge, hydrophobicity, and aggregation; this increases MP stability and mobility while binding pollutants/metals to modulate bioavailability (Yao et al. 2023). In soils, NOM reduces mineral protection of carbon, accelerating decomposition and elevating CO_2 emissions compared to MP-free systems (Shi et al. 2025). NOM acts as a nutrient source, enriching degradative microbes (e.g. nitrogen-fixers, phosphorus-solubilisers) and fostering biofilms on MP, which boosts biodegradation but reduces overall diversity and nitrifier abundance (Y. Li et al. 2023). MP-derived dissolved organic matter (DOM) from NOM interactions heightens microbial respiration and alters community structure more than natural NOM alone (J. Wang et al. 2025a, b). NOM molecular segments interact with various pollutants such as heavy metals, pesticides, and pharmaceuticals, by binding to them or altering their mobility and bioavailability (X. Wang et al. 2022a, b). Coexistence of NOM and MP disrupts soil health via nutrient imbalances and enhanced pollutant transport, with NOM mitigating acute MP toxicity but amplifying long-term carbon loss and toxicity in aquatic species (Ijaz et al. 2025). The structural complexity and high degree of heterogeneity pose significant challenges in understanding its chemical structure and behaviour, particularly with respect to its impact on water quality, mobility, and bioavailability of metals and other species (Philippe & Schaumann 2014; Schulten 1999).

Objectives of the review

The above discussion substantiates the role of MP in establishing the properties and functioning of various environmental compartments. Thus, a clear-cut understanding of the mechanism by which MP enter and behave within each environmental matrix is to be drawn essentially. A critical analysis of recent research works brings out sufficient evidence to consider that these polymer particles engage with organic moieties in aquatic and terrestrial systems: MP and NOM exhibit an affinity for each other and enter into interplay, dependent on various factors. It would be interesting to examine the evidence on MP-NOM interaction as well as the nature and consequences of the interplay. This review, therefore, consolidates and critically assesses the state-of-the-art research that points towards MP-NOM interaction, with a focus on the following aspects:

Evidence for MP-NOM interaction
Properties of MP, NOM, and the environment, relevant to MP-NOM interaction
Alteration in properties of MP and NOM induced by each other
Consequences of MP-NOM interaction for ecosystem processes

This critical review assesses the possibility of the existence of an ‘MP-NOM association’ through the interaction between MP particles and NOM structures. It is aimed at constructing a model for the guiding interaction mechanism and consequences of the MP-NOM association.

Evidences for MP-NOM interactions

In an attempt to collect evidence for the MP-NOM interaction, we came across several observations which are suggestive of (1) the ways in which MP is incorporated into the OM matrix, (2) various controlling factors, and (3) resultant changes, as detailed below.

Mechanism of MP-NOM interaction

MP can adsorb NOM molecules onto their surface, similar to other organic chemicals (Abdurahman et al. 2020; Zuo et al. 2019). Sorption even leads to the formation of an 'eco-corona' on MP by absorbed layers of humic and fulvic acids (FA), excreted waste products, and molecules of lipids, polysaccharides, proteins, and macromolecules (Galloway et al. 2017; Yao et al. 2023; Junaid & Wang 2021). This phenomenon of 'eco-corona' formation was mostly observed on nano plastic particles with sizes less than 100 nm.

The sorption process is led by the surface charge of polymer particles as well as the structural dynamicity and the electrical charge of OM molecules (Paul et al. 2023; Gao et al. 2023; Dong et al. 2020). Derjaguin-Landau-Verwey-Overbeek (DLVO) analysis by Li et al. (2018a, b) confirmed that sorption of humic acid (HA) on PS MP caused the zeta potential to be more negative than that of the uncoated particles (S. Li et al. 2018a, b). The contribution of the electrical double layer outweighed the effect of van der Waals' attraction between the particles, in the case of HA-coated PS particles, resulting in dispersal. This idea was further supported by Paul et al. (2023), who confirmed spectroscopically that dissolved organic matter (DOM) molecules obtained from a surface water sample were able to sorb onto low-density polyethylene (LDPE) particles within the treatment time of 72 h (Paul et al. 2023). The authors proposed that the electrical charge and the structural flexibility of OM could enhance the dispersal of polymer particles in water. Additionally, π-π conjugation and electrostatic attraction were attributed as the interaction mechanisms for MP-DOM association when PS is the MP counterpart (W. Chen et al. 2018). PS, with its rich aromatic structure, can conjugate with aromatic structures of OM through π-π interaction. A couple of recent studies further confirm the above models, indirectly (Zhao et al. 2020). Since polyurethane has a benzene ring, it exhibited more sorption than the other two polar MP polybutylene succinate (PBS), polycaprolactone (PCL), suggesting that π (n) -π electron donor-acceptor interactions exist (Zhao et al. 2020).

Factors governing MP-NOM association

The previous section already discussed the fact that MP properties (such as chemical structure, surface charge, zeta potential), as well as the chemical structure of NOM, are crucial in the formation of MP-NOM associations. This has been further confirmed by several authors (X. Li et al. 2020a, b). The surface charge of both the MP and the NOM can be influenced by the pH of the solution, salinity, ionic strength, and nature of ions constituting the medium (Ateia et al. 2022; Takács et al. 2023). Hence, these environmental factors are also decisive for the development of the electrical double layer between the MP particle surface and the NOM molecules (W. Chen et al. 2018; Dong et al. 2020; X. Li et al. 2020a, b; Hüffer & Hofmann 2016), potentially affecting the formation and stability of MP-NOM associations. In short, polymer properties, NOM properties, and environmental properties govern the association, which are discussed below.

Polymer properties

Physicochemical properties of plastic particles such as size, surface area, porosity, weight, aging status, and molecular structure are crucial for their interaction (W. Chen et al. 2018; Reaume-Zabalgoitia; Sabrina Nöel 2020; Ali et al. 2022b). More adsorption sites may be offered by surfaces that are rougher and more porous (Joo et al. 2021; Reaume-Zabalgoitia; Sabrina Nöel 2020; Agboola & Benson 2021). The same would happen when the MP size is reduced, as indicated by recent studies: interaction between a DOM sample and PS particles was found to be pronounced when the particle size was reduced from microscale to nanoscale (K. Zhang et al. 2018a, b, c). IR- and fluorescence investigations on PS-HA interaction revealed a higher affinity of humic acid for small MP particles than for larger particles when applied in the same concentrations (W. Chen et al. 2018). It could be because more sorption sites are exposed by the reduction in particle size (Ateia et al. 2022). A study on vertical migration of various MP through a sand column in the presence and absence of DOM implied that DOM binding was more efficient for Poly ethylene terephthalate (PET) and PE than for PP and PA, revealing the importance of the chemical structure of the MP polymer for sorption of NOM (S. Gao et al. 2023). Spectroscopic evidence obtained by Paul et al. (2023) for the adsorption of NOM onto LDPE microparticles was presented, which suggests that the adsorption process is influenced by both the chemical composition of NOM and the surface properties of MP (Paul et al. 2023). In saturated goethite-coated sand columns, allochthonous NOM (mostly HA and cellulose) produced from agricultural organic inputs may facilitate the transportation of PS MP (0.4 µm). The strong interaction between PS-nanoplastics (NP) and HA/cellulose, on the other hand, significantly contributed to the slowing of PS-NP (50 nm) transit. These results suggested that while smaller-size NP would remain in the tillage layer, an abundance of allochthonous NOM in agricultural soils would lead to the downward transit of larger-size plastic particles (Ali et al. 2022b).

The intrinsic chemical structure of MP plays a vital role in their interactions with NOM. The aromatic rings in PS facilitate π-π interactions with aromatic moieties of NOM, which enhance adsorption affinity and lead to stable eco-corona formation on the polymer surface (F. fei Liu et al. 2019b; Abdurahman et al. 2020). In contrast, polyolefins like PE and PP, being highly hydrophobic and non-aromatic, predominantly interact with NOM through hydrophobic forces such as van der Waals interactions and hydrophobic partitioning, which influence adsorption strength and aggregation behaviour (Q. Wang et al. 2022a, b). Beyond surface area, polymer polarity and aromaticity therefore fundamentally determine the nature and extent of MP-NOM associations, impacting their environmental fate and transport.

NOM properties

The chemical structure of NOM, defined by the nature and abundance of functional groups, protonation-deprotonation status of acidic moieties, and size of OM molecules, could be the determinant for their sorption on MP. However, currently available data are insufficient to draw a generalisation. The major challenge is that NOM is highly complex and heterogenous and its structural characterisation cannot be done unambiguously. The currently available data give indirect evidence through the influence of pH, as indicated in the works below. Polyvinyl chloride (PVC) exhibited enhanced adsorption capabilities as the pH value climbed from 3.0 to 6.0. The functional groups of MP were deprotonated as the pH level rose, increasing their electronegative characteristics. HA and MP can readily form a copolymer, which would improve the heavy metal adsorption behaviour. It typically has a negative charge and is made up of different oxygen functional groups. The combination of HA copolymer and MP improved the electrostatic response by increasing electronegativity on the PVC surface. Furthermore, the MP surfaces readily absorbed the complexations of metal ions and HA (Q. Wang et al. 2023).

DOM binding characteristics with MP vary with type and composition, with aromatic and hydrophobic substances dominating. Oxygen-containing functional groups in MP are the most preferred DOM binding structure (Ding et al. 2022). Soil humic acid (HA) was divided into different HA fractions and analysed for adsorption on PS MP. High molecular weight-fractionated HAs dominated, exhibiting higher adsorption affinities and active adsorption sites. These HAs exhibited stronger adsorption affinities and complexation capacities to PS MP (R. Gao et al. 2022).

Environmental factors

It could be expected that factors like temperature, moisture, pH, salinity, ionic strength, and the presence of other pollutants influence MP-NOM associations (Joo et al. 2021). Surface charge of polymer particles and protonation/deprotonation status of NOM functional groups are affected by pH (J. Zhang et al. 2023), which would thence control the formation of NOM-MP associations. This was evidenced by a fluorescence study, which showed that binding of PS to DOM was more pronounced at neutral pH than in alkaline or acidic conditions (W. Chen et al. 2018). Studies have shown that at high salinity levels, the adsorption of NOM onto MP decreases due to the increased competition between salt ions and NOM for adsorption sites on the MP surface (Munoz et al. 2021; Q. Wang et al. 2023). In addition, ions in highly saline water/soil solution could bind strongly at the functional groups of NOM, making them unavailable for sorption at MP surfaces. Presence of other pollutants such as organic molecules and/or heavy metals could induce a similar competition effect. As seen previously, the weak interactions holding the NOM suprastructure together are vulnerable to rearrangement, even at slightly elevated temperatures (Kunhi Mouvenchery et al. 2013). This implies that MP-NOM associations could also be easily disrupted by alterations in environmental temperature.

In a study in which the effects of HA and the clay mineral bentonite, separately and together, on the mobilisation of MP particles were investigated, it was found that the ionic strength of the medium determines which component plays the crucial role. For example, when HA and bentonite were present in equal amounts in MP suspensions, bentonite dominated the control of MP transport at low ionic strength, while HA and bentonite both made significant contributions at high ionic strength. The two kinds of natural colloids would have a significant impact on MP movement in porous media under solution conditions (M. Li et al. 2021a, b).

Consequences of MP-NOM association

On properties, fate, and transport of MP

NOM can adsorb or complex with MP and control their fate, transport, and toxicity in aquatic and terrestrial environments (Wagner et al. 2014; J. Gao et al. 2021a, b; Qiao et al. 2019). The presence of OM could modify the surface of MP, with consequences for properties such as surface area, surface charge, size, and hydrophobicity. Such changes could have implications for processes such as aggregation/dispersal of MP particles, surface sorption of other contaminants or microorganisms, and biological intake of MP by aquatic organisms (Horton et al. 2017; Eerkes-Medrano et al. 2015; Koelmans et al. 2017; W. Chen et al. 2018; Ateia et al. 2022; J. Li et al. 2015). The following case studies are suggestive of the same.

Enhancement in dispersion, wettability, and microbial colonisation was observed for PS microparticles due to the presence of NOM (Enfrin et al. 2019). This was explained to be because of the development of hydrophilic sites on the particle surface, as NOM carries deprotonated functional groups in the tested pH range (Anbumani & Kakkar 2018; W. Chen et al. 2018; Enfrin et al., 2019). In this way, MP particles, which are hydrophobic, would become hydrophilic and be more dispersible and vulnerable to microbial attack than otherwise, in the presence of OM. In line with these, Chen et al. (2023a, b), with the help of scanning electron microscopy, have observed that the surface morphology of PS MP was altered, with increased surface roughness, when they were treated with DOM (Y. Chen et al. 2023a, b). They observed DOM-induced aggregation for very small particles of around 80 nm. Also, the authors have produced strong spectroscopic evidence for changes in the chemical structure of the MP surface. OM can induce aging of MP particles, as observed for PS under conditions of UV irradiation, possibly driven by hydroxyl radicals and evidenced by electron paramagnetic resonance spectroscopy (Anbumani & Kakkar 2018; Qiu et al. 2022).

Aggregation of micro-PS particles was greatly enhanced by the presence of a relatively low concentration of HA, according to typical aggregation profiles of micro-PS with HA as a function of the electrolytes, and it confirms that HA enhanced the stability of micro-PS (S. Li et al. 2018a, b). While the presence of NOM enhances the colloidal stability of PS MP through eco-corona formation (Yang et al. 2025), this stabilisation effect is also relevant to biodegradable plastics such as polylactic acid (PLA), albeit modulated by their distinct physicochemical properties and biodegradability. For biodegradable plastics like PLA, NOM can similarly adsorb onto the polymer surface, potentially forming an eco-corona that impacts stability; however, the overall effect is modulated by the distinct physicochemical properties of PLA, including its biodegradability and more hydrophilic nature. Unlike PS, PLA's biodegradation involves hydrolysis leading to polymer chain scission, which contributes to surface morphology changes intrinsic to the polymer breakdown process (Brdlík et al. 2021; Withana et al. 2025). Surface morphology changes observed in biodegradable MP like PLA arise both from intrinsic degradation processes such as hydrolysis and microbial breakdown, and from interactions with NOM, which can promote biofilm formation and microbial colonisation, further influencing degradation dynamics (Brdlík et al. 2021; Narancic et al. 2018).

Owing to the enhancement in dispersion of MP particles by the presence of NOM, they are kept longer in water and are transported to other locations (Y. Zhou et al. 2020a, b; Horton et al. 2017; X. Gao et al. 2021a, b). This was further evidenced and explained by Chen et al. (2018): when PE MP were preloaded with NOM, they exhibited enhanced adsorption of micropollutants. This can lead to an increase in the density of the plastic and enhance aggregation, promoting transport of MP into deeper water layers (W. Chen et al. 2018; Lobelle & Cunliffe 2011). MP tend to gradually sink until they attain the same density as the encompassing seawater. Consequently, they remain adrift and have the potential to be carried across extensive distances through marine currents (Cózar et al. 2014). Vertical transport of various MP through a sand column was observed, and it was found that the transport depends on the chemical nature of MP. O'Connor et al. (2019) reported on the vertical migration of PE and PP microplastics in sand columns, showing size-dependent penetration with smaller PE particles migrating deeper, influenced by wet-dry cycles (O'Connor et al. 2019). Dong et al. (2020) delivered contradicting results when functionalised PS particles were coated with Suwannee River HA, depending on the nature of the functionalising material. When the PS surfaces were altered by electron-dense chemical structures, further coating by HA would lead to the disaggregation of plastic particles. On the other hand, when the PS surfaces were made electron-deficient, HA molecules induced bridging effects such that the particles get aggregated, adversely affecting transportation in the water medium (Dong et al. 2020).

NOM coating can alter the sorption behaviour of MP towards anthropogenic pollutants (Ali et al. 2022b), making the process more complex (B. Xu et al. 2018; Ali et al. 2022b). There are contradicting observations: for sorption of phenanthrene, naphthalene, and 1-naphthol on HA-coated multi-walled carbon nanotubes (MWNT40), the HA coating did not significantly alter sorption, indicating that it did not significantly alter its physical form and surface properties. Peptone coating (NOM) significantly suppressed phenanthrene, naphthalene, and 1-naphthol sorption by MWNT40, reducing the accessibility of sorption sites (X. Wang et al. 2008).

On the other hand, sorption of Pb ions on PVC microparticles was diminished by coating with NOM, arguably because sorption sites were already occupied by NOM molecules (Q. Wang et al. 2023). Similarly, a sorption study conducted by Xu et al. (2018) using tetracycline on three types of MP (PE, PP, and PS) in the presence of FA suggested that FA can hinder the MP-tetracycline interaction, possibly because of the higher affinity of tetracycline for FA than for MP (B. Xu et al. 2018). Wang et al. (2019) investigated the role of HA in controlling the adsorption of lead on PVC (J. Wang et al. 2019) and found that HA molecules complexed the aqueous lead ions, in parallel with sorption on the PVC surface (Ali et al. 2022b). Growth of biofilms, which can also be considered a very simplified analogue of NOM, resulted in increased adsorption of heavy metals onto MP (Q. Wang et al. 2023).

That means the interplay between the dispersity effect resulting in increased surface area and the blocking effect resulting in decreased number of sorption sites would decide the ultimate consequences, in the actual environmental situation (X. Wang et al. 2009; S. Zhang et al. 2011). Also, the chemical nature of the polymer plays a determining role: it was found by Zhou et al. (2020a, b) that as the HA concentration increases, the amount of adsorbed Cd (II) on the PA, acrylonitrile butadiene styrene (ABS), and polyethylene terephthalate (PET) decreased while sorption onto PVC and PS decreased (Y. Zhou et al. 2020a, b). Enhanced adsorption of contaminants on MP in the presence of NOM would imply that MP serve as potential contaminant transfer agents, meaning they can transport pollutants and other harmful substances from one location to another (Ateia et al. 2020). Different types of NOM influence the adsorption capacity of MP for pollutants variably; while some NOM fractions competitively adsorb onto MP, reducing the availability of pollutant binding sites, others, such as humic substances, can enhance adsorption through complexation and bridging effects, leading to ternary complex formation that increases overall pollutant retention (Ali et al. 2022a; J. Li et al. 2021a, b; Q. Wang et al. 2023). Humic acids, characterised by higher molecular weight, aromaticity, and hydrophobicity, mitigate microplastic toxicity by forming a protective eco-corona on the plastic surface and scavenging reactive oxygen species, whereas FA, which have lower molecular weight and are more hydrophilic, exhibit a lesser capacity to reduce toxicity due to weaker interactions with microplastics (Ijaz et al. 2025; Hamid et al. 2025). FA, due to their higher solubility and lower affinity for microplastic surfaces, are less effective at forming protective barriers and may facilitate pollutant transport. This difference arises from variations in sorption capacity, surface adsorption, aggregation behaviour, and interaction strength with microplastics, driven by their lower aromaticity, molecular weight, and hydrophobicity compared to humic acids. Therefore, the overall impact of NOM on microplastic toxicity is determined by the prevalence of HA or FA structures and their molecular characteristics (Hamid et al. 2025; Ijaz et al. 2025). Therefore, NOM effects on pollutant adsorption are not always competitive but depend on NOM composition, pollutant type, and environmental conditions. Retention of smaller-sized plastic particles in the presence of allochthonous NOM in tillage can build up in the roots and go to the shoots, potentially having a direct or indirect impact on crop and plant yields. It is necessary to conduct more research since their accumulation in the tillage layer would increase the risk of NP being transmitted from the food chain to humans (Ali et al. 2022b).

On the toxicity of MP affected by NOM coating

It is already well-established that MP are harmful to aquatic organisms such as fishes and invertebrates, through ingestion or entanglement (Chaukura et al. 2021; Ali et al. 2022b; Lei et al. 2018; Sharma & Chatterjee 2017; Ma et al. 2019; M. He et al. 2022). Qiao et al. (2019), in their study to investigate the influence of NOM on the toxicity of PS MP for zebrafish embryos, found that the presence of NOM has exacerbated the toxicity of MP (Qiao et al. 2019). A similar effect was found on the ingestion and toxicity of PS MP in the case of krill (Dawson et al. 2018) and *Daphnia magna* (Schür, 2022). The authors suggested that the presence of NOM on MP surfaces enhances their bioavailability and hence uptake. Apart from that, enhanced dispersal of NOM-coated MP particles might also contribute to the enhanced bio-uptake. It was also found that different types of NOM (with respect to structural composition) showed different levels of toxicity enhancement on MP (Qiao et al. 2019). Allochthonous NOM in tillage can accumulate smaller plastic particles, potentially impacting crop yields and increasing the risk of transmission from the food chain to humans. Further research is needed (Ali et al. 2022b).

Different structural components of NOM distinctly influence the toxicity of MP; aromatic-rich humic substances containing quinone and phenolic functional groups tend to enhance toxicity via increased reactive oxygen species (ROS) production and co-contaminant adsorption, while polysaccharide- and protein-rich NOM fractions generally mitigate toxicity by forming protective biofilms and steric barriers on MP surfaces, reducing cellular uptake and oxidative stress (W. Chen et al. 2018; Enfrin et al., 2019; Velzeboer et al. 2014). HA, with their higher molecular weight and aromaticity, reduce MP toxicity by forming protective coatings and scavenging ROS, while FA, being lower in molecular weight and more soluble, are less effective and may enhance pollutant transport. Their differing capacities arise from variations in sorption, surface affinity, and aggregation behaviour driven by molecular structure (Hamid et al. 2025). These contrasting effects are mediated by NOM's modulation of MP surface charge, hydrophobicity, and electron transfer properties, necessitating detailed NOM characterisation for accurate toxicological predictions.

On properties, fate, and transport of NOM

MP-NOM interaction can change the mobility and bioavailability of NOM due to the increase in density, concentration, etc. (W. Chen et al. 2018). The presence of MP can increase the density of the water column, which can lead to a decrease in the mobility of NOM (Ali et al. 2022b). Additionally, aquatic species can consume MP-NOM complexes, which can improve NOM's bioavailability (Ali et al. 2022b). In marine ecosystems, MP may lead to an increase in the generation of OM in particle form. They can promote carbon cycling and aid in the development of gel-like particles (Galgani et al. 2019). Recent studies have placed significant emphasis on the impact of MP on the content of dissolved organic carbon (DOC) within the soil's DOM and found that MP continuously reduce DOC contents in soil (H. Liu et al. 2019a, b, c). Interactions between MP and NOM can affect DOC content in soil through a combination of physical sorption, altered microbial processing, and changes in OM molecular composition. MP possess a high affinity for DOM, leading to adsorption and sequestration of DOC fractions on MP surfaces, which can decrease DOC bioavailability and change the molecular diversity of SOM (Z. Guo et al. 2023a, b; Qiu et al. 2024; Q. Q. Guo et al. 2021). Simultaneously, some MP, especially biodegradable and weathered forms, may also release labile DOC or promote its production by stimulating microbial degradation of NOM, producing a context-dependent effect on overall DOC content (M. Chen et al. 2022).

It has also been found that MP can facilitate aggregation and accumulation of DOM, leading to changes in DOM composition and structure (Boldrini et al. 2021; W. Chen et al. 2018; Ali et al. 2022b). NOM sample showed an increase in fluorescence after treatment with PS microparticles, although PS itself is non-fluorescent. It was presumed that MP might act as an electron-donating bridge to HA, thus increasing the fluorescence intensity in aromatic moieties (W. Chen et al. 2018). However, these structural changes were found to be sensitive to the size of PS particles: the NOM structure, as observed by IR and fluorescence spectroscopy, was altered by PS particles with sizes of 500 nm and smaller. This suggests that the surface area of MP particles is crucial for observable structural changes in NOM molecules.

The aforementioned and similar changes in the chemical structure of OM could have significant consequences for the microbial communities that depend on DOM as a source of energy and nutrients (Boldrini et al. 2021). That means the diversity and population of microbial communities in the soil and water could be significantly affected.

On environmental processes

Nutrient cycling and microbial activity MP-NOM interaction can influence nutrient cycling. Through the leaching of dissolved organic materials, MP-NOM interactions can impact the carbon, nitrogen, and phosphorus cycles (Wijesooriya et al. 2023; H. Liu et al. 2017). That means nutrient availability can be affected, which in turn could affect biological growth. Further, it was found that MP particles act as a substrate for microbial growth (Yi et al. 2021). Coating of the surface by NOM could alter the quality of the surface such that the potential to hold the microbial community can be changed. MP fibres cannot alter water-stable aggregate and enzyme activities in the absence of OM but decrease in the presence of Plantago or wheat straw (Liang et al. 2021). Thus, changes in nutrient cycling, MP particle features, etc. caused in the presence of NOM would affect microbial growth and activity more than MP alone. The interaction between MP and NOM shapes soil microbial communities differently compared to MP alone by altering surface properties and nutrient availability, thereby enhancing microbial colonisation and biofilm formation (J. Wang et al. 2025a, b; Z. Feng et al. 2024). The interaction of PS microfiber and OM increases the activities of soil cellulase and laccase (Q. Q. Guo et al. 2021). It is also found that MP coated with humic-rich NOM promote increased abundance of OM-degrading genera such as *Pseudomonas* and *Bacillus*, while proteinaceous NOM fractions stimulate nutrient-cycling taxa including *Nitrosomonas* (K. Wang et al. 2025a, b). HA amendment has been shown to mitigate the negative effects of MP pollution on crop growth and rhizosphere microbial community composition; for instance, in black gram cultivation, HA enhanced the abundance of beneficial bacteria such as *Sphingomonas* and improved chlorophyll content and plant growth parameters in soils contaminated with microparticles of PE and PP, demonstrating its potential to restore soil microbial balance and promote plant health under MP stress (Virachabadoss et al. 2024; Senko et al. 2024). Different polymer types such as PE, PS, and PVC exhibit distinct surface chemistries and hydrophobicities that govern the selective adsorption of NOM fractions, forming conditioning films with varying compositions and thicknesses. These NOM coatings mediate the initial microbial colonisation by influencing cell adhesion and nutrient availability, thereby directing early biofilm succession and microbial community structure uniquely for each MP type. PE MP with hydrophobic NOM coatings reduce populations of sensitive groups like *Actinobacteria*, whereas PVC MP exhibit modulation due to leached plasticisers interacting with NOM (J. Li et al. 2022; Qiu et al. 2024). Weathered plastics often show increased oxygen-containing functional groups that further enhance NOM binding, altering biofilm characteristics compared to pristine MP. Consequently, the interplay between MP polymer characteristics and NOM composition determines the ecological functions and potential toxicity of MP in soil and aquatic environments (Rummel et al. 2021). Such MP-NOM synergies create unique microhabitats not observed with MP alone, affecting microbial diversity, abundance, and function.

The MP-NOM association is significant for the mobilisation and toxicity of other species like heavy metals. For example, Qiao et al. (2019) showed how NOM could promote Cu absorption, accumulation, and hence toxicity in zebrafish (Qiao et al. 2019). The increased toxicity could be the result of decreased Cu-ion transport and increased oxidative stress, according to transcriptomic analyses.

On sorption of small organic molecules and other contaminants

Formation of NOM-MP associations could lead to enhanced sorption of contaminants (Santschi et al. 2021). Sorption of contaminants on MP could be affected by NOM, involving two opposing mechanisms (Ateia et al. 2022): (i) better dispersion of MP induced by NOM may increase the accessible surface area of the sorbent (Li et al. 2018a, b), and (ii) NOM compete with other pollutants for the active sites (Zuo et al. 2019). MP particles serve as a transport medium for toxic chemicals. SOM possess strong sorptive capabilities for hydrophobic organic compounds (HOC) (B. Xu et al. 2019). This could suggest that MP compete with NOM for adsorption of chemicals in the soil and water environment (Andrady and Neal 2009). π-π conjugation between HA and the MP surface increases the electrostatic attraction for polar organic contaminants (OC) on MP, and hence, the adsorption of polar OC was found to be more pronounced in the presence of HA than FA (K. Zhang et al. 2018a, b, c; Abdurahman et al. 2020). On the other hand, the MP sorption process can be largely dominated by molecular sieving and pore blocking (Munoz et al. 2021; Ateia et al. 2020). NOM molecules are larger than the majority of contaminants; thus, they can ideally enter or block the pores of MP and stop other contaminants from going on to the active sites (Zuo et al. 2019). When MP are broken down or converted into NP, the NOM molecules have less access to the interior of the NP, since the contaminant molecules have less of a challenge getting to the NP's active sites (Ateia et al. 2022; K. Zhang et al. 2018a, b, c). These overlapping effects make the interactions between pollutants and NP complex. It has been assessed how DOC content affects the adsorption of pollutants onto MP. At greater DOC concentrations, in general, the adsorption of pollutants onto MP declines, but it also depends on the kind of MP (Tourinho et al. 2019). Altogether, it can be seen that the effect of NOM on OC adsorption depends on a number of variables, including NOM composition (HA vs FA) and concentration, charge, size, and polarity of pollutants, as well as the pore structure and surface chemistry and aging status of MP (X. Wang et al. 2022a, b; Ali et al. 2022b; Munoz et al. 2021; B. Xu et al. 2018; Tourinho et al. 2019; H. Feng et al. 2022; Wu et al. 2016; H. Zhang et al. 2018a, b, c; Seidensticker et al. 2017; Shen et al. 2018).

Is MP-NOM interaction analogous to the interaction of MP with small organic contaminants?

NOM is a complex supramolecular assembly composed of diverse small and large organic molecules held together by weak intermolecular forces such as hydrogen bonding, van der Waals forces, and hydrophobic interactions (Leenhee and Croué, 2003). Consequently, the interactions of MP with NOM segments can be parallelled to sorption observed for small organic contaminants such as pesticides, although NOM represents heterogeneous macromolecular structures rather than single molecules (F. Wang et al. 2018). Sorption of NOM to MP involves multiple interaction modalities including hydrophobic interaction, π–π electron donor-acceptor interactions with aromatic NOM fractions, hydrogen and halogen bonding facilitated by functional groups such as hydroxyls and carbonyls, and electrostatic interactions when charged species are present (H. Chen et al. 2023a, b; Hüffer & Hofmann 2016). The multicomponent nature of NOM results in heterogeneous sorption patterns, where the combined effects of size, polarity, and molecular structure differentially influence MP surface binding compared to smaller organic molecules (Seidensticker et al. 2018; Zhang et al. 2016). These insights help bridge the understanding of MP interaction with complex NOM systems from simpler models based on single organic pollutants. A wide range of organic compounds has been documented to undergo sorption onto MP, demonstrating a discernible pattern of sorption affinity (F. Wang et al. 2018; Ziccardi et al. 2016). For example, toxic chemicals such as polychlorinated biphenyls (PCB), polycyclic aromatic hydrocarbons (PAH), dichlorodiphenyltrichloroethane (DDT), perfluoroalkyl substances (PFA), pharmaceuticals, and personal care products. It was found that the concentration of PCB and dichloro diphenyl dichloro ethylene collected on PP pellets was up to 106 times higher than the levels found in the surrounding seawater because of the hydrophobic nature of plastic surfaces (Mato et al. 2001).

Mei et al. (2020) discussed the primary mechanisms of interaction between MP and organic compounds. Size, specific surface area, crystallinity and chemical structure of MP, functional groups, ionic form, and strength of both MP and organic compounds, as well as environmental factors (such as temperature, salinity and ionic strength) are important variables impacting the interactions (B. Xu et al. 2018; Wu et al. 2016; X. Liu et al. 2019a, b, c; Zhan et al. 2016; X. Zhang et al. 2018a, b, c; X. Guo et al. 2018; X. Guo et al. 2019; S. Zhang et al. 2019). A number of interactions such as electrostatic repulsion and attraction, van der Waals interaction, π-π interaction, hydrogen bonding, and halogen bonding were proposed. Due to the control of non-selective functional moieties, PE and PP can only combine with organic chemicals through van der Waals interactions. However, when dealing with aromatic organic compounds, the benzene rings allow PS to undergo π-π interactions, and thus, PS typically has a higher sorption affinity or potential for aromatic compounds (Hüffer & Hofmann 2016; Zhang et al. 2016). Furthermore, the sorption of organic compounds such as amoxicillin, tetracycline, ciprofloxacin, and 17β-estradiol to PA MP was found to be enhanced through hydrogen bonding of these molecules with the amide functional groups of PA (X. Liu et al. 2019a, b, c; X. Guo et al. 2019; S. Zhang et al. 2019).

Increased ionic strength/salinity increased the sorption of diethyl phthalate, dibutyl phthalate, triclosan, and perfluoro octane sulfonate (F. fei Liu et al. 2019a; F. Wang et al. 2015; Wu et al. 2016) to PE, PP, and PS, while there were no major effects on the sorption of tetracycline, carbamazepine, 17a-ethinyl estradiol, or musk ketone (Wu et al. 2016; B. Xu et al. 2018; X. Zhang et al. 2018a, b, c). Effect of polymer crystallinity was demonstrated by the following result: Guo et al. (2012) reported that phenanthrene, naphthalene, and lindane sorption coefficients to PE decreased with rising PE crystallinity (X. Guo et al. 2012), while Liu et al. (2019a, b, c) found a positive relation between 17b-estradiol sorption and MP PE crystallinity (X. Liu et al. 2019a, b, c). In addition, the nature of sorption isotherms was found to depend on polymer crystallinity: on rubbery polymers, linear sorption isotherms were commonly observed, whereas on glassy polymers, non-linear sorption behaviour was observed due to the pore-filling phase of organic chemicals into glassy polymers (Seidensticker et al. 2018).

The influence of MP particle size on the sorption of organic compounds was demonstrated as follows: the lower the MP particles, the higher their affinity for sorption of organic compounds (F. Wang et al. 2018; S. Zhang et al. 2019). However, the scale of MP and the resulting surface area are not significant factors determining the sorption of organic compounds by the various forms of MP, but rather the chemical properties of MP (Hüffer & Hofmann 2016). MP have a large specific surface area and high hydrophobicity, which allow them to bind to other organic and inorganic contaminants in the environment (Medyńska-Juraszek & Jadhav 2022).

MP-NOM associations

The above discussion evidences that MP engage in significant interaction with NOM segments to induce serious consequences in terms of both MP and NOM. This is demonstrated through the schematic diagram shown in Fig. 1.

Based on the available observations, it could even be suggested that MP enter various environmental compartments, such as soil, water, and sediments, through their respective OM. If true, MP-NOM associations would serve as the key to investigating the behaviour and mechanisms by which MP operate within the environment. However, this needs to be critically addressed and verified with targeted experiments.

Critical gaps in knowledge on MP-NOM interactions

Critical information gaps in the interactions between MP and NOM include the following:

> Lack of common analytical techniques: For the time being, no standardised analytical techniques exist to study interactions between MP and NOM. This limits our capacity to reach broad generalisations and makes it challenging to compare findings across many investigations.
> Limited knowledge of the interaction mechanisms: The precise mechanisms involved and their relative importance under various environmental conditions are not fully understood, despite the fact that it is known that MP and NOM can interact through a range of mechanisms, including adsorption, complexation, and aggregation.
> Limited understanding of the ecological effects of interactions between NOM and MP: Despite the potential ecological consequences of interactions between MP and NOM, such as the transmission of MP up the food chain, there is currently little understanding of the scope of these consequences and of how they differ across various ecosystems.

Environmental factors’ influence on interactions between MP and NOM is poorly known. Examples of these elements include pH, temperature, and salinity. This limits our capacity to forecast how MP would behave and move throughout various aquatic habitats. The complex nature of MP-NOM interactions also poses a challenge, as it requires

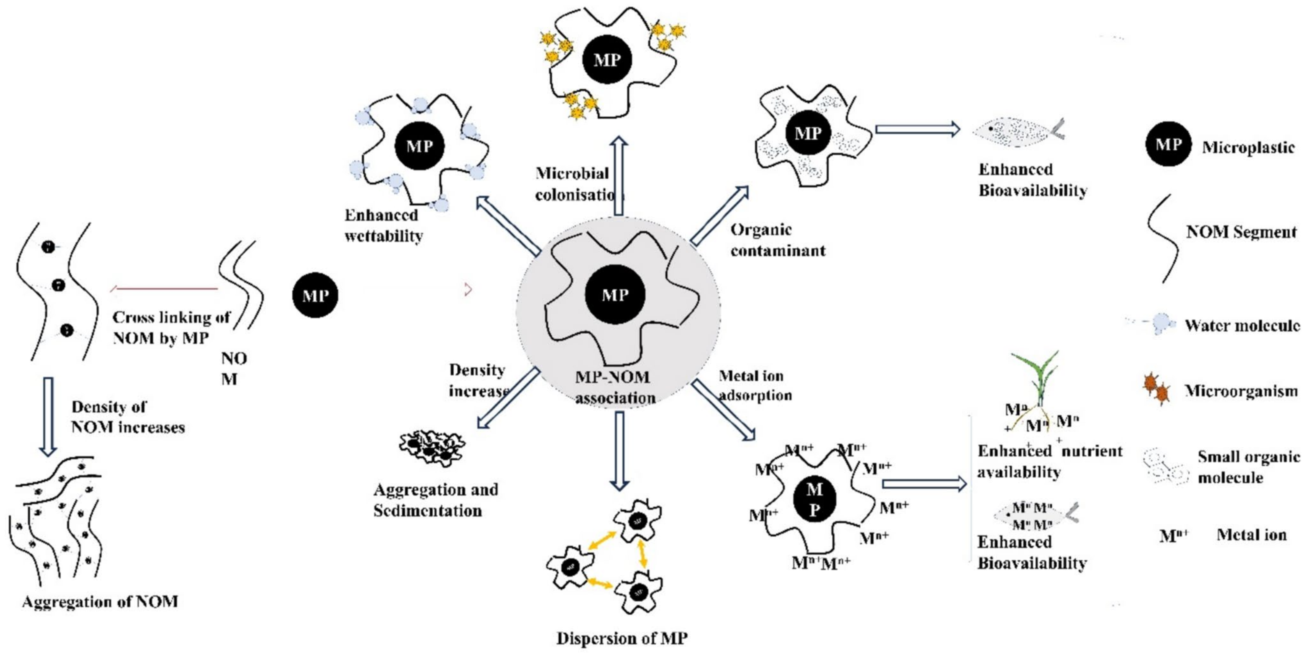

Fig. 1 Schematic diagram representing the formation of the MP-NOM association and possible interactions with selected other components in the environment

interdisciplinary research efforts to fully understand the mechanisms involved.

Technical challenges

Numerous studies have then investigated how either humic substances or proteins impact MP fate and transport (Abdurahman et al. 2020; X. Li et al. 2020a, b). However, these organic compounds may also interact with one another in addition to MP. Investigating OM adsorption with individual compounds does not allow the identification of synergies or competing effects that may be present. Additionally, because river water OM may change the surface properties of MP differently than that of wastewater, exploring MP fate and transport with more complex OM solutions is needed.

A number of technological difficulties and constraints must be overcome in the study of the interactions between MP and NOM, which is a complicated and difficult topic of inquiry. The following are some of the main technological difficulties and restrictions related to this field:

The necessity for intricate and time-consuming sample preparation and analysis processes is one of the major difficulties in studying MP and NOM. Because of the difficulty in standardising these methods, it might be difficult to compare the findings of various investigations.

MP and NOM quantification

Due to their low concentrations and the complexity of the matrices in which they are present, accurately quantifying MP and NOM in environmental samples can be difficult. The accuracy and precision of the data may be constrained as a result of problems with sensitivity and selectivity in analytical procedures.

It is necessary to develop more complex methodologies for characterising MP and NOM, including their size, shape, and chemical make-up. This knowledge is essential for figuring out how MP and NOM interact, as well as for forecasting how they will behave in aquatic environments.

Lack of standardised approaches

The absence of standardised approaches for researching MP and NOM can make it challenging to compare findings across studies and draw broad generalisations. Given the variety of methodologies and strategies applied in this subject, this is especially difficult.

Interaction complexity

There are many different environmental elements that have an impact on the complicated and dynamic interactions between MP and NOM. Because of this intricacy, it may be challenging to forecast the movement and fate of MP in aquatic systems as well as to comprehend the potential environmental effects of the interactions between MP and NOM.

Summary

This critical review demonstrates that microplastics (MP) engage in significant interactions with natural organic matter (NOM) through mechanisms including hydrophobic partitioning, π–π interactions, hydrogen bonding, and electrostatic forces, fundamentally altering MP surface properties, colloidal stability, and environmental fate compared to pristine MP. NOM coatings form eco-coronas that enhance MP dispersion and microbial colonisation while modulating pollutant sorption—either competitively reducing or facilitating it through ternary complex formation—yielding context-dependent effects distinct from MP alone that profoundly influence toxicity, transport, and bioavailability. These MP-NOM associations disrupt key ecosystem processes including carbon sequestration, nutrient cycling, and soil microbial community structure more substantially than MP independently, with humic-rich NOM promoting degraders like *Pseudomonas* while proteinaceous fractions favour nutrient cyclers like *Nitrosomonas*. The importance of MP-NOM interactions cannot be overstated, as they represent the dominant form of MP encountered in natural environments, necessitating their consideration in risk assessment models currently based on pristine polymers. Future research should prioritise the following: (1) standardised protocols for quantifying eco-corona composition across MP-NOM combinations, (2) long-term field studies tracking MP-NOM dynamics under realistic environmental gradients, (3) molecular-level investigations of NOM restructuring induced by MP using advanced spectroscopy, and (4) mitigation strategies exploiting NOM amendments (e.g. humic acids) to reduce MP bioavailability and restore soil microbial function. Addressing these gaps will enable accurate prediction of MP ecological impacts and inform targeted pollution management.

Author contribution Suhada Kottakkuth Mattayil: data curation, formal analysis, methodology, writing–original draft, writing—review and editing. Yamuna Kunhi Mouvenchery: conceptualisation, formal analysis, methodology, visualisation, writing—original draft, writing—review and editing

Data availability Data sharing is not applicable to this article as no new data were created or analysed in this study.

Declarations

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Consent to participate Not applicable.

Consent for publication Not applicable.

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