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Sediment matters as a route of microplastic exposure: A call for more research on the benthic compartment

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Microplastics (MPs) are ubiquitous in the marine environment. Here, most MPs are expected to sink, either due to polymer density or environmental processes, such as biofouling, leading to sediment being proposed to act as a final sink for marine MPs. There is a discrepancy between the anticipated accumulation of MPs in the sediment compartment and the MP experiments conducted, since most MP effect studies have been conducted with pelagic species using water-only exposures. Here we address fundamental questions in relation to MP pollution to close the knowledge gap related hereto. A systematic literature search was performed to address these questions. We found that benthic invertebrates ingest MPs and that, even though these organisms evolutionary are adapted to handle particles, adverse effects may be observed upon ingestion of MPs. The analysis further revealed that there is a major knowledge gap on the impacts of sediment-associated MPs in marine, benthic invertebrates. To facilitate further and structured research within this topic, we recommend more studies with emphasis on the sediment as an important exposure pathway, and to focus on sediment-associated MP effects on benthic invertebrates. We recommend studies with ecological relevant exposure concentrations and ecological relevant exposure durations with emphasis on impacts on population- and community-level to reduce the knowledge gap within this central area of MP pollution research.

KEYWORDS
marine environment, ecotoxicology, benthic invertebrates, effect, chronic exposure, long-term exposure, particles, plastic pollution

1 Introduction

Microplastic (MP) pollution is a global concern due to the continuous introduction and persistence of plastics in the environment (OECD, 2022), and the documented adverse effects of MPs on marine organisms (Darabi et al., 2021). It is estimated that 30 million tons of plastic floats in the oceans, and additional 1.7 million tons is introduced to the marine environment annually (OECD, 2022). Despite this significant pollution, the fate of the majority of marine plastic pollution is still unaccounted for, although it is believed to accumulate in marine sediments (Kane et al., 2020). MP accumulation in sediment place benthic organisms at particular risk of MP exposure as these are exposed to sediment-associated MPs potentially at high concentrations and for long durations. From an ecological point of view, benthic organisms are important in various aspects: as bioturbators impacting environmental fate *via* irrigation and particle mixing, and as a point of entry into food-webs as benthic organisms constitute a major food source for higher organisms (Banta and Andersen, 2003). Consequently, accumulation of MPs and effects on benthic fauna will potentially affect not only benthic communities and ecosystems but also the pelagic food-web through food transfer of MPs from benthic organisms to pelagic predators. However, scientific literature on MPs in sediments specifically is limited (Khalid et al., 2021) resulting in knowledge gaps related to environmental fate, effects, bioaccumulation, and trophic transfer. This combination of low focus and high importance, makes sediment a central compartment to focus on for future MP research. The growing attention is relevant but could gain even greater importance if combined efforts were structured around answering fundamental questions. Based on many years of experience studying biological impacts of contaminants in sediments, including MPs and other novel entities, we emphasize three simple but fundamental questions, and propose these as possible beacons for future research into MPs associated with sediments. 1) Are marine sediments the final sink for MPs? 2) Can MPs affect marine organisms evolutionary adapted to particle handling? 3) Will realistic MP exposure scenarios affect these organisms negatively? Although we acknowledge the challenges and needs related to method optimization for better prediction and measurements of MPs in the benthic compartment, this aspect is beyond the scope of this contribution. Additionally, potential hazard of MP-associated chemicals is not separately addressed in this paper. We address three hypotheses based on the questions above and provide recommendations to structurally address the knowledge gaps related to sediment as a route for MP exposure. We hypothesize that:

i. Sediment is the ultimate sink for MPs
ii. Benthic particle-ingesting organisms are not impacted by MPs in the sediment due to their evolutionary ability to handle particles
iii. No effect of MPs occurs with environmentally realistic exposure scenarios

2 Approach for testing our hypotheses

We primarily used reviews, when possible, to answer hypothesis *i*. To address hypotheses *ii*. and *iii*., a comprehensive literature search was performed in September 2022, using the Web of Science and Google Scholar databases, and based on combinations of keywords ("microplastic OR plastic microparticles OR microfibers" AND "toxicity OR effect OR impact OR ecotoxicity" AND "sediment OR benthic"). We also complemented our search with relevant references included in the selected articles and relevant literature reviews. We exclusively selected articles where exposure was performed *via* the sediment (*i.e.*, sediment-associated MP exposure), and excluded studies where MP addition to the systems was performed *via* the water phase. Studies where ingestion was the sole focus (*i.e.*, neglecting effects) were also excluded, as well as studies where additives or contaminants were associated with the exposure (*i.e.*, did not include "clean" MP particles and/or "clean" sediment). This resulted in the following MP effect papers (addressed in hypothesis *ii*. and *iii*.): Besseling et al. (2013); Van Cauwenberghe et al. (2015a); Green et al. (2016); Bour et al. (2018); Gomiero et al. (2018); Leung et al. (2018); Hope et al. (2020); Urban-Malinga et al. (2021); Urban-Malinga et al. (2022); and Wright et al. (2013). Endpoints were categorized according to a) level of biological organization: sub-organismal, organismal and higher level (*i.e.*, populations, communities), b) Exposure durations: >28 days and ≤28 days, c) MP exposure concentrations: ranked according to prevalence of environmental MP concentrations being reported in the scientific literature. Some studies included several MP concentrations, MP size-classes, multiple endpoints and more than one species. In such cases, our analysis only included one test concentration, *i.e.*, lowest effect concentrations (LOECs) (for tests where effect was observed) and highest concentration without effect (NOEC) (for tests without observed effects).

3 Sediment is the ultimate sink for MPs

Sediment is considered a final sink of MPs, with 99% of all MPs released into the aquatic environment estimated to eventually end up in the sediment (Kane et al., 2020). However, these estimates are governed by large uncertainties due to the lack of robust data. Environmental fate of MPs is not only controlled by inherent properties of the MPs (*i.e.*, shape, size, density), but also environmental factors influencing transport and distribution of MPs, including physical, chemical and biological factors (*e.g.*, hydrodynamic conditions, temperature, UV-radiation, MP polymer type) (Uzun et al., 2022) (Figure 1A). However, little attention has been given to the mechanisms that govern transport and distribution of MPs within the sediment. While several modelling studies have predicted the fate of MPs in the marine environment, these are based on several assumptions that reduce the reliability of the model predictions. Such assumptions ignore hydrodynamic events, MP physical properties (*e.g.*, shape), biological processes (*e.g.*, biofouling), and the role of biota, due to the complexity and lack of consistent data (Darabi et al., 2021). Benthic organisms impact the distribution of MPs greatly due to their activity, such as bioturbation, resulting in MPs being both re-suspended and re-buried (Näkki et al., 2019). Such interactions contribute to heterogeneous mixing of the upper layer (<5cm) of the sediment, preventing MPs to permanently stay in the sediment after settling. Additionally, benthic organisms potentially reintroduce MPs into the food-web as they serve as a major food source for organisms at higher trophic levels. However, this has been poorly studied to date (Uzun et al., 2022). The first hypothesis must therefore be rejected, as the sediment rather serve as a reservoir than a final sink of MPs.

4 Benthic particle-ingesting organisms are not impacted by MPs in the sediment due to their evolutionary ability to handle particles

Particle-ingesting organisms, such as deposit-, detritus-, filter- and suspension-feeders, are especially susceptible to

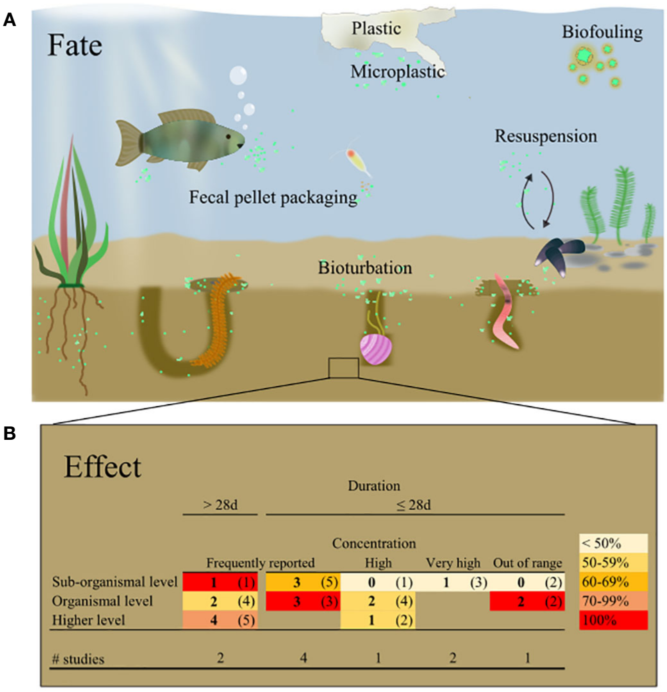

FIGURE 1
General fate processes **(A)** and occurrence of effects (bold numbers) and effects tested (numbers in brackets), based on 10 effect studies of sediment-associated MPs **(B)** (Besseling et al., 2013; Wright et al., 2013; Van Cauwenberghe et al., 2015a; Green et al., 2016; Bour et al., 2018; Gomiero et al., 2018; Leung et al., 2018; Hope et al., 2020; Urban-Malinga et al., 2021; Urban-Malinga et al., 2022). Each endpoint studied in a specific experimental condition (*i.e.*, combination of concentration, duration, polymer type) was counted as one observation, and for each observation we recorded whether a significant effect was reported at the lowest observed effect concentration (LOEC). If no effects were observed, the highest concentration included in the study, i.e., the no observed effect concentration (NOEC), was reported. Endpoints are grouped according to level of biological organization (*i.e.*, sub-organismal, organismal and higher level of biological organization). Exposure durations were divided as >28 days and ≤28 days. Based on field concentrations reported in the literature, studied MP concentrations was sorted as "most frequently reported ranges and lower" for concentrations ranging 0.0001-0.08 mg MPs/kg sediment (Van Cauwenberghe et al., 2015b; VKM et al., 2019; Deng et al., 2021) "high concentrations" reported from known contamination hot-spots (Carson et al., 2011) ranging 0.1-0.7 mg MPs/kg sediment, "very high concentrations" for concentrations that has been reported once ranging 1-7 mg MPs/kg sediment (Haave et al., 2019) and "out of range" when exceeding highest reported concentrations, which is above 200,000 particles/kg.

plastic ingestion because of food item similarity with MP-particles and their lack of ability to differentiate the two (Bour et al., 2021). In fact, sediment ingestion is recognized as the major influx pathway in particle-ingesting organisms for many conventional and emerging contaminants (Chiaia-Hernández et al., 2022), including MPs (Pinheiro et al., 2020). For aquatic organisms, the chance of encountering and ingesting MPs increases with MP concentration (Bour et al., 2021). MP ingestion by benthic invertebrates has been demonstrated in monitoring studies (Piarulli et al., 2020) as well as in controlled laboratory experiments (references in Figure 1 legend). Thus, though many benthic species are capable of handling naturally occurring particles in the marine environment, they also ingest a multitude of anthropogenic particles, such as MPs (Santos et al., 2021). The literature search provided ten effect studies (Figure 1B), all of which employed pristine MPs. Only two studies did not report ingestion of MPs in invertebrates. Seven, of the eight studies that considered ingestion, reported effects on sub-organismal and organismal level, whereas only one study did not detect effects. Four of the seven studies reporting effects applied concentrations within the range of "frequently reported" concentrations, two at "high" concentration and one at "very high" concentration. In these studies, only four species were tested (two polychaetes and two bivalves), all deposit-feeders. Therefore, we reject the hypothesis, as effects have been observed in particle-ingesting organisms, although this is not conclusive due to the low number of studies.

5 No effect of MPs at environmentally realistic exposure scenarios

A frequent criticism of MP effect studies is that exposure is not conducted under environmentally relevant conditions (*i.e.*, concentration, duration, experimental set-up (incl. route of exposure)) (Weis and Palmquist, 2021), and that observed effects might therefore not be representative of what happens in the environment. The literature search revealed scarcity of experimental studies conducted using contaminated sediments. Six of the ten studies used MP concentrations belonging to the "frequently reported ranges or lower". Although this single category shows the highest number of observations (56%), the remaining 44% of the experiments conducted use concentrations at (very) high concentrations or exceed the reported field concentration (Figure 1B). Only two studies were conducted at a duration >28 days, and thus exceeding durations usually perceived as the minimum for sediment effect studies (e.g., OECD guidelines). Another striking result is that the majority of observations are made at sub-organismal- and organismal-level (38 and 41%, respectively) overlooking effects at higher levels of biological organization (22%). When effects were investigated at higher level (*i.e.*, population, community), they occurred in five of seven cases (Figure 1B). However, it is important to note that the focus was on microbial communities and on changes in oxygen consumption and nutrient concentration in porewater, leaving large knowledge gaps on impacts on benthic invertebrates at population- and community-level. The scarcity of effect studies on benthic organisms leaves a major knowledge gap that prevents drawing robust conclusions. However, our analysis showed that adverse effects of MPs are observed with ecologically relevant exposure scenarios, and we therefore reject the third hypothesis.

6 Recommendations

The traditional understanding of the word "sink" is that sedimented MPs have become unavailable for organisms and thus are not reintroduced into the food-web. Though MPs will likely accumulate in the sediment, this compartment also serves as a food source for benthic organisms which again feed pelagic species. Based on this definition, and with the knowledge that MPs are re-introduced to benthic invertebrates once reaching the sediment compartment, sediments are probably a reservoir, where MPs accumulate, rather than a sink. However, once MPs get buried into deep sediment, they might be unavailable for benthic organisms, and in this scenario, sediment could be an ultimate sink. But it is important to recognize the dynamics at stake in the upper layer. However, more knowledge is needed regarding the extent of MP re-suspension into the water column, of MPs re-entering the pelagic food-web, and of burial into deeper layers of the sediment.

Based on the limited number of effect studies conducted *via* the sediment, it seems that MP ingestion can lead to effects on particle-ingesting organisms, but more studies are needed to verify whether this is a general concern. The driving mechanisms of MP ingestion as well as the internal fate (*i.e.*, egestion, accumulation (trapped in the gut) or uptake (*i.e.*, translocation)) is crucial to better understand the potential hazards of MP exposure. Natural particles have been documented to induce effects in aquatic organisms at concentrations similar to the ones tested with MPs (Ogonowski et al., 2018), which emphasize the need to include particle controls (*i.e.*, particles of natural origin) in experimental designs.

Despite continuous calls for more focus from researchers working with sediment MP research, we are still lacking knowledge on the impact of MPs on benthic invertebrates. To address this, we need targeted experiments on sediment-associated MP effects on benthic species and we suggest focusing on ecosystem-level, but also individual (predicts population-level effects) and subcellular levels (unravels underlying mechanisms). Similarly, results of the present analysis show that although environmental relevance is accounted for in the experimental studies, evidence of adverse effects is limited due to the limited numbers of studies. Currently, it is thus not possible to draw robust conclusions on whether MPs have negative impacts on benthic invertebrates. More experimental studies are therefore needed at environmentally relevant concentrations and for exposure durations > 28 days, to understand the potential hazard of long-term MP exposure. To evolve our understanding of the consequences of MP pollution, we need to shift our focus to the benthic compartment. We recommend doing so in a structured approach that focuses on the three hypotheses on sediment as a sink of MPs, potential effects on particle-ingesting invertebrates and environmental realism we present in this paper, to answer questions that are fundamental to fully understand the impacts of MP on the benthic compartment.

Author contributions

MS: Conceptualization, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualization. AP: Conceptualization, Writing – Original Draft, Writing – Review & Editing, Funding acquisition. AB: Data Curation, Writing – Original Draft, Writing – Review & Editing. SG: Writing – Original Draft, Writing – Review & Editing, Visualization. AH: Writing – Original Draft, Writing – Review & Editing, Visualization. HS: Writing – Original Draft, Writing – Review & Editing. AT: Writing – Original Draft, Writing – Review & Editing. KS: Conceptualization, Writing – Original Draft, Writing – Review & Editing, Funding acquisition. All authors contributed to the article and approved the submitted version.

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Conflict of interest

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