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Plastics in the Sea: Occurrence and Impacts

Chapter 9

Microplastics in Marine Food Webs

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Abstract: The identification of microplastics (**MPs**; 1 µm - 5 mm) and the inferred presence of nanoplastics (**NPs**; <1 µm) in a wide variety of marine animals, including many seafood species, has raised important questions about the presence, movement, and impacts of these particles in marine food webs. Understanding microplastic dynamics in marine food webs requires elucidation of the processes involved, including bioaccumulation, trophic transfer, and biomagnification. In the context of microplastics and nanoplastics, however, these concepts are often misunderstood. This chapter provides a critical review of the literature on the behavior of plastic particles in marine food webs. There is clear evidence of trophic transfer, equivocal evidence for bioaccumulation, and no evidence for biomagnification. There are, however, several knowledge gaps that limit the ability to draw firm conclusions at this time.

Key words: microplastics; nanoplastics; trophic transfer; bioaccumulation; biomagnification; food webs; translocation

I. Introduction

A. Introduction and Scope.

Global contamination by plastic waste has emerged as one of the most pressing environmental problems of this century. Plastic pollution has been referred to as a “planetary boundary threat” (MacLeod et al., 2014; Galloway et al., 2017; Arp et al., 2021; Persson et al., 2022) and an “evolutionary trap” (Santos et al., 2021). Although plastic pollution is global, impacting terrestrial, aquatic, and atmospheric environments, contamination of the oceans has raised the most concern and galvanized both the public and the research community (Galloway et al. 2017; Law 2017; Hale et al., 2020; Law and Thompson, 2014).

The identification of microplastics (MP; 1 µm - 5 mm) in an enormous number of marine animals, including many seafood species (Smith 2018; Danopoulos et al., 2020), has raised important questions about the presence, movement, and impacts of these particles in marine food webs. Of special concern are the potential impacts on top predators, including humans, as well as the overall impacts on ecosystem health. Answering questions about microplastic dynamics in marine food webs requires an understanding of the processes involved, including bioaccumulation, trophic transfer, and biomagnification; however, a reading of the scientific literature on microplastics indicates that in the context of microplastics and nanoplastics (NP; <1 μm) these concepts are often misunderstood, and this has hindered the understanding of the behavior of these particles in marine food webs.

An important distinction should be made between the behavior of the plastic particles themselves and the behavior of MP-associated chemicals, including additives and adsorbed chemical contaminants. These are not completely separable, of course, but once the MP-associated chemicals are released from the particles their bioaccumulation and trophic transfer will be independent of the particles and for many of these chemicals (e.g., POP, plasticizers) this behavior already is well understood. Therefore, this chapter will focus on the particles themselves.

This chapter presents a critical review of the literature on plastic particles in marine food webs, building on previous reviews on this topic (Carbery et al., 2018; Provencher et al., 2019; Gouin, 2020; Miller et al., 2020; Walkinshaw et al., 2020) while providing additional perspectives on some of the major questions regarding the behavior of plastics in food webs.

- Do MP and NP bioaccumulate in marine organisms, undergo trophic transfer, and biomagnify in marine food webs?
- Does the answer depend on properties of the plastic particles, and if so, which ones?
- Do plastic particles behave like the well-known persistent organic pollutants (POP) such as polychlorinated biphenyls (PCB) and dichlorodiphenyltrichloroethane (DDT)?

In addition to addressing these and other questions, elements of study design and technical limitations that affect the ability to answer these questions will be discussed.

Before discussing the studies themselves, the key concepts dealt within this chapter are defined, because ambiguity about these terms has led to confusion, and sometimes misuse, in the literature.

B. Definitions

Trophic Transfer – A key process involved in food webs is trophic transfer, which is defined as the movement of a material from one trophic level to another, e.g., from prey to predator or consumer (Suedel et al., 1994; Nordberg, 2009). An important aspect of this definition is that it does not imply that there is an increase in the concentration of the material as it moves up the food chain. Thus, demonstrating trophic transfer does not necessarily indicate that there is biomagnification (see below).

Bioconcentration – Bioconcentration is a process that results in accumulation of a substance in an organism to levels that are greater than those in its environment. It usually is understood to apply to uptake directly from water. The concept of bioconcentration may have less relevance for particles than for molecules, and thus has been largely ignored in studies of MP to date; it is included here for completeness and to point out that its relevance for MP and (especially) NP remains unknown and unexplored.

Bioaccumulation – Bioaccumulation refers to the uptake of a substance from all sources, including water and food, leading to a progressive increase over time in the concentration of the substance in an organism or its tissues (Suedel et al., 1994; Nordberg, 2009). It implies that the rate of intake exceeds the rate of elimination (egestion) or breakdown (biotransformation). Features associated with bioaccumulative substances typically include lipophilicity, resistance to biotransformation, and/or sequestration in an internal compartment. Bioaccumulation of ingested materials typically would require translocation into tissues (see below).

Biomagnification – Biomagnification is defined as an increase in the concentration of a substance at higher trophic levels as compared to lower trophic levels (Suedel et al., 1994; Nordberg, 2009; Provencher et al., 2019). For lipophilic chemicals, concentrations are typically lipid-normalized to account for differences in lipid content among trophic levels (Gray, 2002). Concentrations of plastic particles are typically not lipid-normalized, but one could ask whether they should be, especially for the smaller particles (NP and small MP). The assessment of biomagnification is complicated by the fact that chemical measurements are usually made on the whole body of smaller organisms but in specific tissues of larger organisms (Gray, 2002).

Internal vs External Dose – An important consideration that affects the assessment of both bioaccumulation and biomagnification is whether one considers material in the gastrointestinal tract to be part of the organism (internal) or the environment (external). Because material in the GI tract has not crossed any absorption barrier (e.g. biological membranes), it is sometimes considered to be external to the body (Gouin, 2020) (Fig. 1). This material is considered an "exposure" and is sometimes referred to as an "intake dose" or "potential dose", but it is not considered an "absorbed dose" (EPA, 2011). Despite this, use of whole organisms for measuring bioaccumulation or biomagnification will include this material as part of the body burden, even though the material may ultimately pass through the GI tract and be excreted in the feces. While this concept applies to all environmental contaminants, it is especially relevant for particles such as MP and NP, which may be more poorly absorbed across the intestinal cell barrier than other contaminants.

Translocation – In order to be taken up from the gastrointestinal tract and distributed to tissues (Fig. 1), MP and NP particles must cross the intestinal epithelial cell barrier, a process typically referred to as "translocation" (Handy et al., 2008; Løvmo et al., 2017; Jin et al., 2018; McIlwraith et al., 2021; Clark et al., 2022). Translocation can occur by different mechanisms, including transcellular uptake (e.g., by endocytosis) or paracellular transport, but the relative roles of these mechanisms and how they may change with particle properties such as size and shape are not well understood for environmental MP and NP (De Sales-Ribeiro et al., 2020; McIlwraith et al., 2021); however, some insights may be obtained from the literature on use of nanoparticles for drug delivery (Pelaz et al., 2017; Brown et al., 2020).

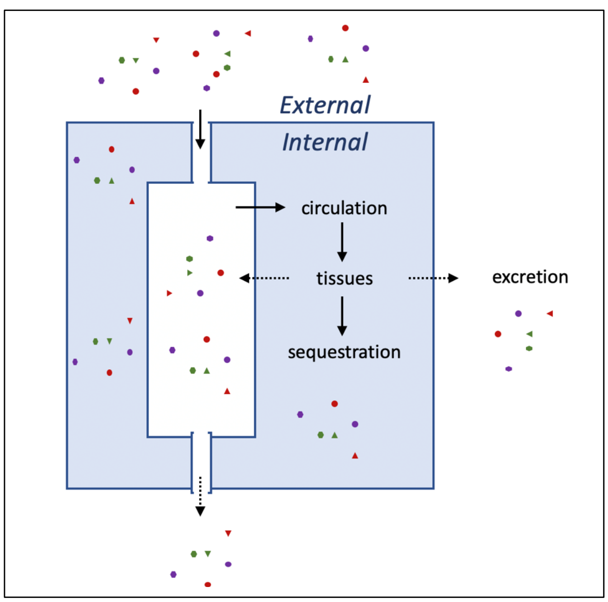

Figure 1. Internal and external doses in assessing bioaccumulation and biomagnification. This diagram illustrates the processes involved in bioaccumulation of plastic particles within an organism, including ingestion into the gastrointestinal tract, uptake across the intestinal epithelial barrier (translocation) into the circulation, distribution to tissues, and excretion. Blue shading: internal environment. White shading: external environment, including the GI tract. Colored shapes: MP or NP.

C. Challenges and Limitations

In attempting to assess and draw conclusions about the behavior of MP and NP in marine food webs, there are several challenges and limitations. One obvious challenge is the complexity of the materials included under the heading of "microplastics." As pointed out by others (Kooi and Koelmans, 2019; Rochman et al., 2019; Kooi et al., 2021), MP and NP comprise a complex suite of materials that vary tremendously by size, shape, polymer, surface properties, additives, sorbed contaminants, and other properties. This presents a challenge in trying to generalize results from studies that, individually and collectively, represent only a slice of this complexity. Indeed, it may be that generalization is not only difficult, but also inappropriate; the answers to the questions that are posed in this chapter are likely to vary by particle type. This chapter focuses primarily on the influence of particle size on food web dynamics, in part because it may be one of the most relevant variables (Hampton et al., 2022) and many (but not all) studies provide some information on the sizes analyzed.

Another challenge is in distinguishing the dynamics of MP themselves versus those of MP-associated chemicals (additives and sorbed contaminants). As noted earlier, this chapter will focus on the particles themselves, ignoring the food web behavior of the plastic-associated chemicals. The potential and processes involved in desorption of these chemicals and their contribution to total chemical exposure have been explored in several excellent reviews (Teuten et al., 2009; Bakir et al., 2016; Koelmans et al., 2016; Lohmann, 2017).

The lack of standardization in the field of microplastics research is another limitation of this assessment. This limitation applies to sampling methods, tissue processing techniques, analytical methods, and even terminology used to describe results. In addition, information that is important for assessing the results (e.g., size range; polymer) often is not collected or is not provided in the published paper. Although there has been progress recently in standardizing research in this field (Rochman et al., 2017; Brander et al., 2020; de Ruijter et al., 2020; Provencher et al., 2020; Hung et al., 2021), at present it is difficult to compare results of studies being carried out in different laboratories using different approaches.

Finally, a major challenge in assessing the movement of MP and NP in food webs, and the extent to which they may bioaccumulate or biomagnify, is understanding the behavior of particles and how it may differ from more typical chemical contaminants. Much of the theoretical and empirical understanding of bioconcentration, bioaccumulation, biomagnification, and trophic transfer has been generated with halogenated aromatic hydrocarbons (e.g., organochlorine pesticides and PCB) and non-halogenated aromatic compounds (e.g., PAH), which typically have a molecular mass of less than 1000 daltons and a molecular size of ~2 nm in the longest dimension. In contrast, plastic particles typically have molecular masses of 10,000 to 500,000 daltons (Jansen, 2016) and range in size from a few nanometers to hundreds of microns or more. Moreover, a single plastic particle will consist of multiple polymer molecules that exhibit a range of molecular masses and are assembled together in a semi-crystalline or completely amorphous structure. Theoretically, as particle size decreases it may reach a size at which the NP behaves more like a molecule than a particle. In the environment, this process may be facilitated by chemical, photochemical, or biochemical reactions that reduce the polymer size and introduce functional groups that may affect solubility and other properties. An additional consideration is that very small plastic particles may not exist as individual particles but rather as colloids or aggregations of particles (Gigault et al., 2021; Mitrano et al., 2021), which may behave differently from both molecules and larger particles. A complete discussion of these topics is beyond the scope of this chapter; however, researchers and policy-makers concerned with the behavior of MP and NP in food webs need to be aware of these complexities.

II. CURRENT STATE OF THE SCIENCE REGARDING THE BEHAVIOR OF MICROPLASTICS IN MARINE FOOD WEBS

A. Literature Survey

To assess the current understanding of the movement of MP and NP through marine food webs, a literature search was conducted using the key words “microplastics” and “food web” or “trophic”. The search identified 263 papers published through January 2021, of which 143 were selected for analysis; reviews, terrestrial-focused papers, and non-biota focused papers were excluded (see Appendix 1 & 2). The selected papers included a mixture of lab, field, and modeling studies, the analysis of which revealed some striking patterns. Two common themes emerged: 1) there is a size mismatch between the particles generally considered to be of greatest concern (<150 µm) and those that have been measured in marine samples, and 2) the majority of studies have used biological samples that reflect the external dose of MP rather than the internal dose (i.e., GI tract samples).

The first notable pattern was that there appears to be a mismatch between the size of particles that are capable of being internalized by organisms and particles that have been measured or detected in the studies examined. Of the 143 studies included in the analysis, only 54 (38%) reported particles smaller than 150 µm, which has been suggested as the upper size limit for particle translocation (Lusher et al., 2017); however, the majority of studies did not report their lower size detection limit (Fig. 2A), information that would be important for determining whether the methods used were capable of detecting particles in this size range. For studies reporting a size detection limit, the median was 206 µm, with a range of 2 µm to 1000 µm (Fig. 2B). Ingested particles larger than 150 µm are unlikely to undergo translocation and so are likely to only be present in the animal during their gut residence time and thus are unlikely to bioaccumulate. Of the 18 studies that reported both the size detection limits of their methodology and the smallest detected particle size, roughly half (7/18) detected particles at their size detection limits (Fig. 2C). Since the majority of studies did not report these size metrics, it is not known whether this pattern extends to the rest of the studies surveyed. This finding does indicate that improving analytical capabilities is crucial for ensuring discovery of the actual size range of plastic particles in biota.

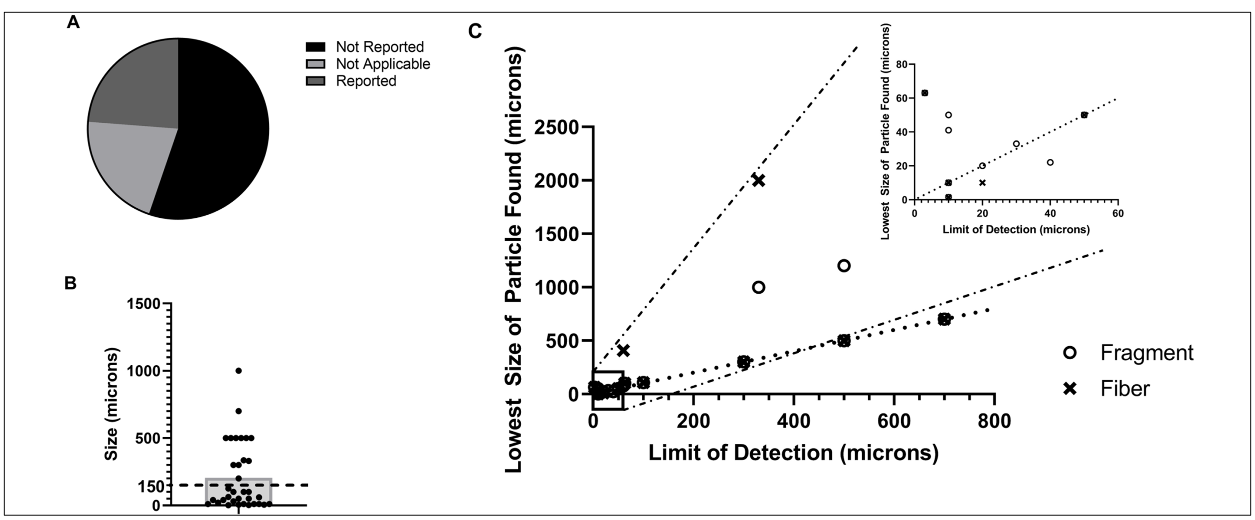

Figure 2: Summary of the microplastic size limits of detection reported in the literature. A) Pie chart representing the size limit of detection reporting status of the surveyed literature (n = 143). B)

Distribution of the different sizes reported as the limits of detection in the literature. Dotted line denotes 150 µm. Grey box indicates the median of the reported sizes. C) Lowest size of particles found, separated by fragments and fibers, plotted by the reported limit of detection. The dotted line indicates the line of identity. Studies reporting fragment data are plotted with a hollow circle, and fiber data are displayed with a grey 'x'. The inset graph in the top-right corner shows the studies reporting size limits of detection 50 µm and smaller. See Appendix 1 for compiled data.

Further, while the FAO report (Lusher et al., 2017) suggests that particles up to 150 µm can translocate, other studies have found translocation limited to particles of only about 1 µm in size (Jani et al., 2011). Evidence for translocation appears to differ between laboratory and field studies (McIlwraith et al., 2021). The rates of translocation for various sized particles through the intestinal epithelium are not precisely known. This leads to general confusion over what sizes of particles are more likely to accumulate within organisms and throughout food webs.

This issue is further confounded by the second pattern revealed by this survey: most studies examining organisms for microplastics focused on the gastrointestinal tract ("gut") and its contents (Fig. 3). These data are useful in determining relative rates of ingestion, but because the gut is able to rapidly excrete particles (Grigorakis et al., 2017), such data are not adequate for determining potential uptake into other tissues, bioaccumulation, or biomagnification (Fig.1)(Gouin, 2020). Additionally, as stated earlier, the gut can potentially be considered an environment that is external to the organism, in which case microplastics present there represent the external dose of an organism, but not an internal dose (Fig. 1). While a majority of particles found in the gut are unlikely to persist, there is a potential for these particles to impact the organism via interactions with the intestinal epithelium or gut microbiome (Fackelmann and Sommer 2019). Field-based studies analyzed gut, gut contents, and feces samples (69%; 82/118) more frequently than lab-based studies (39%; 15/38). It is challenging to compare the results of lab-based studies to data from field-based studies when they frequently examine different tissues (Fig. 3; Appendix 2). Such comparisons are important for determining the relevance of the lab-based results for real-world exposures. It is understandable that field-based studies will more frequently use the feces or gut contents of their sample organisms in order to collect data without harming the organisms; however, this does limit the information that can be gleaned about plastic movement through the food web.

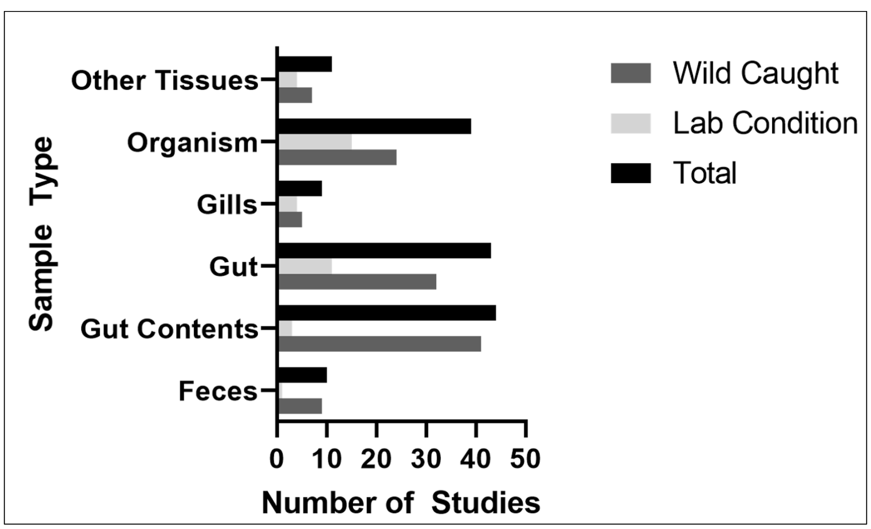

Figure 3: The number of published studies that analyzed different types of biological samples, sorted by laboratory and field-based studies (n = 143). See Appendix 2 for compiled data.

The lack of information about 1) particle size detection limits and 2) the occurrence of particles in tissues outside of the gut make it difficult to determine the degree to which bioaccumulation, trophic transfer, or biomagnification occur in marine ecosystems. Taking these aspects of study design into account, it appears that many of the surveyed studies were not designed or executed in a way that would allow them to determine whether plastic particles move through food webs utilizing these processes (Fig. 4A).

Of the studies whose experimental design could answer these questions, there was mixed evidence for trophic transfer and bioaccumulation, with 75% (n = 20/25) and 67% (n = 29/43) of studies, respectively, finding evidence for these processes in their data (Fig. 4B). Looking at a subset of these studies that reported plastic particles in the 1-150 µm range, 100% (n = 10/10) found evidence for trophic transfer and 50% (8/16) found evidence of bioaccumulation. This trend of about 50% of studies finding evidence of bioaccumulation continues down to the 1-10 µm range (n = 6/11). These mixed results concerning bioaccumulation indicate either that bioaccumulation happens rarely at this size or that size is not the determining factor in bioaccumulation of microplastics. Of the studies that found evidence of trophic transfer, only 60% (9/15) found evidence of bioaccumulation. This trend once again holds true irrespective of the size of plastic. Trophic transfer, especially of the smaller sized particles, seems to be more well supported, indicating that it is a potential pathway through which MP can move through food webs, but trophic transfer does not necessarily lead to bioaccumulation or biomagnification. In the light of these results, it is perhaps not surprising that 90% (9/10) of the studies that were designed to detect biomagnification found no evidence of this process (Fig. 4B). The one study that did find evidence of biomagnification was a modeling study predicting environmental behavior (Ma and You, 2021). The small number of studies that assessed biomagnification illustrate why movement through food webs of MP is still not well understood; however, it does seem that uptake (trophic transfer) from prey does not necessarily lead to bioaccumulation or biomagnification, and that particle size may not be the determining factor in these processes.

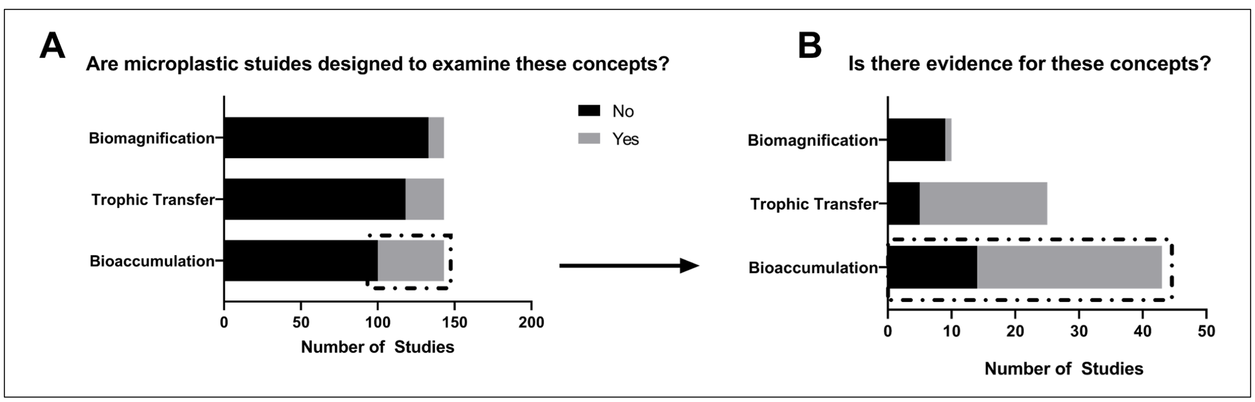

Figure 4: Summary of the suitability of experimental designs of published studies to address questions concerning bioaccumulation, trophic transfer, or biomagnification. A) Number of studies that were appropriately designed to address the concepts. B) Of the appropriately designed studies, the ones that showed evidence of bioaccumulation, trophic transfer, or biomagnification. See Appendix 2 for compiled data.

The following are the results from these papers as they pertain to different size classes of plastics.

A. Macroplastics (> 5 mm)
Macroplastics, consisting largely of fishing gear, have been increasing in prevalence over the last 60 years (Ostle et al., 2019). These larger pieces of plastic can entangle wildlife leading to significant mortality in species like whales (Johnson et al., 2005; Knowlton et al., 2012), seabirds (van Franeker, 1985; Wilcox et al., 2015), and turtles (Wilcox et al., 2018; Kühn and van Franeker, 2020). These plastic items are large enough that they would not be able to translocate to tissues outside of the GI tract. As a result, the bioaccumulation, trophic transfer, and biomagnification potential of particles >5 mm is likely negligible.

B. Large microplastics (300 µm – 5 mm)
All of the studies surveyed (n=17) found ingestion of MP in environmental samples, but most did not assess trophic transfer. Bioaccumulation is not expected to occur in this size range, but again this was not assessed by the majority of the studies. In the one study that did examine bioaccumulation (Garcia et al., 2021), examination of macroinvertebrates and fish in a riverine ecosystem found no evidence of bioaccumulation of 700 µm - 5 mm plastic particles. These authors also did not find any evidence to support the occurrence of trophic transfer or biomagnification of particles in this size range. It is highly unlikely that bioaccumulation, trophic transfer, or biomagnification would occur within this size class, although the paucity of studies limits the ability to draw firm conclusions, especially regarding larger animals.

C. Small microplastics (1 µm – 300 µm)
Plastic particles within this size range include some that appear to have the capacity to translocate through the gut to other tissues (Lusher et al., 2017). In this literature survey, 63 papers found particles in this size range; however, only 22, 12, and 5 of these papers had a study design capable of evaluating bioaccumulation, trophic transfer, and biomagnification, respectively. Overall, this underscores how few studies have quantified the potential movement of plastics through food webs and the large knowledge gaps that remain. One major limiting factor in furthering the knowledge in this area is the quantification of small MP in field samples. This area of research is actively under development, but so far has led to few field studies that measured smaller MP (≤10 µm) in organisms (Fig. 2). Most (64%) of the studies that include particles in this size range represent laboratory studies; however, without field data from the same sizes of MP, it is difficult to assess the accuracy of lab-based studies for predicting environmental behavior. This problem is worsened by a lack of reporting on the MP size detection limits, as noted above. Of the 63 studies discussed here, only 12 reported the smallest size of MP that they were able to detect.

There is conflicting evidence of bioaccumulation for 1 µm - 300 µm particles. Of the 22 studies that examined the bioaccumulation potential of MP in this size range, 17 found evidence of bioaccumulation and 5 did not see bioaccumulation. More studies examined the bioaccumulation potential of MP smaller than 150 µm than in the 150-300 µm range. These studies were conducted using both field and lab-based techniques. One lab study of fish larvae fed MP-contaminated prey (Cousin et al., 2020) found that there was limited ingestion of 20 µm particles compared to 5 µm particles, there was no translocation of either sized particle, and all particles were egested within 48 h; thus, there was no bioaccumulation. Similarly, for 10-40 µm particles there was no persistence within sea bass larvae after 48 h (Mazurais et al., 2015). Larger particles are potentially egested more quickly (Hurley et al., 2017). Particles of 1-5 µm had limited signs of accumulation in intestinal epithelial cells of *Danio rerio* exposed via their diet; however, it was noted that most of the particles are likely to have been cleared with the next feeding (Batel et al., 2016). Sea urchins fed polyethylene MP <10 µm were able to clear the particles at rates similar to those at which they clear algae, and there were no signs of accumulation within the urchins (Beiras and Tato, 2019). Another study found evidence of bioaccumulation in mussels with the smallest MP size found (about 5 μm) (Naidu, 2019). A study sampling muscle and gills from various benthic feeders found that most samples contained MP and that MP were more numerous in the gills than in the muscle (Akhbarizadeh et al., 2019). The smallest MP found by these authors were "less than 50 μm", but no details about the actual sizes were provided. A field study found an increased abundance of MP in bivalves feeding at higher trophic levels, suggesting that ingestion of prey and trophic transfer could lead to bioaccumulation (Sun et al., 2017; Naji et al., 2018). An experimental study found that the MP that were detected decreased in size when going up a food chain (tadpoles to fish to mice) (Araújo and Malafaia, 2021), illustrating how size-dependent behavior might dictate bioaccumulation potential. In a study on marine crabs, 5-μm MP particles accumulated in soft tissues, but the concentration of MP in feces was greater than in those tissues (T. Wang et al., 2021). Overall, within a given size class there appears to be mixed evidence of bioaccumulation. This points to other factors such as the weathered state and polymer type partially determining the bioaccumulation potential of these particles.

Trophic transfer appears to be size-dependent. Studies examining particles smaller than 150 μm found that trophic transfer occurred (Batel et al., 2016; Mateos-Cárdenas et al., 2019; Cousin et al., 2020; Malafaia et al., 2020; Piarulli and Airoldi, 2020; Van Colen et al., 2020; T. Wang et al., 2021), while studies examining larger particles found mixed evidence of trophic transfer (Chagnon et al., 2018; Nelms et al., 2018; Roch et al., 2019; Zhang et al., 2019); however, it is important to note that the studies examining particles smaller than 150 μm were exclusively lab-based studies, and the studies examining larger particles were exclusively field-based studies. Thus, it is difficult to disentangle other potential factors that might be driving the apparent size-dependent differences in trophic transfer. One potential factor might be size-dependent, selective ingestion of smaller particles (Zhao et al., 2018; Ward et al., 2019; Mladinich et al., 2022). It is also worth noting that several of the studies observing trophic transfer of plastic particles found that this did not lead to bioaccumulation or persistence of MP in the highest trophic level organism studied (Batel et al., 2016; Piarulli and Airoldi, 2020).

The only studies that were designed to detect biomagnification found no evidence for its occurrence in laboratory settings (Cousin et al., 2020; Malafaia et al., 2020; T. Wang et al., 2021). All of these studies showed that trophic transfer occurred, but it did not appear to result in biomagnification.

D. Nanoplastics (< 1 μm)

Nanoplastics (NP) offer the greatest potential for bioaccumulation and biomagnification due to their small size, which enables them to more easily move through membranes and between cells (Domenech et al., 2020; Sendra et al., 2020; Liu et al., 2021). Nanoparticles of various materials have been extensively studied in the context of engineered nanomaterials and nanomaterials for drug delivery (Singh and Lillard, 2009; Shang et al. 2014; Blanco et al. 2015). Although differences in material and surface charge complicate the extrapolation of these results to NP particles, these studies may provide some insight into the behavior of NP in organisms (Bouwmeester et al., 2015; Hurley et al., 2017; Mitrano et al., 2021; James et al., 2022). Fewer studies have focused directly on NP, and these are almost entirely limited to lab-based studies with manufactured, spherical nano-polystyrene particles (Phuong et al., 2016; Shen et al., 2019; Martin et al., 2022). The real-world relevance of these studies has yet to be fully determined, but it seems likely that factors such as the weathered state, polymer type, and shape will also influence the biodistribution of environmental NP.

Few studies have detected NP in the environment, much less in biota. This makes it difficult to design lab-based studies to examine bioaccumulation and trophic transfer, as there is little information on measured environmental concentrations of different polymers to guide experimental design. Some studies used concentrations predicted by extrapolating from MP concentrations (Lenz et al., 2016). NP quantification techniques remain the largest limiting factor here. There are some promising techniques (i.e., Pyrolysis-Gas Chromatography Mass Spectrometry and ultracentrifugation) that have been used to detect NP in environmental samples (Ter Halle et al., 2017; Ribeiro et al., 2021; Zhou et al., 2021; Kokilathasan and Dittrich, 2022). The techniques typically used to detect NPs in lab-based studies require custom-synthesized plastic particles modified by radiolabelling, a metal core, or fluorescent labelling (van Pomeren et al., 2017; Mitrano et al., 2019; Al-Sid-Cheikh et al., 2020). Future lab and field studies of NP behavior will benefit from advances in analytical methods.

In laboratory studies, NP have been found to distribute to tissues beyond the gut, including the brain and liver, suggesting that particles of this size have a greater potential for bioaccumulation (Lu et al., 2016; Mattsson et al., 2017; Skjolding et al., 2017; van Pomeren et al., 2017; Pitt et al., 2018; Lee et al., 2018). These studies were all conducted in fish following either an aqueous or oral exposure. Other studies have also found that various invertebrate species, including benthic grazers and filter feeders, also show NP distribution in tissues (Jiang et al., 2019; Sendra et al., 2020; Kuehr et al., 2022). It should be noted that while Kuehr et al. (2022) found accumulation in the tested bivalve species, the freshwater amphipod *Hyalella azteca* did not demonstrate accumulation of NP. This contradictory evidence for bioaccumulation could be due to differences in particle ingestion rates between amphipods and filter feeders, pointing to the importance of understanding the relative rates of uptake and translocation of these particles in order to assess the bioaccumulation potential.

Despite the evidence of NP uptake into various tissues, the actual rates of this accumulation in tissues, and their persistence, have yet to be fully described in the literature. Some studies have found that NP are present in the organisms beyond the period of exposure by at least a few days, although there is noticeable egestion (Al-Sid-Cheikh et al., 2018; Rist et al., 2019; Sendra et al., 2020). Translocation to various tissues appears to occur within a few hours (Sendra et al., 2020; DeLoid et al., 2021; Clark et al., 2022) but appears to be rather limited. For example, Clark et al. (2022) demonstrated that only 0.6% of 200 nm particles translocated through the intestinal membrane in an *ex-vivo* fish gut preparation after a 4 h exposure. Similar observations were made in freshwater amphipod *Gammarus pulex* (Redondo-Hasselerharm et al., (2021). These studies were limited to assessing potential uptake from the gut, which is only one of the multiple routes of exposure to plastic particles for organisms such as fish. Nevertheless, it seems that following a single exposure event, NP are able to translocate to tissues and persist in organisms for days, indicating bioaccumulation potential. S. He et al. (2022) found that a chronic exposure to plastic in an aquatic microcosm led to an increase in accumulated plastic as compared to after a pulse exposure, further indicating the potential for environmental bioaccumulation. This scenario represents a greater environmental relevance as organisms in the environment are continuously exposed to plastic particles. The bioaccumulation potential of NP in organisms is further supported by one study that found a bioconcentration factor greater than 1 for clamworms (*Perinereis aibuhitensis*) exposed to NP (Jiang et al., 2019). It should be noted that the majority of these studies use pristine, spherical, polystyrene particles. Factors such as the surface charge, polymer type, and weathered state will also impact the rates of uptake (Kulkarni and Feng, 2013; Salatin et al., 2015; Rochman et al., 2019). Overall, there have been relatively few studies focused on examining the bioaccumulation potential and dynamics of NP and there remain many different factors to consider when assessing their potential for bioaccumulation.

The trophic transfer potential of NP is high. Studies have found that organisms occupying different trophic levels generally do not avoid food contaminated with plastics (Mateos-Cárdenas et al., 2022). Additionally, several studies have constructed simple food chains that demonstrated the ability of these particles to be transferred from prey to the guts of predators (Chae et al., 2018; Kim et al., 2022; Mateos-Cárdenas et al., 2022). While these studies provide evidence that trophic transfer is a potentially important exposure pathway, they do not indicate the importance of this pathway for plastic retention within an organism, because these studies were limited to examining the gut of the predators. Monikh et al. (2021) showed the retention of NP following trophic transfer and a depuration period, indicating that trophic transfer does occur at this scale. This finding is in line with the idea that trophic transfer occurs with particles smaller than 150 μm (Lusher et al., 2017). It should be noted that trophic transfer reflects only an oral exposure to plastic particles, and the relative importance of trophic transfer compared to other routes of exposure (i.e., dermal, respiratory) has yet to be demonstrated; however, many studies have found potential harmful impacts of plastic acquired through trophic transfer, albeit at relatively high concentrations (Cedervall et al. 2012; Mattsson et al., 2015, 2017; Lai et al., 2021).

Only one study examined the biomagnification potential of NP. S. He et al. (2022) found evidence that biomagnification did not occur within a constructed freshwater ecosystem, following either a pulse or chronic exposure; instead, these authors provided evidence for trophic dilution—the opposite of biomagnification. This finding is consistent with the few studies examining the biomagnification potential of larger size classes of plastic; however, the evidence that NP can undergo both bioaccumulation and trophic transfer suggests that biomagnification is possible in some circumstances. Thus, much more research is needed to provide a more definitive answer to this question.

III. Implications for Human Health

As omnivores, humans are intimately connected with both aquatic and terrestrial food webs. Given the ubiquitous distribution of MP (and presumably NP) in the environment and in organisms at every trophic level, humans are inevitably exposed to MP and NP through food, including seafood. In addition, humans are exposed to MP through drinking water and inhalation. Numerous recent reviews have discussed the potential routes of exposure of humans to MP and NP and the predicted mechanisms of uptake and translocation into different tissues (Galloway, 2015; Carbery et al., 2018; Prata, 2018; Cox et al., 2019; Campanale et al., 2020; van Raamsdonk et al., 2020; Walkinshaw et al., 2020; Dawson et al., 2021; Rahman et al., 2021; Senathirajah et al., 2021; Danopoulos et al., 2022). Due to multiple routes of exposure, humans are likely exposed to different concentrations and types of MP and NP particles than aquatic organisms. In addition, human exposure levels could vary based on factors such as age (infants, youth, and adults), environmental conditions (urban vs rural; polluted vs clean), socioeconomic status etc., however, there is very little empirical evidence on the role of these different factors and how they influence human exposure levels, which would be needed to determine the risks associated with plastic exposure.

It is clear that humans can ingest plastic by eating seafood. The data currently available indicate that seafood eaten whole, such as some bivalves, may be a greater source of exposure than seafood that consists of only muscle tissue (e.g., fillets). Whether MP or NP from seafood are taken up across the intestinal barrier is not as well understood. The identification of MP in human stool samples (Schwabl et al., 2019) provides evidence of ingestion but not uptake; however, the recent detection of plastic polymers in human blood (Leslie et al., 2022) suggests that some systemic uptake may occur. Overall, the degree of MP or NP bioaccumulation in humans is unknown and in need of research.

IV. Key Issues, Knowledge Gaps, and Future Directions

This analysis of 143 papers published between 2013 and 2021 revealed patterns, trends, and limitations regarding questions about the ability of MP and NP to undergo trophic transfer, bioaccumulation, or biomagnification. It is notable that among the papers commenting on these processes, most were not properly designed to test hypotheses about whether these processes are occurring with plastic particles. Thus, many of the conclusions that can be drawn are limited by the small number of properly designed experiments, making them somewhat tentative.

One notable observation was the mismatch between the size of particles that were studied (mostly those >150 μm) and the sizes that appear most likely to be taken up, bioaccumulated, and biomagnified (<150 μm, especially those <1 μm). This limits the conclusions that can be drawn from many of the published studies. Another important observation is that most of the studies include or even focus on plastic particles found in the GI tract, which do not represent internal doses and thus have questionable relevance for studies of trophic transfer, bioaccumulation, and biomagnification.

From the studies that were reviewed, the evidence for trophic transfer and bioaccumulation is mixed. Trophic transfer, which simply concerns transfer from one trophic level to another, appears common, although most of the studies do not exclude the GI tract, which as noted above has questionable relevance for this question. When trophic transfer occurs, it appears to be particle size-dependent. Bioaccumulation is more difficult to establish but has been documented in some studies. Although within the MP size class there was no apparent size-dependence of bioaccumulation, there appeared to be more evidence of bioaccumulation for NP as compared to MP.

There is no experimental or field evidence for biomagnification of plastic particles, and in some cases the evidence points to trophic dilution—the opposite of biomagnification (Akhbarizadeh et al., 2019; Y. He et al., 2022). Similar conclusions have been reached by others (Covernton et al. 2019, 2021, 2022; McIlwraith et al., 2021). A glaring caveat to this conclusion is that NP—the sizes with greatest potential to undergo biomagnification—have not been well studied in this regard. Although there is some evidence suggesting that NP may persist in tissues, in general the persistence of MP and NP in tissues—which is required for biomagnification to occur—is not well understood.

These conclusions are tempered by the many limitations that currently characterize the field of MP research, and especially those that impact specifically on the ability to assess trophic transfer, bioaccumulation, and biomagnification. The complexity of plastic particles, which is well-known, certainly limits the ability to generalize from specific studies, most of which (lab studies at least) have used pristine, spherical, polystyrene particles. The problem is compounded by the lack of standardization in many published studies, hindering the ability to compare across laboratories.

Perhaps the major limitation is the lack of robust and reproducible analytical methods for measuring NP in animals and the environment, as noted above. Among the various plastic particle size classes, NP are the most likely—on theoretical grounds—to exhibit behavior approaching that of well-known POP, which undergo trophic transfer, bioaccumulation, and biomagnification. Thus, although the food web behavior of MP (>1 μm) appears to be different from that of POP, no such conclusion can yet be reached for nano-sized plastics. Thus, understanding the behavior of NP in food webs remains an important challenge.

V. Conclusions

In attempting to answer the questions posed at the beginning of this chapter, some tentative conclusions can be made while also identifying open questions and important gaps in current knowledge about the behavior of plastic particles in food webs. There is convincing evidence that trophic transfer of MP and NP occurs. The evidence for bioaccumulation is mixed but suggests that bioaccumulation may be more likely for NP rather than MP. Biomagnification of MP does not appear to occur, suggesting an important difference between their behavior and that of well-known POP; however, it is not yet possible to answer questions about the possible biomagnification of NP.

The behavior of MP and NP in marine food webs is directly relevant for human exposure and thus for questions regarding human health impacts of MP/NP in people. The uncertainties regarding translocation and accumulation of plastic particles in marine species are paralleled and even amplified when considering human exposure. The degree of trophic transfer and bioaccumulation of MP and NP in humans is simply unknown. Understanding this is yet another challenge for MP researchers—one that will likely drive research in this field for some time to come.

VI. Supplementary Data

Appendices:
- Appendix 1. Literature Survey of Microplastic Size and Abundance.
- Appendix 2. Literature Survey of Trophic Transfer, Bioconcentration, Bioaccumulation, and Biomagnification of Microplastics.

Supplementary data files, including the list of papers analyzed and the study-specific analytical results, can be found at https://hdl.handle.net/1912/29556.

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Appendix 1. Literature Survey of Microplastic Size and Abundance.

A literature search was conducted using the key words "microplastics" and "food web" or "trophic". The search identified 263 papers published through January 2021, of which 143 were selected for analysis. This table summarizes data from a subset of the papers reporting information on particle size and abundance. The species analyzed in these studies are listed in Appendix 2. A description of the overall results is provided in the chapter text and Figure 9.2.

GI: gastrointestinal tract; NR: Not Reported

Reference	MP Smallest Analyzed Size (µm)	MP Largest Analyzed Size (µm)	MP average size (µm)		MP lower size found (µm)		MP upper size found (µm)		MP Average Concentration
			Fibers	Fragments	Fibers	Fragments	Fibers	Fragments	
Zhang et al. (2021)	NR	NR	1690	780	<500	<250	1000-5000	1000-5000	53 ± 35.2 items·individual^{-1}
Wang, Q. et al. (2021)	NR	NR		794.85		18.73		4995.27	2.14 ± 1.81 items·individual^{-1}
Taghizadeh et al. (2021)	NR	NR	700.39	316.6	25	42	6105	1323	11.4 ± 1.68 items·individual^{-1}
Garcia et al. (2021)	700	5000	macroinvertebrates 2190, fish 2070		700		5000		Macroinvertebrates: 0.02 ± 0.15 MP·individual^{-1} Fish: 0.13 ± 0.42 MP·individual^{-1}
Zakeri et al. (2020)	NR	NR	*C. aurata* 1940 ± 710, *R. kutum* 1770 ± 530		500-1000		2000-4750		*C. aurata* 2.95 ±1.98 MP·individual^{-1} *R. kutum* 1.66 ±1.23 MP·individual^{-1}
Winkler et al. (2020)	3	NR	1160		63		3.09		Not reported
Tien et al. (2020)	50	5000	NR	NR	50-297		297-5000		14–94 MP·individual^{-1}
Talley et al. (2020)	NR	5000	NR	NR	50		5000		Not reported
Sfriso et al. (2020)	30	5000		NR		33		1000	1.0 items·individual^{-1}
Savoca et al. (2020)	NR	NR	*Engraulis encrasicolus* 790, 1900		250		5000		0.4 items·individual^{-1}
Ribeiro et al. (2020)	NR	NR	NR	NR	NR	NR	NR	NR	0.01-2.9 mg·g^{-1}
Renzi et al. (2020)	10	NA	NR	NR	1.4		10493		Silba Islands: 0.74 ± 3.7 items·animal^{-1} Telašćica Bay: 4.5 ± 5.6 items·animal^{-1}
Oliveira et al. (2020)	NR	NR	NR	NR	NR		NR		28.5 MP·individual^{-1}

Reference	MP Smallest Analyzed Size (µm)	MP Largest Analyzed Size (µm)	MP average size (µm)		MP lower size found (µm)		MP upper size found (µm)		MP Average Concentration
			Fibers	Fragments	Fibers	Fragments	Fibers	Fragments	
O'Connor et al. (2020)	100	5000	350-5000	350-5000	GI 106.6, Stomach Contents 119.4		GI 4700, Stomach Contents 2900		GI (1.88 ± 1.53 MP·individual^{-1}) Stomach Contents (1.31 ± 0.48 MP·individual^{-1})
Moore et al. (2020)	NR	NR	NR	NR	0-500		4000-4500		97 ± 42 MP·individual^{-1} (extrapolated from sampled tissue (11.6 ± 6.6 MP·individual^{-1}))
McGregor et al. (2020)	NR	NR	postflexion 2100, early juvenile 2300, juvenile 2300, sub-adult 1900, adult 3600	In surface area: postflexion 1300, early juvenile 5200, juvenile 600, sub-adult 700, adult 1600	300	600	8600	2900	Postflexion (2.1 fibers·individual^{-1}, <0.1 fragments/individual) Early juvenile (1.2 fibers·individual^{-1}, 0.2 fragments/individual) Juvenile (3.3 fibers·individual^{-1}, 0.3 fragments/individual) Sub-adult (1.5 fibers·individual^{-1}, 0.1 fragments/individual) Adult (1.8 fibers·individual^{-1}, 0.1 fragments/individual)
Mancia et al. (2020)	NR	NR	20-100		1-10		10000-50000		1.32 items·individual^{-1} 1.04 items·individual^{-1} (two different sites)
Koongolla et al. (2020)	NR	5000	20-1000		20-1000		2000-3000		0.228 ± 0.080 items·individual^{-1}
Iannilli et al. (2020)	NR	NR	55	55	NR		NR		Site 1: 2.2 MP·individual^{-1} Site 2: 1.8 MP·individual^{-1}
Gedik & Eryasar (2020)	NR	NR	1660	1660	70		4940		0.69 MP·individual^{-1}
Garcia-Garin et al. (2020)	500	NR	NA	NA	NA		NA		0 MP·scat^{-1}
Filgueiras et al. (2020)	300	5000	1110-1780 (different species)	530-570	300-500		2000-5000		*E. encrasicolus*: 1.92 ± 0.95 MP·individual^{-1} *S. pilchardus*: 1.77 ± 1.42 MP·individual^{-1} *C. lyra*: 2.53 ± 1.88 MP·individual^{-1} *M. surmuletus*: 1.56 ± 0.53 MP·individual^{-1}
de Barros et al. (2020)	NR	NR	NR	NR	NR	NR	NR	NR	NR
Dantas et al. (2020)	NR	5000	NR	NR	NR	NR	NR	NR	0-14 MP·individual^{-1}
D'Souza et al. (2020)	500	5000	500-5000	500-5000	500		30600		Faeces (7.6 ± 1.6 particles·g dw^{-1}) Regurgitate (15.8 ± 2.8 particles·g dw of plastic^{-1})
Corami et al. (2020)	5	100	<50 length <25 width	NR	NR	NR	NR	NR	NR

Reference	MP Smallest Analyzed Size (µm)	MP Largest Analyzed Size (µm)	MP average size (µm)		MP lower size found (µm)		MP upper size found (µm)		MP Average Concentration
			Fibers	Fragments	Fibers	Fragments	Fibers	Fragments	
Carlin et al. (2020)	NR	NR	NR	NR	NR	NR	NR	NR	11.9 ±2.8 MP·individual^{-1}
Bianchi et al. (2020)	NR	5000	<300	<300	NR	NR	NR	NR	2.1 ± 0.2 MP·individual^{-1}
Battaglia et al. (2020)	125	5000	NR	NR	NR	NR	NR	NR	280.6 ± 113.0 MP·individual^{-1}
Bagheri et al. (2020)	NR	NR	1000-2000		100-500		2000-5000		4.29 - 39 MP·g ww^{-1}
Avio et al. (2020)	NR	NR		10-300		10.0-50.0		>5000	1.34 ± 0.61 microparticle·individual^{-1} 20.8 ± 8.88 microfiber·individual^{-1}
Amorim et al. (2020)	NR	NR		12500		180		4700	1.3 ± 0.5 MP·individual^{-1}
Al-Salem et al. (2020)	NR	NR		NA		960		1570	0.15 MP·individual^{-1}
Adeogun et al. (2020)	NR	NR		NR		124		1530	NR
Zhang et al. (2019)	NR	5000	Gills (655.39 ± 753.77) GI (727.03 ± 1148.22)		Gills (24.64), GI (32.9)		Gills (268.03), GI (4092.15)		Gill: 0.77 ± 1.25 MP·individual^{-1} GI tract: 0.52 ± 0.90 MP·individual^{-1}
Windsor et al. (2019)	500	5000	NR	NR	NR	NR	NR	NR	0.01-0.04 MP·mg^{-1}
Wagner et al. (2019)	10	5000	NR		10	50	50	1500	NR
Savoca et al. (2019)	NR	NR	NR	NR	NR		NR		NR
Saley et al. (2019)	NR	NR	NR	NR	NR	NR	NR	NR	Macroalgae: *Pelvetiopsis limitata* (2.34 ± 2.19 plastics·g^{-1}); *Endocladia muricata* (8.65 ± 6.44 plastics·g-1) Snail: 9.91 ± 6.31 plastics·g^{-1}
Naidu (2019)	NR	NR		30	5	30	25	30	NR
Ryan et al. (2019)	335	NR	NR	NR	NR	NR	NR	NR	9.0 ± 8.8 MP·individual^{-1}
Rotjan et al. (2019)	40	NR	NR	NR	NR	NR	NR	NR	112 ± 5.01 MP·individual^{-1}
Roch et al. (2019)	40	5000		899		22		4986	0.2 ± 0.5 MP·individual^{-1}
Renzi et al. (2019)	100	5000	206.1-1862.5	206.1-1862.5	NR	NR	NR	NR	3-23 MP·individual^{-1}
Pozo et al. (2019)	NR	NR	<500		100		2800		NR
O'Hara et al. (2019)	1000	5000	NR	NR	NR	NR	NR	NR	1.6 ± 6.8 MP·individual^{-1}

Reference	MP Smallest Analyzed Size (µm)	MP Largest Analyzed Size (µm)	MP average size (µm)		MP lower size found (µm)		MP upper size found (µm)		MP Average Concentration
			Fibers	Fragments	Fibers	Fragments	Fibers	Fragments	
Nelms et al. (2019)	NR	NR	2000	900	100	100	20000	4000	5.5 ± 2.7 MP·individual^{-1}
Masia et al. (2019)	500	5000	NR	NR	NR	NR	NR	NR	12.7 ± 9.1 MP·individual^{-1}
Iannilli et al. (2019)	NR	NR	25.73	25.73	3		370		72.5 MP·individual^{-1}
Hudak & Sette (2019)	500	NA		2295		1200		3500	0.025 MP·individual^{-1}
Horn et al. (2019)	NR	NR	NR	NR	NR	NR	NR	NR	0.65 ± 1.64 MP·individual^{-1}
Hernandez-Milian et al. (2019)	200	5000	NR	NR	NR	NR	NR	NR	27.9 ± 14.7 MP·individual^{-1}
Gomiero et al. (2019)	20			Coastal (20-40) Offshore (40-80)	10-100	20-40	100-300	100<	Coastal (fragments 1.06–1.33 items·g ww^{-1}, fibers 0.62–0.63 items·g ww^{-1}) Offshore (fragments 0.65–0.66 items·g ww^{-1}, fibers 0.24–0.35 items·g ww^{-1})
Garnier et al. (2019)	NR	NR	<300		31		2440		0.15 ± 0.10 - 0.39 ± 0.14 MP·individual^{-1}
Ferreira et al. (2019)	NR	5000	1250 ± 60		NR		NR		*C. undecimalis*: 1.5 ± 0.1 MP·individual^{-1} *C. mexicanus*: 1.4 ± 0.1 MP·individual^{-1}
Duncan et al. (2019)	NR	1000	Mediterr. (1400 ± 540) Atlantic (2870 ± 200) Pacific (2850 ± 230)	Mediterr. (70 ± 10) Atlantic (310 ± 40) Pacific (260 ± 10)	NR	NR	NR	NR	NR (had a graph displaying data for each species)
Donohue et al. (2019)	330	NA	<2000	<1000	<2000	<1000	2000-10000	5000-10000	16.6 ± 19.1 MP·scat^{-1}
Costa et al. (2019)	300	5000	NR	NR	NR	NR	NR	NR	NR
Choy et al. (2019)	NR	NR	NR	NR	NR	NR	NR	NR	Larvacean: 10.7 ± 5.3 MP·sinker^{-1} Crab: 5 MP·individual^{-1}
Choi et al. (2020)	NA	NA		0.05 and 10		0.05		10	NR
Burkhardt-Holm & N'Guyen (2019)	NA	NA	NA	NA	NA	NA	NA	NA	NA
Bottari et al. (2019)	500	5000	1000-2500		NR		NR		*Zeus faber*: 1.77 MP·individual^{-1} *Lepidopus caudatus*: 4.72 MP·individual^{-1}

Reference	MP Smallest Analyzed Size (µm)	MP Largest Analyzed Size (µm)	MP average size (µm)		MP lower size found (µm)		MP upper size found (µm)		MP Average Concentration
			Fibers	Fragments	Fibers	Fragments	Fibers	Fragments	
Bessa et al. (2019)	60	NA	1889	312	408	76	4945	738	0.23 ± 0.53 MP·scat^{-1}
Andrade et al. (2019)	NR	NA	7500-10000		1000		15000		NR
Akhbarizadeh et al. (2019)	NR	NR	NR	<50	50	<50	8000	100-500	Muscle: 0.158-0.36 MP·g ww^{-1} Gills: 0.251-0.931 MP·g ww^{-1}
Abidli et al. (2019)	50	5000	1090	210	50-100		1000-5000		1031.10 ± 355.69 MP·kg ww^{-1}
Zhao et al. (2018)	NR	NR	295.5	295.5	1030.1		47.9		0.3 ± 0.6-0.4 ± 0.7 MP·individual^{-1}
Xiong et al. (2018)	NR	NR	NR	NR	NR	NR	NR	NR	19.1 ± 7.2 MP·individual^{-1}
Welden et al. (2018)	NR	NR	NR	NR	NR	NR	NR	NR	1.39 ±0.79 - 1.75 ±0.83 MP·individual^{-1}
Silva et al. (2018)	NR	5000	NR	NR	NR	NR	NR	NR	NR (had graph)
Renzi et al. (2018A)	NR	NR	1150-2290		750		6000		3-12.4 MP·individual^{-1}
Renzi et al. (2018B)	63	5000	100-2000	100-2000	<100		4000-5000		2.4±1.2 - 12.0 ± 6.6 MP·individual^{-1}
Pegado et al. (2018)	NR	NR		1820		380		4160	1.2 ± 5.0 MP·individual^{-1}
Nelms et al. (2018)	NR	NR	fish (2000±1800), scat (1500±1200)		500	100	6000	5500	Fish: 0.58 ± 1.05 MP·individual^{-1} Seal: 0.87 ± 1.09 MP·scat^{-1}
Naji et al. (2018)	10	5000	10.0-25.0		10.0-25.0		250-5000		3.7 - 17.7 MP/individual
Naidu et al. (2018)	NR	NR	NR	NR	NR	NR	NR	NR	NR
Morgana et al. (2018)	NR	NR	1600	1600	NR	NR	NR	NR	*B. saida:* 1.1±0.3 MP·individual^{-1}
McNeish et al. (2018)	NR	NR	<1500		NR		NR		0 - 22 MP·individual^{-1}
Markic et al. (2018)	NR	NR	100-500		<100		>5000		2.4 ± 0.2 MP·individual^{-1}
Lusher et al. (2018)	NR	NR	NR (size distribution graph present)		200-1000		600000		NR
Karthik et al. (2018)	100	4750	NR	NR	NR	NR	NR	NR	0.16 MP·individual^{-1}
Iannilli et al. (2018)	NR	NR	NR	NR	NR	NR	NR	NR	NR

Reference	MP Smallest Analyzed Size (µm)	MP Largest Analyzed Size (µm)	MP average size (µm)		MP lower size found (µm)		MP upper size found (µm)		MP Average Concentration
			Fibers	Fragments	Fibers	Fragments	Fibers	Fragments	
Hu et al. (2018)	NR	5000	NR	NR	NR	NR	NR	NR	0-2.5 MP·individual^{-1} Most common averages between sites: 0.5-1.5 MP·individual^{-1}
Hipfner et al. (2018)	NR	NR	NR	NR	750		142400		0.075 - 0.249 MP·individual-1
Goss et al. (2018)	NR	NR	NR	NR	NR	NR	NR	NR	Microbeads: 0.75 ± 0.25 MP·blade grass^{-1} Microfiber: 3.69 ± 0.99 MF·blade grass^{-1}
Ferreira et al. (2018)	NR	NR	Juvenile (1700 ± 830) Sub-adults (1950 ± 350) Adults (1660 ± 510)		NR	NR	NR	NR	3.03 ± 4.06 MP·individual^{-1}
Fang et al. (2018)	NR	NR	1450		170		9730		0.17–0.83 MP·individual^{-1}
Chagnon et al. (2018)	NR	5000		600		100		2100	1.5 ± 0.7 MP·individual^{-1} with ingested MP
Bour et al. (2018)	10	NA		<100-200		41		9000	1.8 MP·positive individual^{-1}
Bernardini et al. (2018)	NR	NR	5000-25000		NR		NR		NR
Beer et al. (2018)	NR	NR	plankton (1600 ± 1700) fish (1200 ± 2400)		100		27500		Plankton: 0.21 ± 0.15 particles·m^{-3} Fish: 0.21 ± 0.47 - 0.25 ± 0.52 MP·individual^{-1}
Ballkhuyuer et al. (2018)	NR	NR	2390		1000		3000		0.146 MP·individual^{-1}
Sun et al. (2017)	NR	NR	125, 167		4		2399		NR
Steer et al. (2017)	NR	NR	338		100	50	1100	100	1.2 MP·individual^{-1}
Ory et al. (2017)	NR	NR		1300		200		5000	2.5 ± 0.4 MP·individual^{-1}
Lourenco et al. (2017)	NR	NR	2377		300		20000		1.72 ± 2.40 MP·individual^{-1}
Hurley et al. (2017)	NR	NR	847		55	50	4100	4500	0.8 ± 1.01 MP·individual^{-1}
Guven et al. (2017)	NR	NR	656	656	9.07		12074.11		2.36 MP·individual^{-1}

Reference	MP Smallest Analyzed Size (µm)	MP Largest Analyzed Size (µm)	MP average size (µm)		MP lower size found (µm)		MP upper size found (µm)		MP Average Concentration
			Fibers	Fragments	Fibers	Fragments	Fibers	Fragments	
Wojcik-Fudalweska et al. (2016)	NR	NR	NR	NR	500		5000		NR
Peters & Bratton (2016)	NR	NR	NR	NR	NR	NR	NR	NR	0.3-1.3 $MP \cdot individual^{-1}$
Gusmao et al. (2016)	NR	NR	NR		2000		4000		1 $MP \cdot individual^{-1}$
Davidson & Dudas (2016)	NR	NR	NR	NR	NR	NR	NR	NR	0.07 - 5.47 $MP \cdot g^{-1}$
Phillips & Bonner (2015)	NR	NR		73-1565	NR	NR	NR	NR	NR
Lusher et al. (2015)	NR	NR	2160	2160	300		7000		2.95-7.25 $MP \cdot section^{-1}$
Desforges et al. (2015)	NR	NR	951-1040	196-273	461	123	1778	299	0.026-0.058 $MP \cdot individual^{-1}$
Goldstein & Goodwin (2013)	NR	NR		1410		609		6770	NR

Appendix 2. Literature Survey of Trophic Transfer, Bioconcentration, Bioaccumulation, and Biomagnification of Microplastics.

A literature search was conducted using the key words “microplastics” and “food web” or “trophic”. The search identified 263 papers published through January 2021, of which 143 were selected for analysis. This table summarizes data for tissues analyzed and whether the studies found evidence for trophic transfer, bioconcentration, bioaccumulation, or biomagnification. A description of the overall results is provided in the chapter text and Figures 9.3 and 9.4.

y: yes (evidence for the process in question), n: no (evidence against the process in question); na: not applicable (the study did not address the process or was not properly designed to address the process).

Reference	lab vs field vs modeling	Tissues MP Found In	# Trophic Transfers	Trophic Transfer (y/n/na)	Bioconcentration (y/n/na)	Bioaccumulation (y/n/na)	Biomagnification (y/n/na)	Species Examined
Abidli et al. (2019)	field	pooled individuals, whole organism (*C. gigas*), digestive tract (*S. officinalis*)	na	na	na	na	na	*Mytilus galloprovincialis, Ruditapes decussatus, Crassostrea gigas, Hexaplex trunculus, Bolinus brandaris, Sepia officinalis*
Adeogun et al. (2020)	field	stomach contents	na	na	na	na	na	*Coptodon zillii, Oreochromis niloticus, Sarotheron melanotheron, Chrysicthys nigrodigitatus, Lates niloticus, Paranchanna obscura, Hemichromis fasiatus, Hepsetus odoe*
Akhbarizadeh et al. (2019)	field	gill and muscle	na	na	na	y	n	*Penaeus semisulcatus, Portunus armatus, Epinephelus coioides, Platycephalus indicus, Liza klunzingeri armatus*
Al-Salem et al. (2020)	field	GI tracts	na	na	na	na	na	*Epinephelus coioides, Plicofollis layardi, Acanthopagrus latus, Eleutheronemaa tetradactylum, Pampus argenteus, Liza klunzingeri, Pomadasys kaakan, Lutjanus quinquelineatus*
Allen et al. (2017)	lab	na	na	na	na	na	na	*Astrangia poculata*
Amorim et al. (2020)	field	GI tracts	na	na	na	na	na	*Stellifer brasiliensis*
Andrade et al. (2019)	field	stomach contents	na	na	na	na	na	*Acnodon normani, Metynnis guaporensis, Metynnis luna, Myloplus asterias, Myloplus rhomboidalis, Myloplus rubripinnis, Myloplus schomburgkii, Ossubtus xinguense, Pristobrycon* cf. *scapularis, Pristobrycon eigenmanni, Pygocentrus nattereri, Serrasalmus* cf. *altispinis, Serrasalmus manueli, Serrasalmus rhombeus, Tometes ancylorhynchus, Tometes kranponhah*
Araujo et al. (2020)	lab	gills, liver, brain	1	y	y	y	n	*Poecilia reticulata* (fry), *Danio rerio*

Reference	lab vs field vs modeling	Tissues MP Found In	# Trophic Transfers	Trophic Transfer (y/n/na)	Bioconcentration (y/n/na)	Bioaccumulation (y/n/na)	Biomagnification (y/n/na)	Species Examined
Araujo et al. (2021)	lab	tadpole (whole organism), fish (gills, liver, GI tract), mice (liver)	2	y	y	y	n	*Physalaemus cuvieri, tambatinga* (♀*Colossoma Macropomum x* ♂*Piaractus Brachypomus*), *Mus musculus*
Avio et al. (2020)	field	fish (GI tracts), invertebrates (whole soft tissue)	na	na	na	na	na	*Sardina pilchardus, Scomber scombrus, Trachurus trachurus, Merluccius merluccius, Mullus barbatus, Chelidonichthys lucerna, Solea solea, Sardinella aurita, Diplodus vulgaris, Pagellus erythrinus, Spondilosoma cantharus, Tracinus draco, Lithognathu mormyrus, Mytilus galloprovincialis, Ostrea edulis, Sabella spallanzanii, Actinia* sp.*, Squilla mantis, Penaeus kerathurus, Nephrops norvegicus, Paracentrotus. Lividus, Mnemiopsis leydi, Palaemon* sp.*, Rhizostoma pulmo*
Bagheri et al. (2020)	field	fish (GI tracts), benthic organisms (whole)	na	na	na	na	na	*Cerastoderma lamarcki, Mytilaster lineatus, Litopenaeus vannameiin, Liza saliens, Neogobius melanostomus, Rutilus caspicus*
Ballkhuyuer et al. (2018)	field	GI tract	na	na	na	na	na	*Acanthurus gahhm, Pristipomoides typus, Epinephelus areolatus, Pristipomoides multidens, Lutjanus kasmira, Lethrinus microdon, Epinephelus chlorostigma, Gymnocranius grandoculis, Parascolopsis eriomma, Sargocentron spiniferum, Epinephelus radiatus, Lipocheilus carnolabrum, Plectorhinchus gaterinus, Epinephelus epistictus, Pygoplites diacanthus, Cephalopholis argus, Abudefduf sexfasciatus, Acanthurus sohal, Dascyllus trimaculatus, Chaetodon austriacus, Neoniphon sammara, Naso unicornis, Thalassoma rueppellii, Benthosema pterotum, Maurolicus mucronatus, Vinciguerria mabahiss*
Batel et al. (2016)	lab	whole organism, GI tract	1	y	na	y	na	*Artemia* sp.*, Danio rerio*
Batel et al. (2020)	lab	intestinal tract, liver, gallbladder, swim bladder, gonads	1	y	na	n	na	*Artemia, Danio rerio*
Battaglia et al. (2020)	field	GI tract contents	na	na	na	na	na	*Tursiops truncatus*
Beer et al. (2018)	field	plankton (whole organism), fish (GI tract)	na	na	na	na	na	Plankton, *Clupea harengus, Sprattus sprattus*

Reference	lab vs field vs modeling	Tissues MP Found In	# Trophic Transfers	Trophic Transfer (y/n/na)	Bioconcentration (y/n/na)	Bioaccumulation (y/n/na)	Biomagnification (y/n/na)	Species Examined
Beiras & Tato (2019)	lab	whole organism	na	na	na	n	na	*Paracentrotus lividus*
Bernardini et al. (2018)	field	stomach contents	na	na	na	na	na	*Prionace glauca*
Bessa et al. (2019)	field	scat	na	na	na	na	na	*Pygoscelis papua*
Bianchi et al. (2020)	field	GI tract	na	na	na	na	na	*Scomber colias, Merluccius merluccius, Trigla lyra*
Bottari et al. (2019)	field	gut contents	na	na	na	na	na	*Zeus faber, Lepidopus caudatus*
Bour et al. (2018)	field	non-fish (whole organism excluding shell), fish (GI tract	na	na	na	na	na	*Ennucula tenuis, Ophiura albida, Brissopsis lyrifera, Hediste diversicolor, Amphiura filiformis, Sabella pavonina, Crangon allmanni, Hippoglossoides platessoides, Enchelyopus cimbrius, Trisopterus esmarki*
Burkhardt-Holm & N'Guyen (2019)	modeling	prey	1	y	na	na	na	*Balaenoptera acutorostrata, Balaenoptera borealis*
Carlin et al. (2020)	field	GI tracts	na	na	na	na	na	*Buteo lineatus, Pandion haliaetus, Strix varia, Megascops asio, Coragyps atratus, Cathartes aura, Bueto jamaicensis, Accipiter cooperii*
Chagnon et al. (2018)	field	GI tract contents	na	n	na	na	na	*Cheilopogon rapanouiensis, Thunnus albacares*
Choi et al. (2020)	lab	whole organism	na	na	n	n	na	*Tigriopus japonicus*
Choy et al. (2019)	field	discarded particle-filtering houses and GI tract contents	na	na	na	na	na	*Bathochordaeus* spp., *Pleuroncodes planipes*
Cole et al. (2013)	lab	whole organism	na	na	na	n	na	*Acartia clausi, Calanus helgolandicus, Centropages typicus, Temora longicornis, Doliolidae, Euphausiidae, Parasagitta* sp., *Obelia* sp., *Siphonophorae, Oxyrrhis marina*
Corami et al. (2020)	field	gills, heptopancreas	na	na	na	y	na	*Crassostrea gigas*
Costa et al. (2019)	field	gut contents	na	na	na	na	na	*Ocypode quadrata*
Cousin et al. (2020)	lab	whole larvae	1 (multiple ways)	y	n	n	n	*Paramecium spec., Artemia, Danio rerio, Oryzias melastigma*
Critchell & Hoogenboom (2018)	lab	GI tract contents	na	na	na	na	na	*Acanthochromis polyacanthus*
D'Souza et al. (2020)	field	regurgitate and faecal samples (from birds)	na	na	na	na	na	*Cinclus cinclus*
Dantas et al. (2020)	field	stomach contents	na	na	na	na	na	*Opisthonema oglinum, Bagre marinus, Cathorops spixii, Sciades herzbergii, Chloroscombrus chrysurus, Conodon nobilis, Haemulopsis corvinaeformis*
Davidson & Dudas (2016)	field	whole organism	na	na	na	na	na	*Venerupis philippinarum*
Dawson et al. (2018)	lab	whole organism	na	na	na	n	na	*Euphausia superba*
de Barros et al. (2020)	field	stomach contents	na	na	na	na	na	*Pachygrapsus transversus*

Reference	lab vs field vs modeling	Tissues MP Found In	# Trophic Transfers	Trophic Transfer (y/n/na)	Bioconcentration (y/n/na)	Bioaccumulation (y/n/na)	Biomagnification (y/n/na)	Species Examined
Desforges et al. (2015)	field	whole organism	na	na	na	y	na	*Neocalanus cristatus, Euphausia pacifia*
Donohue et al. (2019)	field	scat	na	na	na	na	na	*Callorhinus ursinus*
Duncan et al. (2019)	field	gut contents	na	na	na	na	na	*Chelonia mydas, Caretta caretta, Lepidochelys kempii, Dermochelys coriacea, Natator depressus, Eretmochelys imbricata, Lepidochelys olivacea*
Elizalde-Velazquez et al. (2020)	lab	all internal organs	2	y	n	n	na	*Raphidocelis subcapitata, Daphnia magna, Pimephales promelas*
Fang et al. (2018)	field	whole organism	na	na	na	na	na	*Asterias rubens, Ctenodiscus crispatus, Leptasterias polaris, Pandalus borealis, Chionoecetes opilio, Ophiura sarsii, Retifusus daphnelloides, Latisipho hypolispus, Euspira nana, Astarte crenata, Macoma tokyoensis*
Farrell & Nelson (2013)	lab	haemolymph, stomach, hepatopancreas, ovary, gill	1	y	na	y	n	*Mytilus edulis, Carcinus maenas*
Fernandez & Albentosa (2019)	lab	digestive gland and biodeposits	na	na	y	y	na	*Mytilus galloprovincialis*
Ferreira et al. (2018)	field	GI tract contents	na	na	na	na	na	*Cynoscion acoupa*
Ferreira et al. (2019)	field	gut contents	na	na	na	na	na	*Centropomus undecimalis, Centropomus mexicanus*
Filgueiras et al. (2020)	field	GI contents	na	na	na	na	na	*Engraulis encrasicolus, Sardina pilchardus, Callionymus lyra, Mullus surmuletus*
Fueser et al. (2019)	lab vs field vs modeling	whole organism	na	na	na	na	na	*Caenorhabditis elegans, Panagrolaimus thienemanni, Plectus acuminatus, Poikilolaimus regenfussi, Acrobeloides nanus*
Fueser et al. (2020)	lab	GI tracts	na	na	na	na	na	*Chironomidae*, Copepoda, Rotifera, Nematoda (authors did not identify to a species level for these)

Reference	lab vs field vs modeling	Tissues MP Found In	# Trophic Transfers	Trophic Transfer (y/n/na)	Bioconcentration (y/n/na)	Bioaccumulation (y/n/na)	Biomagnification (y/n/na)	Species Examined
Garcia et al. (2021)	field	macroinvertebrates whole organism/pooled organisms, fish GI tract	NA	n	y	n	n	*Asellidae sp, Echinogammarus sp, Corbicula fluminae, Radix sp, Theodoxus fluviatilis, Ancylus fluviatilis, Faxonius limosus, Procambarus clarkii, Atyaephyra desmarestii, Diptera* sp., *Ecdyonurus* sp., *Ephemeroptera* sp., *Baetis* sp., *Caenis* sp., *Ephemerella* sp., *Ephoron virgo, Potamanthus luteus, Ephemera* sp., *Hydropsyche* sp., *Aphelocheirus aestivalis, Odonata* sp., *Anisoptera* sp., *Zygoptera* sp., *Onychogomphus* sp., *Platycnemis* sp., *Calopteryx* sp., *Oligochete* sp., *Planariidae* sp., *Chironomidae* sp., *Achetae* sp., *Simuliidae* sp., *Rhyacophila* sp., *Brachycentrus* sp., *Lepidostoma hirtum, Trichoptera* sp., *Alburnus alburnus, Barbus barbus, Rhodeus sericeus, Cyprinus carpio, Squalius cephalus, Rutilus rutilus, Gobio occitaniae, Pachychilon pictum, Pseudorasbora palva, Alburnoides bipunctatus, Phoxinus phoxinus, Oncorhynchus mykiss, Salmo trutta, Sander lucioperca, Perca fluviatilis, Anguila anguila, Esox lucius, Barbatula barbatula, Ameiurus melas, Lepomis gibosus, Silurus glanis*
Garcia-Garin et al. (2020)	field	scat	na	na	na	na	na	*Arctocephalus gazella*
Garnier et al. (2019)	field	GI tract	na	na	na	na	na	*Myripristis* spp., *Siganus* spp., *Epinephelus merra, Cheilopogon simus*
Gedik & Eryasar (2020)	field	pooled organisms (3/pool)	na	na	na	y	na	*Mytilus galloprovincialis*
Goldstein & Goodwin (2013)	field	GI tract contents	na	na	na	na	na	*Lepas anatifera, Lepas pacifica*
Gomiero et al. (2019)	field	pooled organisms (n=10)	na	na	na	na	na	*Mytilus galloprovincialis*
Goss et al. (2018)	field	blade grass	na	na	na	na	na	*Thalassia testudinum*
Gusmao et al. (2016)	field	GI tract	na	na	na	na	na	*Saccocirrus pussicus, Saccocirrus papillocercus, Saccocirrus* sp., *Claudrilus ovarium, Claudrilus* sp., *Meiodrilus gracilis, Protodrilus albicans, Protodrilus oculifer, Lindrilus n.sp., Megadrilus schneideri*
Gutow et al. (2016)	lab	GI tract, fecal pellets	na	na	na	na	na	*Fucus vesiculosusm, Littorina littorea*
Gutow et al. (2019)	lab	feces	na	na	na	na	na	*Littorina littorea, Littorina obtusata*

Reference	lab vs field vs modeling	Tissues MP Found In	# Trophic Transfers	Trophic Transfer (y/n/na)	Bioconcentration (y/n/na)	Bioaccumulation (y/n/na)	Biomagnification (y/n/na)	Species Examined
Guven et al. (2017)	field	GI tract contents	na	na	na	na	na	*Argyrosomus regius, Caranx crysos, Dentex dentex, Dentex gibbosus, Diplodus annularis, Lagocephalus spadiceus, Lithognathus mormyrus, Liza aurata, Mullus barbatus, Mullus surmuletus, Nemipterus randalli, Pagellus acarne, Pagellus erythrinus, Pagrus pagrus, Pelates quadrilineatus, Pomadasys incisus, Sardina pilchardus, Saurida undosquamis, Sciaena umbra, Scomber japonicus, Serranus cabrilla, Siganus luridus, Sparus aurata, Trachurus mediterraneus, Trigla lucerna, Umbrina cirrosa, Upeneus moluccensis, Upeneus pori*
Hanslik et al. (2020)	lab	GI tract	1	n	na	na	na	*Daphnia magna, Chironomus riparius, Danio rerio*
Hasegawa et al. (2021)	lab	GI tract	1	y	y	na	na	*Neomysis* spp., *Myoxocephalus brandti*
Hernandez-Milian et al. (2019)	field	intestine content	na	na	na	na	na	*Halichoerus grypus*
Hipfner et al. (2018)	field	stomach contents	na	na	na	na	na	*Ammodytes personatus, Clupea pallasii*
Horn et al. (2019)	field	GI tract contents	na	na	na	na	na	*Emerita analoga*
Hu et al. (2018)	field	pooled organisms (n=5-10)	na	na	y	y	na	*Microhyla ornata, Rana limnochari, Pelophylax nigromaculatus, Bufo gargarizans*
Hudak & Sette (2019)	field	feces	na	na	na	na	na	*Phoca vitulina vitulina, Halichoerus grypus atlantica*
Hurley et al. (2017)	field	whole organism	na	na	na	y	na	*Tubifex tubifex*
Iannilli et al. (2018)	field	pooled GI tracts (n=10)	na	na	na	na	na	*Talitrus saltator*
Iannilli et al. (2019)	field	GI tracts	na	na	na	na	na	*Gammarus setosus*
Iannilli et al. (2020)	field	pooled GI tracts	na	na	na	na	na	*Cryptorchestia garbinii*
Kaposi et al. (2014)	lab	stomach contents	na	na	na	na	na	*Tripneustes gratilla*
Karthik et al. (2018)	field	GI tract contents	na	na	na	na	na	*Rastrelliger kanagurta, Siganus javus, Arius arius, Leiognathus equulus, Mugil cephalus*
Kim et al. (2018)	lab	crop, proventriculus, alimentary canal, ileum, Malpighian tubules, rectal ampulla, reproductive organ	1	y	na	n	n	*Cybister japonicus, Danio rerio*

Reference	lab vs field vs modeling	Tissues MP Found In	# Trophic Transfers	Trophic Transfer (y/n/na)	Bioconcentration (y/n/na)	Bioaccumulation (y/n/na)	Biomagnification (y/n/na)	Species Examined
Koongolla et al. (2020)	field	GI tract and gills	na	na	na	na	na	*Gastrophysus spadiceus, Siganus canaliculatus, Decapterus maruadsi, Trachiocephalus myops, Carangoides chrysophrys, Caranx pectoralis, Saurida tumbil, Lepidotrigla alata, Psenopsis anomala, Nemipterus virgatus, Pennahia macrocephalus, Upeneus sulphureus, Upeneus bensasi, Pseudorhombus oligodon, Branchiostegus argentatus, Apogon quadrifasciatus, Acropoma japonicum, Apogon ellioti, Trichiurus haumela, Apogon semilineatus, Sirembo imberbis, Priacanthus macracanthus, Scorpaena hatizyoensis, Trachurus japonicus* (last 12 species did not have MP detected)
Lourenco et al. (2017)	field	soft tissue, gizzard content, feces	na	na	na	na	na	*Cerastoderma edule, Scrobicularia plana, Hediste diversicolor, Dosinia isocardia, Senilia senilis, Diopatra neapolitana, Glycera alba, Nereis caudatus, Scolelepis squamata, Arenaria interpre, Calidris alba, Calidris alpina, Calidris canutus, Calidris ferruginea, Charadrius hiaticula, Limosa lapponica, Limosa limosa, Numenius phaeopus, Pluvialis squatarola, Recurvirostra avosetta, Tringa totanus*
Lusher et al. (2015)	field	GI tract contents	na	na	na	na	na	*Mesoplodon mirus*
Lusher et al. (2018)	field	GI tract contents	na	na	na	na	na	*Balaenoptera acutorostrata, Balaenoptera borealis, Balaenoptera physalus, Megaptera novaeangliae, Physeter macrocephalus, Kogia breviceps, Hyperoodon ampullatus, Mesoplodon bidens, Mesoplodon mirus, Ziphius cavirostris, Delphinus delphis, Stenella coeruleoalba, Phocoena phocoena, Globicephala melas, Grampus griseus, Lagenorhynchus acutus, Lagenorhynchus albirostris, Orcinus orca, Tursiops truncatus*
Ma & You (2021)	modeling	NA	3	y	n	y	y	*Siniperca chuatsi, Cyprinus carpio, Carassius carassius, Ctenopharyngodon idella*
Mancia et al. (2020)	field	GI tract	na	na	na	na	na	*Scyliorhinus canicula*

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Markic et al. (2018)	field	GI tract contents	na	na	na	na	na	*Cheilopogon pitcairnensis, Hyporhamphus ihi, Ellochelon vaigiensis, Mugil cephalus, Acanthurus lineatus, Ctenochaetus striatus, Naso lituratus, Naso unicornis, Caranx papuensis, Decapterus macrosoma, Decapterus muroadsi, Seriola lalandi, Trachurus novaezelandiae, Schedophilus velaini, Nemadactylus macropterus, Coryphaena hippurus, Thyrsites atun*
Masia et al. (2019)	field	feces	na	na	na	na	na	*Phalacrocorax aristotelis, Larus michahellis, Chroicocephalus ridibundus*
Mateos-Cardenas et al. (2019)	lab	GI tract	1	y	na	na	na	*Lemna minor, Gammarus duebeni*
Mazurais et al. (2015)	lab	NA	na	na	na	n	na	*Dicentrarchus labrax*
McGregor et al. (2020)	field	stomach contents	na	na	na	na	na	*Chelon richardsonii*
McNeish et al. (2018)	field	GI tract	na	na	na	na	na	*Dorosoma cepedianum, Catostomus commersonii, Pimephales promelas, Carpoides cyprinus, Notropis stramineus, Notropis hudsonius, Fundulus diaphanus, Micropterus* sp.*, Notropis atherinoides, Neogobius melanostomus, Cyprinella spiloptera*
Moore et al. (2020)	field	GI tract	na	na	na	y (stomach contents not included)	na	*Delphinapterus leucas*
Morgana et al. (2018)	field	GI tract	na	na	na	na	na	*Triglops nybelini, Boreogadus saida*
Naidu (2019)	field	whole organism	na	na	na	y	na	*Perna viridis*
Naidu et al. (2018)	field	NR	na	na	na	na	na	*Sternaspis scutata, Magelona cinta, Tellina* sp.
Naji et al. (2018)	field	whole organism	na	na	na	y	na	*Cerithidea cingulata, Thais mutabilis, Amiantis umbonella, Amiantis purpuratus, Pinctada radiata*
Nelms et al. (2018)	field	seal (scat) and fish (GI tract contents)	1	y	na	na	na	*Halichoerus grypus, Scomber scombrus*
Nelms et al. (2019)	field	GI tract contents	na	na	na	na	na	*Delphinus delphis, Phocoena phocoena, Halichoerus grypus, Grampus griseus, Kogia breviceps, Lagenorhynchus albirostris, Lagenorhynchus acutus, Phoca vitulina, Stenella coeruleoalba, Tursiops truncatus*
O'Connor et al. (2020)	field	GI tract and stomach contents	na	na	na	y	na	*Salmo trutta*
O'Hara et al. (2019)	field	GI contents	na	na	na	na	na	*Ptychoramphus aleuticus*
Oliveira et al. (2020)	field	GI tract	na	na	na	na	na	*Sepia officinalis*

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Ory et al. (2017)	field	GI tract contents	na	na	na	na	na	*Decapterus muroadsi*
Ory et al. (2018)	lab	na	na	na	na	na	na	*Seriolella violacea*
Pannetier et al. (2020)	lab	imaged whole larvae	na	na	na	n	na	*Oryzias latipes larvae*
Pegado et al. (2018)	field	gut contents	na	na	na	na	na	*Bagre bagre, Bagre marinus, Notarius grandicassis, Batrachoides surinamensis, Caranx crysos, Caranx hippos, Selene setapinnis, Selene vomer, Chaetodipterus faber, Anisotremus surinamensis, Anisotremus virginicus, Conodon nobilis, Genyatremus luteus, Haemulon plumierii, Haemulon steindachneri, Orthopristis ruber, Lutjanus analis, Lutjanus synagris, Cynoponticus savanna, Gymnothorax ocellatus, Rhinoptera bonasus, Narcine brasiliensis, Ophichthus cylindroideus, Ophichthus ophis, Polydactylus oligodon, Polydactylus virginicus, Pomatomus saltatrix, Rachycentron canadum, Bairdiella ronchus, Ctenosciaena gracilicirrhus, Cynoscion jamaicensis, Cynoscion leiarchus, Cynoscion microlepidotus, Cynoscion virescens, Macrodon ancylodon, Menticirrhus americanus, Micropogonias furnieri, Paralonchurus brasiliensis, Scomberomorus brasiliensis, Epinephelus itajara, Sphyrna tiburo, Peprilus paru, Colomesus psittacus, Mustelus canis, Mustelus higmani, Trichiurus lepturus*
Peters & Bratton (2016)	field	stomach contents	na	na	na	na	na	*Lepomis macrochirus, Lepomis megalotis*
Phillips & Bonner (2015)	field	GI tract contents	na	na	na	na	na	*Brevoortia patronus,Dorosoma cepedianum, Dorosoma petenense, Campostoma anomalum, Cyprinella lepida, Cyprinella lutrensis, Cyprinella venusta, Notemigonus crysoleucas, Notropis amabilis, Notropis volucellus, Opsopoeodus emiliae, Pimephales promelas, Pimephales vigilax, Notropis sabinae, Notropis stramineus, Erimyzon oblongus, Minytrema melanops, Astyanax mexicanus, Ameiurus melas, Ameiurus natalis, Ictalurus punctatus, Noturus gyrinus, Mugil cephalus, Fundulus notatus,*

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Piarulli & Airoldi (2020)	lab	whole mussel, depurated water	1	y (via fecal pellets to a detritivore)	na	n	na	*Mytilus galloprovincialis, Hediste diversicolor*
Pozo et al. (2019)	field	GI tract contents	na	na	na	na	na	*Trachurus murphyi, Strangomera bentincki, Merluccius gayi, Eleginops maclovinus, Aplodactylus punctatus, Basilichthys australis*
Renzi et al. (2018A)	field	hepatopancreas and gills	na	na	na	na	na	*Mytilus galloprovincialis*
Renzi et al. (2018B)	field	whole organism	na	na	na	y	na	*Holothuria tubulosa*
Renzi et al. (2019)	field	stomach contents	na	na	na	na	na	*Sardinia pilchardus, Engraulis encrasicolus*
Renzi et al. (2020)	field	pooled organisms	na	na	na	y	na	*Holothuria tubulosa*
Ribeiro et al. (2020)	field	muscle (prawns and sardine), whole organism (oyster), mantle (squid), GI and leg flesh (crab)	na	na	na	y	na	*Crassostrea gigas, Penaeus esculentus, Portunus armatus, Nototodarus gouldi, Sardinops neopilchardus*
Roch et al. (2019)	field	GI tract	na	n	n	na	na	*Leuciscus leuciscus, Barbus barbus, Squalius cephalus, Barbatula barbatula, Gobio gobio, Phoxinus phoxinus, Alburnus alburnus, Neogobius melanostomus, Cobitis taenia, Rutilus rutilus, Scardinius erythrophthalmus, Coregonus wartmanni, Tinca tinca, Perca fluviatilis, Blicca bjoerkna, Gasterosteus aculeatus, Lota lota, Gymnocephalus cernua, Esox Lucius, Abramis Brama, Leuciscus leuciscus, Silurus glanis, Sander lucioperca, Perca fluviatilis*
Roch et al. (2020)	lab	stomach/GI tract	na	na	n	y	na	*Oncorhynchus mykiss, Thymallus thymallus, Cyprinus carpio, Carassius carassius*
Rotjan et al. (2019)	field and lab	de-calcified coral polyps	na	na	na	n	na	*Astrangia poculata*
Ryan et al. (2019)	field	GI tract	na	na	n	na	na	*Alosa aestivalis*
Saley et al. (2019)	field	surface rinsed (algae), whole soft tissue (snail)	1	y	y	y	na	*Pelvetiopsis limitata, Endocladia muricata, Tegula funebralis*
Santana et al. (2017)	lab	GI tract, hepatopancreas, liver, gonads, hemolymph, blood	1	n	na	y	na	*Perna perna, Callinectes ornatus, Spheoeroides greeleyi*
Savoca et al. (2019)	field	stomach contents	na	na	na	na	na	*Pagellus erythrinus, Pagellus bogaraveo*

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Savoca et al. (2020)	field	whole larvae	na	na	na	y	na	*Sardina pilchardus, Engraulis encrasicolus*
Scherer et al. (2017)	lab	GI tract and whole organism	na	na	na	na	na	*Daphnia magna, Chironomus riparius, Physella acuta, Gammarus pulex, Lumbriculus variegatus*
Setala et al. (2014)	lab	GI tract contents	1	y	na	n	na	*Acartia* spp., *Eurytemora affinis, Limnocalanus macrurus, Bosmina coregoni maritima, Evadne nordmannii, Marenzelleria* spp., *Synchaeta* spp., *Neomysis integer, Mysis mixta, Mysis relicta, Tintinnopsis lobiancoi*
Setala et al. (2016)	lab	gills, GI tract	na	na	na	na	na	*Macoma balthica, Mytilus trossulus, Gammarus* spp., Mysid shrimps, *Monoporeia affinis, Marenzelleria* spp.
Sfriso et al. (2020)	field	pooled organisms	na	na	na	y	n	*Edwardsia meridionalis, Cyamiocardium denticulatum, Yoldiella antarctica, Aequiyoldia eightsii, Thyasira debilis, Harpiniopsis similis, Orchomenella franklini, Eatoniella* sp., *Oweniidae* sp., *Aglaophamus macroura, Leitoscoloplos mawsoni, Perkinsiana milae*
Silva et al. (2018)	field	stomach contents	na	na	na	na	na	*Pomadasys ramosus, Haemulopsis corvinaeformis*
Silva et al. (2019)	lab	whole organism	na	na	na	na	na	*Chironomus riparius*
Steer et al. (2017)	field	GI tract	na	na	na	na	na	*Merlangius merlangus, Microchirus variegatus, Trisopterus minutus, Callionymus lyra, Anguilla anguilla*
Sun et al. (2017)	field	whole organism	na	na	na	y	na	Copeopods, Chaetognaths, Jellyfish, Shrimp, Fish larvae
Taghizadeh et al. (2021)	field	GI tract	0	na	na	na	na	*Rutilus frisii kutum*
Taipale et al. (2019)				y	na	y	na	*Cryptomonas sp. CPCC 336, Daphnia magna,*
Talley et al. (2020)	field	GI tract	na	na	na	na	na	*Fundulus parvipinnis, Gillichthys mirabilis, Poecilia latipinna*
Tien et al. (2020)	field	GI tract	na	na	y	na	na	*Oreochromis niloticus niloticus, Pterygoplichthys pardalis, Carassius auratus auratus, Leiognathus equulus, Pomadasys argenteus*
van Colen et al. (2020)	lab	whole larvae	1	y	y	y	na	*Limecola balthica, Cerastoderma edule, Isochrysis galbana*
Vroom et al. (2017)	lab	GI tract	na	na	na	na	na	*Acartia longiremis, Pseudocalanus* spp., *Calanus finmarchicus*
Wagner et al. (2019)	field	stomach contents	na	na	na	na	na	*Salvelinus fontinalis, Oncorhynchus mykiss, Micropterus dolomieu*

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Wang, Q. et al. (2021)	field	GI tract	0	na	na	na	na	*Pampus argenteus, Konosirus punctatus, Pneumatophorus japonicus, Scomberomorus niphonius, Platycephalus indicus, Sebastods schlegelii, Liza haematocheila, Enedrias fangi, Thryssa mystax, Thamnaconus modestus, Cleisthenes herzensteini, Pseudopleuronectes yokohamae, Eupleurogrammus muticus, Argyrosomus argentatus, Seriola aureovittata, Cynoglossus semilaevis, Conge myriaster, Cynoglossus joyneri, Odontamblyopus lacepedii, Synechogobius hasta, Tridentiger barbatus, Hexagrammos otakii, Lateolabrax maculatus, Chaeturichthys stigmatias, Paralichthys olivaceus, Saurida elongata, Sillago sihama, Sardinella zunasi, Johnius belengerii*
Wang, T. et al. (2021)	lab	hepatopancreas, gut, gills, muscle	1	y	y	y	n	*Charybdis japonica* and *Mytilus coruscus*
Welden et al. (2018)	field	stomach contents	na	na	na	na	na	*Pleuronectes plastessa, Maja squinado, Ammodytes tobianus*
Windsor et al. (2019)	field	pooled organisms (3/pool)	na	na	na	y	na	Heptageniidae, Baetidae and Hydropsychidae
Winkler et al. (2020)	field	pellets	na	na	na	na	na	*Alcedo atthis*
Wojcik-Fudalweska et al. (2016)	field	stomach contents	na	na	na	na	na	*Eriocheir sinensis*
Xiong et al. (2018)	field	intestinal contents	na	na	na	na	na	*Neophocaena asiaeorientalis sunameri*
Zakeri et al. (2020)	field	GI tract	na	na	na	na	na	*Chelon aurata, Rutilus kutum*
Zhang et al. (2019)	field	gills and GI tract	na	y	na	na	na	*Johnius* spp., *Larimichthys crocea, Harpadon nehereus, Pennahia argentata, Collichthys lucidus, Chrysochir aureus, Cynoglossus robustus, Muraenesox cinereus, Polydactylus sextarius, Pennahia macroephalus, Collichthys niveatus, Oratosquilla oratoria, Portunus trituberculatus, Carcinoplax vestita, Charybdis bimaculata, Charybdis variegata, Portunus gracilimanus, Charybdis japonica, Oratosquilla kempi*
Zhang et al. (2021)	field	stomach	0	na	na	na	na	*Sousa chinensis*
Zhao et al. (2018)	field	feces, pseudofeces, digestive gland/gut	na	na	na	na	na	*Mytilus edulis*