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Coyle, R., Hardiman, G., & Driscoll, K. O. (2020). Microplastics in the marine environment: A review of their sources, distribution processes, uptake and exchange in ecosystems. *Case Studies in Chemical and Environmental Engineering*, 2, Article 100010. <https://doi.org/10.1016/j.cscee.2020.100010>

Published in:

Case Studies in Chemical and Environmental Engineering

Document Version:

Publisher's PDF, also known as Version of record

Queen's University Belfast - Research Portal:

[Link to publication record in Queen's University Belfast Research Portal](#)

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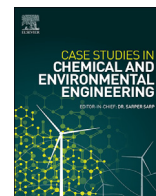
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Microplastics in the marine environment: A review of their sources, distribution processes, uptake and exchange in ecosystems

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ARTICLE INFO

Keywords:

Microplastics
Uptake
Biofouling
Marine aggregate
Faecal pellets

ABSTRACT

As the global production of plastics continues to accelerate, the ubiquitous presence of microplastics (μ Ps) has emerged as a significant marine problem. To comprehend fully the potential impacts and ecological harm caused by μ Ps it is vital that there is an understanding of their potential sources and sinks; the processes affecting their distribution; and their uptake and exchange in ecosystems. We carried out a comprehensive literature review to test the hypothesis that particle density is a key factor in describing the sinking behaviour and vertical distribution of μ Ps and to consider the uptake and trophic transfer of μ Ps. It was found that, whilst polymer density is a key factor in determining the vertical distribution of μ Ps in the water column, interactions with marine organisms better explain the occurrence of buoyant μ Ps at great depths. Furthermore, these interactions increase μ P availability and uptake, leading to trophic transfer and bioaccumulation within the food chain.

1. Introduction

Plastics are synthetic polymers derived from fossil fuels or, occasionally, biomass. Almost 360 million tonnes of plastics were produced in 2018 [1] and by 2050 production is expected to intensify to 2000 million tonnes [2]. Whilst plastic recycling has doubled since 2006 [1], 10% of plastics produced enter the oceans and constitute 80–85% of marine litter [3,4]. Estimates suggest that 92% of the 5.25 trillion plastic particles on the ocean surface are microplastics (μ Ps); small, ubiquitous plastic particles which are less than 5 mm in size [3,5]. They pollute the water column, sediments and biota of coastal waters, the open ocean, and freshwater environments and also wastewater treatment plants worldwide [6–8]. The adverse impacts of μ Ps have led to their classification alongside marine issues including overfishing and bycatch [9,10]. The determination of the ecological harm caused by μ Ps and their associated chemicals is a key objective of the European Union Marine Strategy Framework Directive (MSFD 2008/56/EC) [7]. This requires exploration of potential μ P sources and sinks and the processes affecting their distribution and ecosystem uptake.

2. Sources of microplastics

As an anthropogenic material, marine plastic pollution originates from either terrestrial sources, which account for 80% of marine debris [9,11], or marine activities, such as accidental loss or illegal disposal during fishing or offshore drilling [9]. For example, ships discard 6.5 million tons of plastics each year [12]. Table 1 demonstrates the diversity in μ P properties encountered during sampling, indicating a multitude of sources [6]. Point fluxes of μ Ps have specific and defined points of discharge [13] including riverine input or stormwater and sewage outflows [3,14,15]. Alternatively, diffuse pathways occur over an extended area from an array of sources, such as accidental spillage or degradation of larger plastic debris [3,14,15].

Primary μ Ps are intentionally manufactured for applications including resin pellets and exfoliators in personal care products [3,11, 14]. Items containing plastics including synthetic clothing and car tyres also generate primary μ Ps during use [16,17]. The weathering of larger plastic debris on land and at sea reduces their structural integrity and leads to the formation of fibrous or fragmented μ Ps, known as secondary μ Ps [14,18,19]. Single-use plastic bags are a significant source of secondary μ Ps due to their low resistance to degradation when exposed to seawater and sunlight [20]. Other sources include packaging wastes,

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Table 1
Examples of the range of μ P Properties observed during Sampling.

Location of Microplastic Sample	Sample type	Polymers Identified	Microplastic Particle Size	Microplastic Particle Colour	Microplastic Particle Shape	Reference
NE Atlantic Ocean	Water Column: Depth = 3 m	Not specified	0.2–43.2 mm (Median = 2.4 mm. Most commonly encountered size category = 1.25–2.5 mm)	Black (29.63%) Blue (37.67%) Grey (12.92%) Red/Pink (6.91%) Brown (1.60%) Orange (8.55%) Green (1.68%) Yellow (0.69%) White (0.35%)	Fibre (95.9%) Bead (0.26%) Foam (0.26%) Fragment (3.68%)	[21]
Rockall Trough, North Atlantic Ocean	Water Column: Depth > 2200 m	Polyester (65%) Polyethylene Terephthalate (17%) Acrylic (6%) Acrylic and cellulose (6%) Polyamide (6%)	0.4–8.3 mm	Blue (76%) Red (11.7%) Transparent (11.7%)	Monofilament fibres (100%)	[10]
Rockall Trough, North Atlantic Ocean	Biota: Benthic macro-invertebrates at depths > 2200 m	Acrylic Polyacrylonitrile Polyester Polyethylene and cellulose Acrylic and cellulose Polyamide Polyethylene Alkyd resin Polyamide and cellulose	0.023–6.25 mm (Average 1.191 ± 0.0756 mm)	Blue (42%) Red (42%) Black Green Orange Transparent Multi-coloured	Monofilament fibres (87%) Fragments (13%)	[10]
Irish Continental Shelf	Sediments: Upper 5 cm of Sediments at varying depths from shallow water to below seasonal mixed layer depth	Polyamide (23%) Polyethylene terephthalate (11%) Polypropylene (3%) Acrylic (2%) Cellulosic fibres	Only considered size fraction > 250 μ m	Blue (29%) Transparent (21%) White (16%) Red (16%) Black (12%) Green (3%) Grey (3%)	Fibres (85%) Fragments (15%)	[15]
Plymouth, UK	Sediments: Beach, estuarine and subtidal sediments	Acrylic Alkyd resin Poly(ethylene:propylene) Polyamide (nylon) Polyester Polyethylene Polymethylacrylate Polypropylene Polyvinyl-alcohol	Most particles were approximately 20 μ m in diameter	Most particles were brightly coloured	Some fragments were granular but most were fibrous	[22]
18 shorelines worldwide, Sewage disposal sites in the UK and Sewage Treatment plants in Australia	Shorelines Sewage disposal sites Sewage Effluent	Polyester (56%) Acrylic (23%) Polypropylene (7% on beach) Polyethylene (6% on beach) Polyamide fibres (3%) Polyester (78%) Acrylic (22%) Polyester (67%) Acrylic (17%) Polyamide (16%)	Not specified	Not specified	Fibres	[16]
Various locations including Mediterranean Sea, SW Indian Ocean and NE Atlantic Ocean	Sediments: Sample depth ranged to 3500 m however, most samples were taken at approximately 1000 m.	Acrylic (5.3%) Polypropylene Rayon (56.9%) Polyester (23.0%) Other plastics (polyamides and acetate) (14.7%)	Commonly 2–3 mm in length and less than 0.1 mm in diameter	Blue Black Green Red Other vibrant colours (Pink, purple, turquoise)	All fibrous	[23]
Various locations including Southern Ocean, North Atlantic Ocean, Gulf of Guinea and Mediterranean Sea	Sediments: Sample depths 1176–4844 m	Not specified	118 \times 60 μ m 75 \times 53 μ m 161 \times 137 μ m 83 \times 44 μ m 125 \times 76 μ m	Blue (0.4%), Green (0.4%) Red (0.2%)	Not specified	[24]
Bohai Sea, Western Pacific Ocean	Water Column: Max Depth = 30 m at 5 m intervals	Polypropylene (PP) Polyethylene (PE) Polyvinyl chloride (PVC) Polystyrene (PS) Polyethylene terephthalate (PET) Acrylonitrile butadiene	Mostly between 100 and 3000 μ m. Percentage of microplastics with a size less than 300 μ m increased with depth	White (33.3–74.5%) Black (3.2–33.3%) Red (0–6.5%) Yellow (0–11.6%) Blue (8.1–16.7%)	Fibres (75.0–96.4%) Fragments (3.6–24.6%) Particles (0–6.2%) Films (0–1.1%)	[25]

(continued on next page)

Table 1 (continued)

Location of Microplastic Sample	Sample type	Polymers Identified	Microplastic Particle Size	Microplastic Particle Colour	Microplastic Particle Shape	Reference
Mariana Trench, Pacific Ocean	Sediment: Sample Depth = 5500–11000 m	styrene (ABS) Cellulose Polyester (19%) Polypropylene (15%) Polyurethane (14%) Polyamide (12%) Polyvinyl chloride (10%) Rayon (10%) Polyethylene (9%) Polyethylene (19%) Polyamide (14%) Polyvinylchloride (13%) Polyurethane (12%) Polyester (11%) Polystyrene (11%) Rayon (9%)	0.1–0.5 mm in sediment	Green (0–8.1%) Colourless (0–16.7%) Not specified	Not specified	[26]
Mariana Trench, Pacific Ocean	Water Column: Depth = 2500–11000 m	Polyethylene (19%) Polyamide (14%) Polyvinylchloride (13%) Polyurethane (12%) Polyester (11%) Polystyrene (11%) Rayon (9%)	1–3 mm in seawater	Mostly blue, red, white, green and purple.	Fibrous, rod-like and roundish in shape.	[26]
Monterey Bay, California	Water Column: Depth = 5–1000 m and in 2 types of biota	Most ethylene terephthalate (Most common from all sample types) Polyamide (Second most common from all sample types) Polycarbonate (Thirdmost common from all sample types) Polyvinylchloride (Fourthmost common from all sample types) Polypropylene Polyester High density polyethylene Polylactic acid Polystyrene acrylonitrile Acrylonitrile butadiene styrene Polymethyl methacrylate	Not specified	Not specified	Not specified	[27]

fishing ropes and netting and disposable consumer items.

2.1. Degradation of plastics

In the marine environment plastics degrade through physical, chemical and biological processes [11,19,28]. Plastic degradation requires oxygen and sunlight [19,29,30] and so photodegradation is the most efficient process [11]. Beaches are the most likely locations of plastic degradation within the marine environment as conditions are conducive to high rates of photodegradation [19]. Floating plastics degrade at reduced rates in comparison to terrestrial plastics due to biological interactions that cause a surface film to form and shield the plastic surface from sunlight; and lower temperatures [3,19,30,31]. Lower temperatures and absence of UV-radiation in the deep ocean further reduces the degradation rate [11].

3. Distribution processes

3.1. Horizontal distribution processes

Hydrodynamic processes, such as coastal currents, drift and river outflow act to disperse μ Ps from their sources. Larger, basin scale and regional currents advect μ Ps to remote regions, while in-shore currents carry them to beaches [3,14] from where they may return to the open ocean [6]. Additionally, rotational ocean currents transport surface plastics to convergence zones of oceanic gyres, leading to concentrated areas of accumulation [11,14,32]. It has been estimated from the results of worldwide sampling that between 7000 to 35000 tons of plastics lie on the open-ocean surface [32]. However, 4.8 to 12.7 million tons of plastics entered the oceans in 2010 alone [33], suggesting removal from the

surface to yet unexplained sinks [8].

3.2. Vertical distribution processes

Numerous hypotheses state that polymer density determines μ P distribution in the water column [3,21]. Polymers denser than sea water, included in Table 2, will sink whilst less dense polymers, accounting for approximately 46% of plastics [12], are positively buoyant. The majority of μ Ps identified at 2200 m depth in the Rockall Trough were denser than seawater, accentuating this influence [10]. However, the occurrence of similar polymers in the water column and sediments [22] and of low density polymers at depths of 10,000 m [26] contradicts this hypothesis. Alternate hypotheses include biofouling, aggregation and zooplankton uptake [10].

3.2.1. Biofouling

Biofouling is the successive accumulation of organisms on submerged surfaces [35], illustrated in Fig. 1. It is influenced by the polymer type, surface area, surface energy and roughness of the μ P particle [36] and its rate depends on the productivity of the surrounding seawater and the position of the μ P in the water column [37,38]. Biofouling occurs rapidly, within days or weeks on surface plastics and at slower rates under submerged conditions [35,37].

Initially, the μ P particle undergoes surface fouling by dissolved organic molecules, bacterial cells, algae, larvae and spores [19,37]. This creates a biofilm which acts as a 'conditioning film' [36,37], enabling the attachment of colonizing invertebrates and microalgae including barnacles, tubeworms, hydroids and mussels [38]. Biofouling causes the overall density of μ P particles to increase [36] and when it exceeds the density of seawater, the particle will sink [19].

Table 2

Density and application of common Plastic Polymers (Adapted from Ref. [3,19,27,34]).

Resin Type	Common Applications	Specific gravity	
Low density polyethylene (LDPE)	Containers, tubing, bags, six-pack rings, wrappings	0.92–0.93	Float
Polyethylene (PE)	Plastic bags, storage containers, microbeads in personal care products	0.94–0.95	
High density polyethylene (HDPE)	Bottles (milk and detergent), pipes, geomembranes	0.94	
Polypropylene (PP)	Rope, bottle caps, fishing gear, strapping, packaging, carpets, drinking straws, microbeads in personal care products	0.90–0.92	
Polystyrene (Expanded) (PS)	Cool boxes, floats, cups	0.01–1.05	
Seawater Specific Gravity~ 1.025			
Polystyrene (PS)	Utensils, containers, commercial packaging, medical devices, microbeads in personal care products	1.04–1.09	Sink
Polystyrene Acrylonitrile (PSA)	Packaging material, containers, bottles	1.06–1.07	
Acrylonitrile butadiene styrene (ABS)	Printers, computer monitors, musical instruments, drainage pipes	1.06–1.08	
Polyamide (Nylon) (PA)	Fishing nets, rope, textiles, toothbrush bristles, automotive industry, microbeads	1.13–1.15	
Polymethyl methacrylate (Acrylic) (PMMA)	Transparent sheets, glass alternatives, microbead abrasives in personal care products, cleaning products, drilling fluids and air-blasting media	1.14–1.2	
Polyvinyl Chloride (PVC)	Film, pipe, containers, window frames, flooring, shower curtains	1.16–1.30	
Polylactic acid (PLA)	3D printing, moulds, films and sheets, biodegradable medical devices	1.24	
Polycarbonate (PC)	CDs and DVDs, electronics, lenses, construction industry	1.19–1.25	
Polyethylene terephthalate (PET)	Bottles, strapping, food packaging, thermal insulation, microbeads	1.34–1.39	
Polyoxymethylene (POM)	Mechanical and electrical engineering, vehicle and furniture components	1.35–1.44	
Polyester (Poly)	Textiles, abrasives in cleaning products, drilling fluids and air-blasting media	1.4	
Cellulose acetate	Cigarette filters	1.22–1.24	

Since seawater density increases with depth, sinking particles are suspended at depths where their density equals that of the ambient seawater [35]. Differences in μP particle and seawater density lead to an oscillatory motion characterised by the collision, growth, mortality and respiration rates of the attached microorganisms [35]. The particle will reach maximum depths at approximately midday when the sum of the growth and collision rates exceeds the sum of the mortality and respiration rates [35]. Conversely, the particle will move upwards in the water column when mortality and respiration dominate, which generally occurs during the night. Experimental results suggest that the sinking velocity of initially buoyant particles increases as the incubation period increases, emphasising the influence of biofouling on μP sinking, regardless of polymer density [36].

3.2.2. Aggregation

Oxygen-rich aggregates consisting of faecal pellets, phytoplankton, microbes and particulate organic matter (POM) are abundant at up to 5300 aggregates per litre within the ocean [39,40]. They form a key

component in the transport of inorganic and organic matter from the surface to deep oceans [18,39,40] and influence μP sinking behaviour, bioavailability, mobility and ultimate fate [28]. An outline of the μP aggregation process is depicted in FFig. 2.

Aggregation occurs when two or more particles, including μPs , cells, detritus and mineral particles, collide and attach to one another, forming an agglomerate [28,40]. Transparent Exopolymer Particles (TEPs) formed by coagulation of Extracellular Polymeric Substances (EPSs), enhance aggregation when they collide with organic matter and μPs , provided they are sufficiently sticky [41]. Typically, microorganisms including phytoplankton, algae, microbes and bacteria [40–43] produce EPSs. These organisms adhere to μPs during biofouling, suggesting the processes are interlinked. Aggregation due to the hydrophobicity of μP particles in the absence of EPS [43] is possible but uncommon in the natural environment as the abundance of natural colloids is far greater than μPs [28].

Marine aggregates readily incorporate μPs , with 73% of aggregates sampled *in situ* containing μPs [40]. A critical result from sinking tests was that aggregates efficiently transport initially buoyant μP particles, such as polypropylene and polyethylene, to the seafloor at enhanced sinking rates and in a shorter time than they would as free particles [39]. Therefore, positive buoyancy is overcome more immediately by aggregation than by biofouling [39]. The total aggregate density is much higher than the density of an individual μP particle, causing the sinking velocity to increase by several hundred meters per day [39,41].

4. Ecosystem uptake and exchange processes

μPs are similar in size to plankton and sediments that form the base of the food chain [24,44,45]. Alarming, in the Mediterranean Sea the numbers of μPs and plankton are similar in order, implying lower-trophic level (LTL) planktivores, which are often indiscriminate feeders and capture any particles within an appropriate size range, encounter μPs at similar frequencies to their natural food source [20]. Polymer density also influences μP availability [11]. Low-density μPs are available to organisms in the upper water column, including filter feeders, suspension feeders [11,44] and surface-feeding birds [46,47]. In contrast, benthic suspension and deposit feeders and detritivores consume high-density μPs that sink in the water column [11,44].

Biofouling increases the nutritional value of μP particles, encouraging grazing and ingestion [44,48,49]. The foulants trigger a response from zooplankton that utilise chemoreceptors to detect their algae prey [50], leading to a higher rate of ingestion of fouled μPs than pristine μPs [48]. As the primary source of carbon and nutrients to deep-sea ecosystems [41], aggregates are also key vectors for the uptake of μPs [42]. For example, the uptake of 7–30 μm polystyrene beads by Blue Mussels increased from 340 particles per mussel as freely suspended beads to 1.6×10^5 particles per mussel following incorporation into marine snow [39].

μPs are not digested or absorbed following ingestion since there are no enzymatic pathways available for the breakdown of synthetic polymers [19]. Instead, they are egested [44] or pass through cell membranes and accumulate within tissues, such as the hepatopancreas and ovaries in mussels [51]. The consumption of contaminated prey facilitates the transfer of μPs to higher trophic levels [44]. Trophic transfer has been demonstrated in laboratory experiments between organisms including Blue Mussels and Shore Crabs [51,52]; Whiting Fish and Norway Lobsters [12] and for LTL mesozooplankton including copepods and macrozooplankton such as mysid shrimps [53].

4.1. Zooplankton uptake

Zooplankton are a key component of nutrient cycling within marine ecosystems, transferring carbon from primary-producing phytoplankton to higher trophic levels through ingestion and defecation [54,55]. Some zooplanktons produce faecal pellets: densely packed waste organic

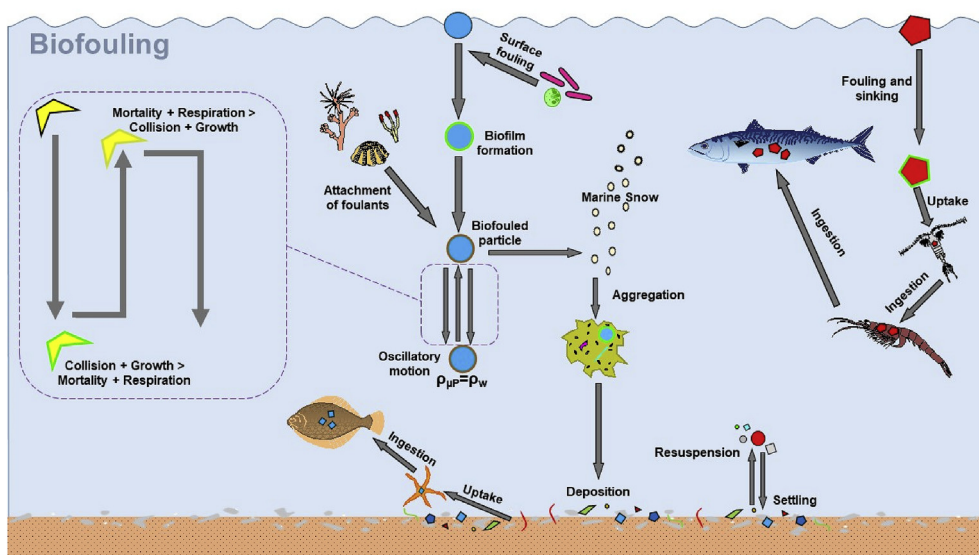


Fig. 1. Schematic outlining the process of μ P biofouling.

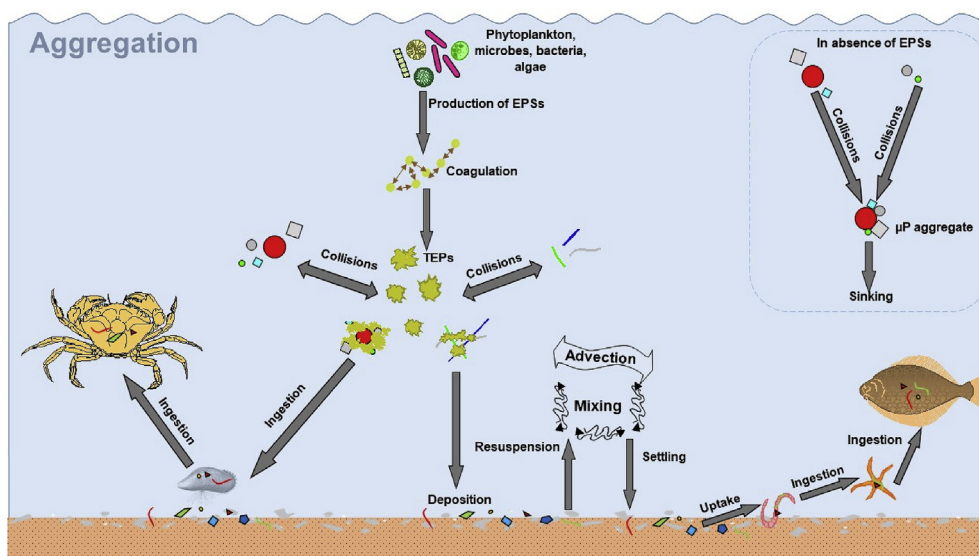


Fig. 2. Schematic outlining the process of μ P aggregation.

matter enveloped within a membrane [56]. Whilst they are an important element of the vertical flux in the ocean their significance depends on the presence of certain phytoplankton and zooplankton [56].

Zooplanktons encapsulate μ Ps into faecal pellets within their guts and subsequently egest them, potentially within hours of initial exposure [50, 56]. Faecal pellets sink beyond the surface layer at high rates that vary between species; faecal pellets produced by Copepods and Giant Larvaceans sink at rates of 86 m/day [56] and 300 m/day, respectively [57], whilst Salp faecal pellets have exceptionally high sinking rates of up to 2700 m/day [55]. The process of μ P ingestion and transfer in zooplankton faecal pellets is depicted in Fig. 3.

The incorporation of high-density μ Ps enhances faecal pellet sinking rates [50]. In contrast, low-density polymers reduce faecal pellet density and sinking rates, leading to longer residence times in surface waters where they degrade rapidly and undergo recycling due to biotic interactions such as coprochaly or coprorhexy [56,58]. Marine suspension feeders, detritivores and coprophagous organisms consume faecal pellets, facilitating further repackaging of μ Ps into faecal pellets and trophic

transfer [55,56,58]. Whilst faecal pellets are a viable mechanism for the removal of small μ P particles from the surface and play a key role in the cycling of nutrients, they are confined to the upper few hundred metres of the water column [18,39], and consequently will not persist to the deep sea.

5. Conclusions

There is a clear lack of consensus regarding the influence of polymer density on the vertical distribution of μ P particles in the water column. In this review we found that, whilst polymer density plays a key role in the initial distribution of μ Ps on entering the marine environment, influencing whether the pristine μ P particles will float or sink, the interactions of μ Ps with marine organisms better explains their occurrence at great depths. Following on from the identification of microplastics as free particles, whether clean or biofouled, or within marine aggregates it would be interesting to quantify the proportion of μ Ps residing in each of these states and the potential cycling between them. This cycling is

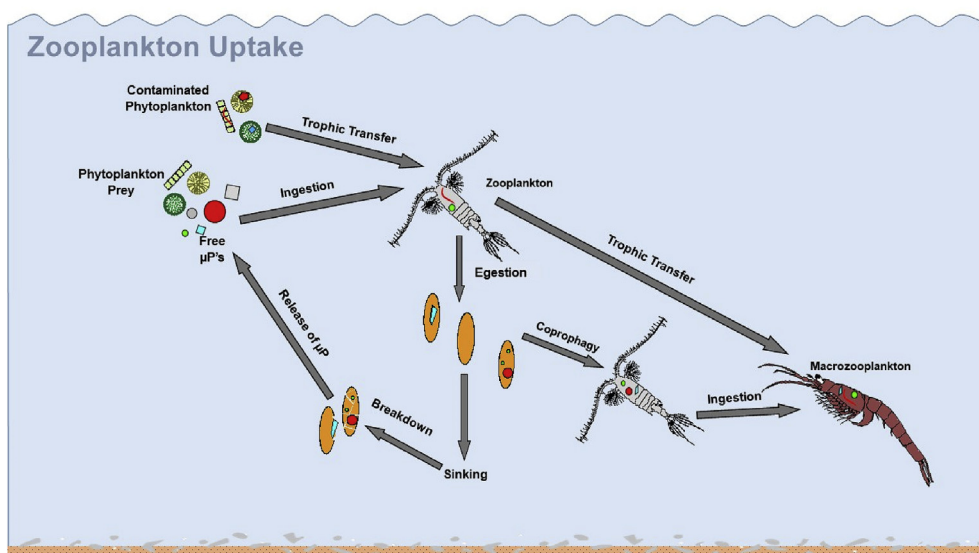


Fig. 3. Schematic outlining the ingestion and transfer of μ Ps in zooplankton faecal pellets.

particularly important in modelling μ P exchange at lower trophic levels since these processes enhance the nutritional value and availability of μ Ps to organisms at locations away from the water surface and increase their uptake.

To determine the ecological impacts of μ Ps it is essential that their various sources and sinks are identified and the processes driving their distribution and ecosystem uptake are clearly understood. Due to their small size, μ Ps are almost impossible to remove from natural water streams [6]. Therefore, mitigation measures which limit the input of μ Ps into the marine environment in the long term, such as reducing plastic consumption, particularly of single-use plastics; encouraging recycling; implementing bans on microbeads in cosmetic products and improving wastewater treatment infrastructure, will be most effective in limiting the deleterious impacts of μ Ps in the marine environment.

Funding

This work was supported by the United Kingdom Natural Environment Research Council under the Queen's University Belfast and University of Aberdeen Doctoral Research and Training Doctoral Training Partnership (QUADRAT DTP) NERC Reference: NE/S007377/1.

Declaration of competing interest

None.

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