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Review

How plastic debris and associated chemicals impact the marine food web: A review☆

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ABSTRACT

Contamination from plastic debris is omnipresent in marine environments, posing a substantial risk to marine organisms, food webs and the ecosystem. The overlap between the size range of marine plastic pollution with prey means that plastics are readily available for consumption by organisms at all trophic levels. Large plastic debris can directly result in the death of larger marine organisms, through entanglement, strangulation, choking and starvation through a false sense of satiation. Whereas smaller plastic debris, such as micro- and nano-plastics can have adverse impact to marine organisms due to their large surface area to volume ratio and their ability to translocate within an organism. Various physiological processes are reported to be impacted by these small contaminants, such as feeding behaviour, reproductive outputs, developmental anomalies, changes in gene expression, tissue inflammation and the inhibition of growth and development to both adults and their offspring. Micro- and nano-plastics are still relatively poorly understood and are considered a hidden threat. Plastic is a complex contaminant due to the diversity in sizes, shapes, polymer compositions, and chemical additives. These factors can each have unique and species-specific impacts. Consumption of plastics can occur directly, through ingestion and indirectly, through trophic transfer, entanglement of prey, adherence of plastics to external surfaces, and adherence of organisms to the external surfaces of plastics. This review investigated the intrusion of plastics into the marine food web and the subsequent consequences of plastic pollution to marine biota.The objective of this review was to identify the complexity of impacts to marine organisms through the food web from plastic contamination. Through a concise analysis of the available literature the review has shown that plastic pollution and their associated additives can adversely impact environmental and biological health.

1. Introduction

Aquatic environments are an integral and dynamic component of our planet, covering nearly 72% of the planet's surface (Costanza, 1999; Marshall, 2013). These environments provide 99% of the viable living space within our biosphere, making it the largest habitat by volume on Earth (Costanza, 1999). Furthermore, conservative estimates value the ocean-economy at A$32 trillion (Hoegh-Guldberg, 2015). Within only a few centuries, numerous anthropogenic pressures have been exerted on the ocean which have had severe ecological and socio-economic repercussions, ultimately influencing ocean processes. Examples of the pressures that oceans are currently under include climate change (Bruno et al., 2018), overexploitation of fisheries (Cordes et al., 2016) and pollution (Derraik, 2002; Landrigan et al., 2020). Ocean pollution is now severe enough that the United Nations' Sustainable Development Goals dedicated a target (14.1) to this issue, with the aim to "*prevent, and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution*" by 2025.

Research shows that marine debris primarily consists of discarded and lost plastics (Van Cauwenberghe et al., 2013). Meanwhile global plastic production is continuously increasing; from 2014 to 2019 there was an increase in plastic production of nearly 60 million tonnes, therefore producing approximately 370 million tonne of plastic in 2019 (this value is not inclusive of the production of polyethylene terephthalate-fibres, polyamide-fibres and polyacryl-fibres) (PlasticsEurope, 2015; PlasticsEurope, 2020). Considering that semi-synthetic plastics were first commercially developed in 1862 as

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Parkesine, an alternative product to ivory and horn. Followed by the first true synthetic plastic becoming commercially availabile in 1907 with the invention of Bakelite. Scientific accounts of plastic litter in the oceans did not occur until the 1970's (Buchanan, 1971; Carpenter et al., 1972; Carpenter & Smith, 1972; Painter & Coleman, 2008). However, the first observation of a marine organism having consumed plastic was reported earlier in 1966 (Kenyon & Kridler, 1969). The environmental and biological impacts of this pollution would not be determined until recent years as indicated by an increase in research intensity. The quantity of plastic debris entering the oceans is conservatively estimated at 10% of plastic waste (Thompson, 2006). The increasing demand for single-use products, the lack of incentives for plastic producers to decrease production volumes, increased fishing demand resulting in lost nets and lines, poorly controlled litter disposal, and poor waste management, paired with urban stormwater runoff and inadequate recycling practices, are the predominant reasons for the accumulation of litter in the ocean. The ubiquity of plastic waste in the ocean is notably demonstrated through records of floating debris from the five-ocean garbage patches, the North Pacific Gyre, the South Pacific Gyre, the North Atlantic Gyre, the South Atlantic Gyre, and the Indian Ocean Gyre (Van Sebille et al., 2012; Froyland et al., 2014; Lebreton et al., 2018).

). As plastics are designed to be durable, plastic waste degradation can take approximately 58–1,200 years through the process of photodegradation, which requires the interplay of light, oxygen, and microbes (Chamas et al., 2020). This causes fragmentation of larger pieces of plastics to micro and nano particles, resulting in the leaching of additives into the environment (Lambert et al., 2017).The rate of plastic degradation in the environment has been determined from experiments conducted under controlled field and laboratory conditions. Further research is required to understand the refined rates of plastic degradation under differing environmental conditions. Byproducts of the degradation of plastics through hydrolysis of hydrocarbons by microbes can not only result in the formation of smaller plastic particles (microplastics and nanoplastics) but also larger molecules (Zettler et al., 2013). This extensive degradation of larger more brittle plastics into fragments increases the bioavailability of plastics to the food web. Microplastics (1 μm - 5 mm) are both the result of non-degraded products, primary microplastics (Fig. 1A), such as the microbeads found in exfoliants, industrial abrasives, nurdles, and fibres from synthetic clothes (Browne, 2015), and the degradation of larger plastics, secondary microplastics, such as plastic waste from lost fishing gear and litter. It is believed that secondary microplastics make up the vast majority of microplastics pollution, however, after a period of weathering, primary microplastics begin to deteriorate too (Boucher & Friot, 2017). This process in addition to the degradation to macroplastics increases the abundance of nanoplastics (<1 μm; Fig. 1A).

In 2014, a minimum of 5.25 trillion plastic particles were thought to be present in the environment (Eriksen et al., 2014) with later predictions estimating a 50-fold increase by 2100 (Everaert et al., 2018). Microplastics, in particular, are present in marine environments worldwide, from the intertidal zones to the abyssal plains (Woodall et al., 2014; Wang et al., 2020). Reports have shown that microplastics are present in marine and terrestrial animals (Horton et al., 2017), on the highest peak of Mount Everest (Napper et al., 2020), at the lowest point in the Mariana Trench (Jamieson et al., 2019), in rainfall (Brahney et al., 2020) and sea ice (Mountford & Morales Maqueda, 2021). The presence of plastic debris does not necessarily indicate an adverse impact to the environment or it's organisms. Manufactured plastics are a complex mix of polymers and chemical additives; therefore, understanding how the diversity of plastic shapes, sizes, polymer compositions, charges, and chemical additives, impact marine organisms, the marine ecosystem, aquatic industries, and human health is a pertinent issue (Fig. 1; Lambert et al., 2017; Rist & Hartmann, 2018). Each of these factors and their impacts are diverse. For example chemical additives in plastics are inclusive of plasticisers, flame retardants, antioxidants and UV stabilisers, heat stabilisers, slip agents, lubricants, anti-statics, curing agents, blowing agents, biocides, colourants, fillers, and reinforcements (Fig. 1A; Hahladakis et al., 2018). Determining the extent of the complications that plastics cause on environmental, biological, and human health is an intricateissue to address. Furthermore, determining the different impacts between plastics compared to its natural additive containing counterparts on organism and ecosystem health, i.e. synthetic fibres versus natural fibres, is still unclear (Le Guen et al., 2020).

The objectives of this review were to identify the complexity of impacts to marine organisms through the food web from the contamination of i) plastic and ii) its associated chemicals, and identify the potential consequences to marine organisms, environmental services, and industries (Fig. 1B). To address this objective, a systematic review of the literature was conducted on Google Scholar and Web of Science™. The literature search was finalised in September 2021 and was restricted to

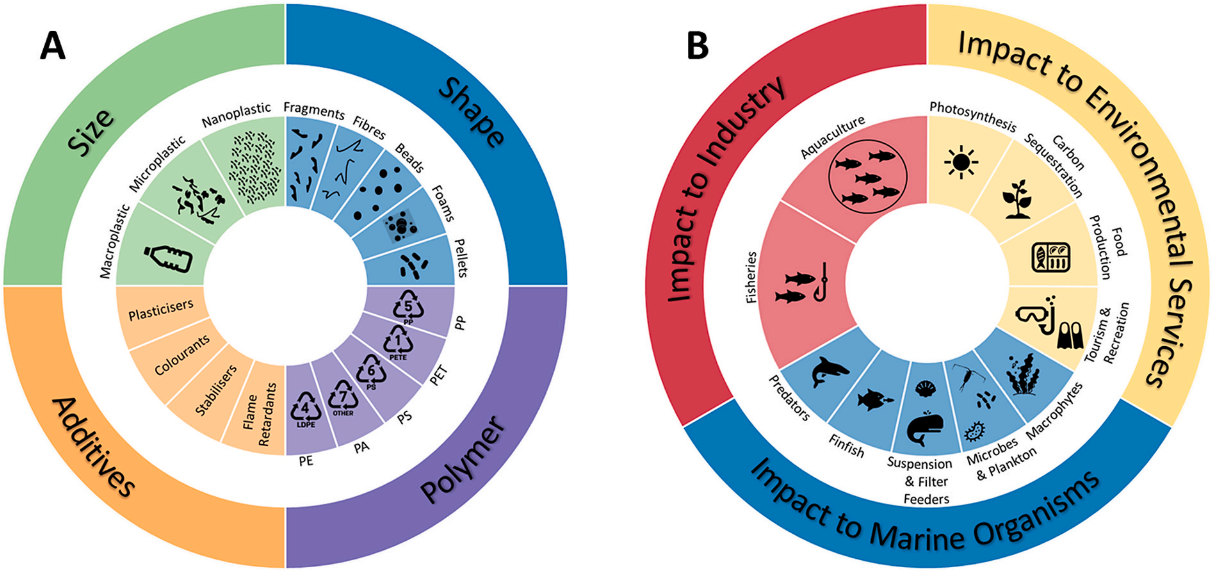

Fig. 1. Schematic representation of A) the composition of plastic pollution such as sizes, shapes, additives and polymers (including, but not limited to, PE = polyethylene, PA = polyamide, PS = polystyrene, PET = polyethylene terephthalate, PP = polypropylene) that can impact on B) industrial processes, environmental services, and on the life of marine organisms.

the years 1960–2022. The search was performed to identify the contamination of plastic debris to organisms through the marine food web. The search of the literature included the following terms: plastic debris, plastic waste, polymer, plastic, macroplastic, microplastic, nanoplastic, plastic additive, additive, macrophyte, seagrass, seaweed, biofilm, plastisphere, microbe, bacteria, phytoplankton, zooplankton, copepod, filter feeder, suspension feeder, marine benthic communities, polychaetes, shellfish, crustaceans, finfish, fish, marine mammals, sharks, predators, seabirds, trophic transfer, ingestion, effect, impact. The publications were assessed based on the organisms that were studied and the contaminants of concern (macroplastics, microplastics, nanoplastics, and/or associated chemical additives). Publications that were theoretical, did not include marine organisms and did not include the listed contaminants were excluded from this study. Information on the ingestion and impact of plastic contamination and/or the associated chemicals on marine organisms was synthesised from a total of 122 publications from both field and laboratory based studies.

2. Sources and pathways of plastic pollution in the marine environment

Plastic debris can enter and be dispersed in coastal marine environments from the land through freshwater streams, stormwater runoff, wastewater treatment plant discharge and atmospheric transportation (Liu et al., 2019; Mora-Teddy & Matthaei, 2020). This discharge into coastal waters results in plastic debris entering highly productive ecosystems and becoming accessible to many marine species. Coastal waters with closer proximity to areas of greater urbanisation generally have higher concentrations of plastic waste (Reisser et al., 2013; Schmidt et al., 2018), however, the presence of plastic pollution in remote areas indicates the significant role of oceanic processes in the dispersal of plastic debris.

Plastic distributions and transportation, vertically and horizontally through the water column is influenced by abiotic (i.e. ocean currents, physical shearing, hydrodynamic resuspension from the benthos and surface waters, bathymetry, sediment grain size distributions, fragmentation and natural sinking) and biotic factors (e.g. microbial fouling or the formation of aggregations with phytoplankton, through consumption and the subsequent egestion as a faecal pellet; Long et al., 2015; Cole et al., 2016; Courtene-Jones et al., 2017; Ramírez-Álvarez et al., 2020). These factors provide vertical and horizontal transport pathways for plastics from the sea surface to the benthos and can be sequestered in the deep sea as part of the biological pump. Future predictions show a decrease in the efficiency of the biological pump due to plastic pollution (Wieczorek et al., 2019). Although some models have been developed to better understand dispersal of small plastics in open oceans and coastal waters, these have focused on surface plastics and have reported concentrations throughout the global ocean (Goldstein et al., 2013; Gajšt et al., 2016). There is a need to develop a better understanding of the abundances of plastic debris vertically distributed through the water column to increase our knowledge on the bioavailability of plastic pollution. Additionally, further work is required to identify environmental concentrations of plastic chemical leachates in global oceans and quantify the sorption of other chemicals by plastic pollution.

3. Plastic contamination in the marine food web

Ecosystems are a complex network of interconnected systems. They are dynamic and are formed by way of interacting biological communities and their physical environments. Due to the diversity in sizes, shapes, and textures of plastic waste, plastics can be easily confused by many animals as prey. This is of concern because of the durability and propensity of plastic to enter marine food webs (Setälä et al., 2014). Plastics have been found in the guts of invertebrates, fish, turtles, and other larger animals, including organisms intended for human consumption and ecologically critical key-stone species (Galloway et al., 2017; Akhbarizadeh et al., 2020). There is an extensive list of marine organisms which have experienced adversities (and for some, death) from the effects of plastic marine litter and the toxicity of contaminants associated with this debris. In 2014, it was reported that at least 170 marine species were exposed to plastic ingestion including threatened species (Vegter et al., 2014); this number was revised to 690 marine species in 2015 (Gall & Thompson, 2015). The consequences and extent of plastic intrusion into food webs are relatively unknown.

Entry of marine debris into the food web occurs both directly and indirectly, and across all trophic levels. Direct entry can occur through filter feeding, respiratory intake and consumption of plastics while foraging. Indirect consumption pathways occur when a predator consumes an organism that has either retained the plastic (trophic transfer), plastic has adhered to the external surfaces or gills of an organism (including entanglement), or an organism has adhered to the surface of the plastic forming a plastisphere making the plastic an alluring food source (Reisser et al., 2014; Savoca et al., 2017; Nelms et al., 2018). The formation of this plastisphere or aggregate, is one of the biotic factors influencing the vertical distributions of plastics in the marine environment. . The formation of the plastisphere or aggregate occurs through the adherence of microbes and phytoplankton to the surfaces of plastics (Zettler et al., 2013; Long et al., 2015). The attachment of these microbes can facilitate the hydrolysis of hydrocarbons from the plastic polymers (Zettler et al., 2013), and can act as a vector for the transport of harmful and invasive species of bacteria vertically and horizontally through the ocean (Zettler et al., 2013; Oberbeckmann et al., 2015; Kirstein et al., 2016).

3.1. Microbes

Marine microbes are major primary producers, influence our climate, dictate the flow of marine energy and nutrients, and provide medicines and natural products. How plastics and their associated leachates affect microbial life at the base of the marine food web is still poorly understood (Tetu et al., 2019; Lear et al., 2021). Studies have found that plastic pollution has a direct impact on bacterial growth, protein production, the acquisition mechanisms of phosphorous, N_2-fixation rates, genome wide transcriptional changes, and photosynthesis (Tetu et al., 2019; Fernández-Juárez et al., 2021; Lear et al., 2021). The response of microbes to plastic pollution are species specific and vary depending on the plastic size, shape, charge, abundance, and the chemical additives and their concentrations.

High concentrations of large microplastics ($>$120 μm) enhanced the growth of autotrophic and heterotrophic bacteria. The growth of *Pseudomonas azotifigens* and *Halothece* sp. was enhanced in the presence of microplastics as it provided a substrate for growth (Table 1; Fernández-Juárez et al., 2021). On the other hand, exposure to nanoplastics induced oxidative stress in *Halomonas alkaliphile* and negative consequences were also recorded for *Cobetia* sp. (Sun et al., 2018; Fernández-Juárez et al., 2021). The cyanobacteria *Halothece* sp. was not impacted at all (Fernández-Juárez et al., 2021). These responses to plastics could be due to the size of the bacteria as opposed to being strictly species specific (Table 1). Laboratory experiments on the marine bacteria *Halothece* sp. and *Fischerella muscicola* showed reduced growth in response to plastic leachates (Table 1, Fernández-Juárez et al., 2021). Additionally, for one of the most common marine cyanobacteria, *Prochlorococcus,* growth, photosynthesis and genome-wide transcription were all negatively impaired when exposed to certain plastic leachates (Tetu et al., 2019).

While experiments have been conducted in the laboratory to assess the effect of plastics on these plankters (Fernández-Juárez et al., 2021), there are limited reports of *in situ* observations. It is plausible that plastic pollutants could influence global N_2-fixation rates in the environment both positively, through the increased growth of cyanobacteria exposed to plastic polymers, and negatively due to decreased growth from

Table 1

A summary of the impacts, both positive and negative to species of marine microbes and phytoplankton. Species responses are dependent on plastic size, volume of the plastics, volume and type of the additives (HBCD = 1,2,5,6,9,10-hexabromocyclododecane, DEHP = Dioctyl-phthalate), and polymer type (PE = polyethylene, PP = polypropylene, PVC = poly-vinyl chloride, PS = polystyrene) . The impact to the organism has been scored as positive or negative. Table does not show occurrences of no changes.

Microbes and Phytoplankton								
Species (size)	Nutritional mode	Plastic Size (μm)	Polymer Type	Chemical Additives	Volume of plastics or additive	Impact	Reference	Positive or Negative
Halothece sp. *(~4 – 7 μm)*	Photoautotrophic	N/A	N/A	Fluoranthene	300 μg L^{-1}	Reduced Growth	Fernández-Juárez et al. (2021)	Negative
Halothece sp. *(~4 – 7 μm)*	Photoautotrophic	N/A	N/A	Fluoranthene	3000 μg L^{-1}	Reduced Growth	Fernández-Juárez et al. (2021)	Negative
Halothece sp. *(~4 – 7 μm)*	Photoautotrophic	N/A	N/A	DEHP	300 μg L^{-1}	Reduced Growth	Fernández-Juárez et al. (2021)	Negative
Halothece sp. *(~4 – 7 μm)*	Photoautotrophic	N/A	N/A	DEHP	3000 μg L^{-1}	Reduced Growth	Fernández-Juárez et al. (2021)	Negative
Halothece sp. *(~4 – 7 μm)*	Photoautotrophic	N/A	N/A	Fluoranthene, DEHP & HBCD	300 μg L^{-1}	Reduced Growth	Fernández-Juárez et al. (2021)	Negative
Halothece sp. *(~4 – 7 μm)*	Photoautotrophic	1–164	PE, PP & PVC	N/A	300 μg L^{-1}	Reduced Growth	Fernández-Juárez et al. (2021)	Negative
Halothece sp. *(~4 – 7 μm)*	Photoautotrophic	1–164	PE, PP & PVC	N/A	3000 μg L^{-1}	Reduced Growth	Fernández-Juárez et al. (2021)	Negative
Halothece sp. *(~4 – 7 μm)*	Photoautotrophic	164 ± 8.03	PVC	N/A	100 μg mL^{-1}	Enhanced Growth	Fernández-Juárez et al. (2021)	Positive
Halothece sp. *(~4 – 7 μm)*	Photoautotrophic	90 ± 7.56	PP	N/A	100 μg mL^{-1}	Enhanced Growth	Fernández-Juárez et al. (2021)	Positive
Halothece sp. *(~4 – 7 μm)*	Photoautotrophic	109 ± 6.29	PE	Fluoranthene	0.01 μg mL^{-1} & 0.3 μg L^{-1}	Reduced Growth	Fernández-Juárez et al. (2021)	Negative
Halothece sp. *(~4 – 7 μm)*	Photoautotrophic	109 ± 6.29	PE	Fluoranthene	100 μg mL^{-1} & 300 μg L^{-1}	Reduced Growth	Fernández-Juárez et al. (2021)	Negative
Pseudomonas azotifigens (~3.5 μm)	Heterotrophic	N/A	N/A	DEHP	300 μg L^{-1}	Enhanced Growth	Fernández-Juárez et al. (2021)	Positive
Pseudomonas azotifigens (~3.5 μm)	Heterotrophic	N/A	N/A	DEHP	30 μg L^{-1}	Enhanced Growth	Fernández-Juárez et al. (2021)	Positive
Pseudomonas azotifigens (~3.5 μm)	Heterotrophic	164 ± 8.03	PVC	DEHP	0.01 μg mL^{-1} & 0.3 μg L^{-1}	Enhanced Growth	Fernández-Juárez et al. (2021)	Positive
Pseudomonas azotifigens (~3.5 μm)	Heterotrophic	109 ± 6.29	PE	Fluoranthene	0.01 μg mL^{-1} & 0.3 μg L^{-1}	Reduced Growth	Fernández-Juárez et al. (2021)	Negative
Pseudomonas azotifigens (~3.5 μm)	Heterotrophic	109 ± 6.29	PE	Fluoranthene	100 μg mL^{-1} & 300 μg L^{-1}	Reduced Growth	Fernández-Juárez et al. (2021)	Negative
Cobetia sp. (~1 μm)	Heterotrophic	164 ± 8.03	PVC	DEHP	100 μg mL^{-1} & 300 μg L^{-1}	Enhanced Growth	Fernández-Juárez et al. (2021)	Positive
Cobetia sp. (~1 μm)	Heterotrophic	109 ± 6.29	PE	Fluoranthene	0.01 μg mL^{-1} & 0.3 μg L^{-1}	Reduced Growth	Fernández-Juárez et al. (2021)	Negative
Fischerella muscicola	Autotrophic	90 ± 7.56	PP	N/A	0.01 μg mL^{-1}	Enhanced Growth	Fernández-Juárez et al. (2021)	Positive
Fischerella muscicola	Autotrophic	90 ± 7.56	PP	N/A	0.1 μg mL^{-1}	Enhanced Growth	Fernández-Juárez et al. (2021)	Positive
Fischerella muscicola	Autotrophic	90 ± 7.56	PP	N/A	10 μg mL^{-1}	Enhanced Growth	Fernández-Juárez et al. (2021)	Positive
Fischerella muscicola	Autotrophic	90 ± 7.56	PP	N/A	100 μg mL^{-1}	Enhanced Growth	Fernández-Juárez et al. (2021)	Positive
Fischerella muscicola	Autotrophic	164 ± 8.03	PVC	N/A	100 μg mL^{-1}	Enhanced Growth	Fernández-Juárez et al. (2021)	Positive
Fischerella muscicola	Autotrophic	N/A	N/A	Fluoranthene	300 μg L^{-1}	Reduced Growth	Fernández-Juárez et al. (2021)	Negative
Fischerella muscicola	Autotrophic	N/A	N/A	DEHP	300 μg L^{-1}	Reduced Growth	Fernández-Juárez et al. (2021)	Negative
Fischerella muscicola	Autotrophic	N/A	N/A	DEHP	30 μg L^{-1}	Reduced Growth	Fernández-Juárez et al. (2021)	Negative
Scenedesmus obliquus (2–15 μm)	Phototrophic	0.07	PS	N/A	44–1100 mg L	Inhibited Growth, Reduced chl-a	Besseling et al. (2014)	Negative
Chlorella (2–10 μm)	Phototrophic	0.02	PS	N/A	2.5 × 10^{6} cm^{2}/g	Decrease Photosynthesis	Bhattacharya et al. (2010)	Negative
Scenedesmus sp. *(2–10 μm)*	Phototrophic	0.02	PS	N/A	2.5 × 10^{6} cm^{2}/g	Decrease Photosynthesis	Bhattacharya et al. (2010)	Negative
Scenedesmus sp. *(2–10 μm)*	Phototrophic	0.02	PS	N/A	2.5 × 10^{6} cm^{2}/g	Increased Respiration	Bhattacharya et al. (2010)	Negative
Rhodomonas salina (12 μm)	Phototrophic	2	PS	N/A	10^{4} beads mL^{-1}	Hetero-aggregates	Long et al. (2015)	Positive

(*continued on next page*)

Table 1 (*continued*)

Microbes and Phytoplankton

Species (size)	Nutritional mode	Plastic Size (μm)	Polymer Type	Chemical Additives	Volume of plastics or additive	Impact	Reference	Positive or Negative
Chaetoceros neogracile (5 μm)	Phototrophic	2	PS	N/A	10^4 beads mL^{-1}	Hetero-aggregates	Long et al. (2015)	Positive
Chaetoceros neogracile (5 μm)	Phototrophic	2	PS	N/A	3.96 μg L^{-1}	Hetero-aggregates	Long et al. (2017)	Positive
Heterocapsa triquetra (23 μm)	Phototrophic	2	PS	N/A	3.96 μg L^{-1}	Phagotrophy	Long et al. (2017)	Negative
Skeletonema costatum	Phototrophic	1	PVC	N/A	5, 10 and 50 mg/L	Decreased Growth	Zhang et al. (2017)	Negative
Skeletonema costatum	Phototrophic	1	PVC	N/A	50 mg/L	Decreased Photosynthesis	Zhang et al. (2017)	Negative

exposure to chemical additives (Fernández-Juárez et al., 2021). However, this would require the plastics and the additives to be at higher concentrations and could potentially cancel each other out. Furthermore, these pollutants could be anthropogenic stressors that can impact microbial diversity (Machado et al., 2020; Seeley et al., 2020).

Further impacts of these plastics to the food web include the growth of threatening bacterial species on the biofilms of environmental plastic pollution. These biofilm coated plastics provide a stable substrate for a wide range of rafting organisms to attach, and due to their ubiquity in the ocean, the plastic could function as vectors for harmful and invasive species (Zettler et al., 2013; Oberbeckmann et al., 2015; Kirstein et al., 2016). The sequencing of biofilms present on microplastics in the North Adriatic Sea identified the bacterial species *Aeromonas Salmonicida* which is pathogenetic and highly contagious to fish (salmonids particularly), and can cause furunculosis (Cipriano & Bullock, 2001; Viršek et al., 2017). In the North and Baltic Sea, the potentially pathogenic bacteria *Vibrio parahaemolyticus,* was confirmed on 11 of the microplastics found in the North Sea (consisting of three polyethylene fibres, two polyethylene films, four polyethylene fragments and two polypropylene fragments) and on one of the microplastics (a polypropylene film) found in the Baltic Sea (Kirstein et al., 2016). *Vibrio parahaemolyticus* can cause bacterial illnesses in humans through seafood consumption such as gastroenteritis (Baker-Austin et al., 2010). It is possible that the occurrence of *V. parahaemolyticus* will increase with warming oceans, as its presence on plastics was suggested to be a result of favourable environmental conditions (Kirstein et al., 2016) and the species growth has been shown to increase with warmer sea temperatures (Iwamoto et al., 2010).

These studies imply that microplastics could influence microbial communities by enabling the dispersal of bacteria through adherence to their surfaces, thereby aiding the transportation of microbes in oceans globally and also into the digestive systems of marine organisms (Lear et al., 2021). There are limited studies on how plastics impact the interactions and compositions of microbial communities. However, there are fundamental differences in the functional potential and taxonomic composition of plastic-associated microbes versus planktonic microbes found in the surrounding open-ocean habitat. These communities vary seasonally and spatially differing in activity, abundance, and taxonomic composition (Zettler et al., 2013; Oberbeckmann et al., 2015; Bryant et al., 2016). The diversity of marine plastic pollution can have differing impacts on microbes. Larger plastics provide a greater surface area for growth, the shape of plastics and their surfaces (smooth or rough) can impact the adherence of microbes to plastics, and different plastic polymers and additives at varying concentrations can either reduce or enhance microbial growth (Table 1). Each of these four factors (shape, size, polymer composition, and chemical additives) can result in positive and negative impacts to marine microbial species.

3.2. Phytoplankton

Phytoplankton play an important role in the biological pump, supporting the oceans' ability to act as a carbon sink while driving primary productivity (Richardson, 2008; Basset et al., 2013). Phytoplankton are composed of three major groups: namely diatoms, dinoflagellates and blue-green algae. Chain-forming phytoplankton such as the diatom *Chaetoceros neogracile* can become associated to microplastic and nanoplastic particles by forming aggregates, such as marine snow, having the potential to be ingested by consumers (Long et al., 2017). Diatoms and other species of phytoplankton also attach to the surface of plastics, forming a plastisphere by adhering to the biofilm formed by marine microbes. The plastiphere attracts primary consumers, which through predation can ingest both the algae and plastic particles (Reisser et al., 2014; Savoca et al., 2017). The adherence of planktonic organisms to these surfaces makes plastic particles a favourable food choice as they mimic the odour of prey (Savoca et al., 2017). A study by Reisser et al. (2014), identified the attachment of coccolithophores, dinoflagellates and diatoms to microplastics. These communities could influence the chemical compositions (Harrison et al., 2011), hydrophobicity (Tu et al., 2020), degradation rate (Andrady, 2011), and sinking rate of plastic particles (Kaiser et al., 2017). To build on this, the lack of knowledge impairs our ability to understand the role of the plastisphere on the rates and extents of plastic dispersal.

Laboratory studies have shown that plastics can impact the chlorophyll content and photosynthetic efficiency of diatoms (e.g. *Skeletonema costatum*) and Chlorophytes (e.g. *Scenedesmus obliquus*; Besseling et al., 2014; Zhang et al., 2017), cause a large variety of physical damages and oxidative stresses to algae cells, as shown in blue-green algae (*Chlorella pyrenoidosa* and *Tetraselmis chuii*; Lagarde et al., 2016; Prata et al., 2018; Yang et al., 2020), modify the expression of genes involved in certain metabolic pathways (Mao et al., 2018), and decrease algal growth in chlorophytes, blue-green algae and diatoms (*Dunaliella tertiolecta, Chorella vulgaris* and *S. obliquus*; Besseling et al., 2014; Sjollema et al., 2016). The impacts and toxicity of plastics to phytoplankton varies with the size of the particles (Sjollema et al., 2016; Zhang et al., 2017), the type of polymer and its chemical constituents (Lagarde et al., 2016), the abundance of plastic particles (Mao et al., 2018), exposure times, the species of phytoplankton (Long et al., 2017), and possibly the age of the plastic (due to changes in the concentrations of chemical leachates with time and potentially an increase in different chemical concentrations through sorption).

Our current understanding of the potential modes and mechanisms of toxic action that plastic particles exert on phytoplankton is limited (Sjollema et al., 2016). Although not all studies agree on the extent and severity of these impacts (Bhattacharya et al., 2010; Sjollema et al., 2016), they all show an increase in adverse effects with increasing plastic quantities which are exacerbated with a decrease in the size of plastic particles. However, we currently do not have estimates for the quantity of nano-sized plastics in the marine environment, and therefore how much damage they might cause to the base of the food web. Furthermore, phytoplankton can be impacted by the four different factors of microplastic contamination (shape, size, polymer composition, and chemical additives). The impacts are similar to those of the microbes, with the surface area and physical plastic characteristics impacting the adherence of phytoplankton to surface, and both positive and negative impacts of plastic polymers and chemical additives reducing or enhancing phytoplankton growth.

3.3. *Macrophytes*

Seagrass meadows and beds provide high-value ecosystem services such as nutrient cycling (Serrano et al., 2021), carbon sequestration (Krause-Jensen & Duarte, 2016), and support commercial fisheries (Unsworth et al., 2019). These grazing grounds are responsible for providing habitat, food, and shelter to diverse communities of associated herbivores including gastropods, fish, turtles, and dugongs (Hoey & Bellwood, 2008; Gutow et al., 2016; Fong et al., 2018).

While phytoplankton have been shown to adhere to the surfaces of plastics, experimental and environmental studies have shown that microplastics can adhere to the surfaces of macrophytes (Gutow et al., 2016; Sundbæk et al., 2018; Sfriso et al., 2021). Recently, the occurrence of microplastics have been reported on environmental samples of *Thalassia testudinum*, *Padina* sp., *Sargassum ilicifolium*, *Cymodocea rotundata*, *Caulerpa serrulate*, *Thalassia hemprichii* and *Enhalus acodoides* (Goss et al., 2018; Huang et al., 2020; Seng et al., 2020). Additionally, 94% of the macrophytes sampled in the Adriatic Sea contained 0.16 to 330 items of microplastic per gram of fresh weight; averaging 14 items of microplastics per gram of fresh weight (Sfriso et al., 2021). The samples collected in Singapore, China, Belize, and Italy (Goss et al., 2018; Huang et al., 2020; Seng et al., 2020; Sfriso et al., 2021), provide evidence that environmental microplastics are readily available for consumption by marine herbivores through predation on seagrasses.

Macrophyte exposure to plastic particles in sediment has been shown to impact sediment rooted macrophyte growth parameters, specifically *Myriophyllum spicatum* L. (1753) and *Elodea* sp. A study by van Weert et al. (2019), showed that microplastics significantly affected the shoot dry weight in *M. spicatum* L. (1753) and *Elodea* sp*.,* in most cases increasing their average weight. In *M. spicatum* as microplastic concentrations were increased there was a coinciding decrease in shoot lengths and a significant impact to the number of side shoots. Microplastics also significantly impacted the relative growth rate in *Elodea* sp. Similarly, when *M. spicatum* was exposed to nanoplastics there was a reduction in the main shoot length, but an increase in the dry root weight. In *Elodea* sp*.,* nanoplastics increased the root and shoot dry weights, the relative growth rate, and the side shoot length. The exposure to nanoplastics for both macrophyte species resulted in a decrease to their shoot to root ratio which was hypothesised to potentially hinder nutrient acclimation in these species.

Seagrass habitats have been shown to act as a catchment for plastic pollution (Huang et al., 2020), increasing the potential for plastics, specifically micro and nanoplastics, to impact the flora and fauna in macrophyte ecosystems. Due to the chemical and physical attributes of seagrasses and seagrass beds, the impact of plastics could not only affect its inhabitants through increased bioavailability, but has the potential to impact the functioning of the ecosystem. For example, macroplastics could have a shading effect for macrophyte beds, impacting photosynthesis and growth. Additionally, microplastics and nanoplastics can impact the growth and physiology of the plants, hindering nutrient acclimation. Further research is required to determine how variation in the sizes, shapes, polymers and chemical additives of plastic pollution could impact different species of macrophytes.

3.4. *Zooplankton*

Zooplankton are natural bioindicators of climatic change due to their rapid response to fluctuating environmental conditions such as changes to aquatic temporal scales, salinities, turbidity, nutrient levels and food availability (Davis & Pineda-Munoz, 2016; Hemraj et al., 2017). They represent an essential trophic link between primary producers and secondary consumers. Zooplankton play an important role in the transportation not only of energy but also potentially aquatic pollutants across the marine food web (Setalä et al., 2014; Cole et al., 2015; Chouvelon et al., 2019). They contribute to the biological pump through the production of dense faecal pellets with fast sinking velocities (Turner, 2015) providing food for sediment-dwelling biota (Small et al., 1979).

Detrimental impacts from microplastic ingestion have been reported in laboratory-based zooplankton cultures (Lee et al., 2013; Cole et al., 2015; Jeong et al., 2016). These impacts have the possibility of occurring in nature as plastic ingestion has been observed in environmental zooplankton samples (Desforges et al., 2015; Steer et al., 2017; Sun et al., 2018). In laboratory studies, *Calanus helgolandicus* ingested 20 μm polystyrene beads impacting its feeding on natural preys, leading to a 40% decrease in carbon biomass uptake and a reduction in reproductive output (Cole et al., 2015). Similarly, copepods, rotifers and Cladocera (such as *Pseudodiaptomus annandalei, Calanus finmarchicus*, *Brachionus koreanus* and *Daphnia magna*) showed a reduction in fitness, ingestion of microalgae, growth, reproductive output, lipid accumulation, survival, and premature moulting, with exposure to microplastics and their associated chemical pollutants (Jordão et al., 2015; Jeong et al., 2016; Cole et al., 2019; Cheng et al., 2020). In an experimental study when grown in a culture with plastics between 0.5 and 6 μm in size, *Tigriopus japonicus*'s fecundity was impacted and the nanoplastics fraction of these plastics were shown to decrease survival in the next generation of copepodites and nauplii (Lee et al., 2013). The effects of plastic ingestion and plastic leachates to zooplankton, surpasses just impacting the organism and their future generations. Cole et al. (2016) demonstrated that the incorporation of microplastics into faecal pellets reduced their densities, provoking a 2.25-fold reduction in sinking velocities and a higher propensity for fragmentation of the pellet. These faecal pellets serve as an indirect pathway of plastic ingestion, and influence the vertical distribution of plastics through the water column.

The ingestion of plastics could thus have severe consequences on the biological pump and on sediment-dwelling biota. Transference of plastics to benthic communities through these faecal pellets could facilitate similar biological impacts (decreased fecundity, growth, fitness, etc.) to benthic organisms. Due to their size and feeding style, grazers and filter feeders can be more susceptible to microplastic ingestion (Setälä et al., 2016) and therefore, they could be potential indicators for how organisms respond over time to increasing quantities of plastic pollution in the environment. Additionally, isynthetic fibres have been shown to block the gastrointestinal tract of these small organisms, however, natural fibres have similar characteristics and could be just as harmful in instances of false satiation. It is apparent that the sizes, shapes, and chemical additives have had negative impacts directly to zooplankton and indirectly to the next generation. Further work is required to identify if the polymer composition plays an important role on how plastic pollution impacts these species.

3.5. *Suspension and filter feeders*

Suspension and filter feeders can readily ingest plastic particles due to the size overlap between microplastic and their prey (Galloway & Lewis, 2016). The size range of the particles that can be consumed by suspension and filter feeders depends on factors such as gape size, feeding mode, and specific feeding mechanisms of the organism (Riisgård & Larsen, 2010). Suspension and filter feeding organisms are widespread throughout marine food webs, from the small planktonic invertebrates at the base of the food web, to shellfish and benthic taxa, to whales and other megafauna. These organisms feed on suspended organic material, such as phytoplankton, zooplankton, fish larvae, and detritus. Suspension and filter feeders are important both ecologically and economically (Gillies et al., 2018). Their ecological significance stems from their ability to filter water, removing organic and inorganic particles from the water column (Gillies et al., 2018). This process benefits other organisms present in the ecosystem as it improves water quality and biodiversity (Galloway & Lewis, 2016; Ward et al., 2019). Additionally, some filter feeders act as bioindicator species as they are widespread, can have long life cycles, can be easily obtained, and can accumulate contaminants such as heavy metals at high capacities (Sacchi et al., 2013).

Bivalves can close their valves after exposure to plastic particles, and chemical leachates (Tran et al., 2007; Wegner et al., 2012). One iconic organism that has been extensively studied in relation to plastic particle consumption are oysters. Oysters typically form reefs in shallow coastal waters, with individual oysters filtering approximately 150 L of water per day (Galloway & Lewis, 2016). These oyster reefs provide shelter and protection, and spawning and nesting areas for the organisms which inhabit them (Galloway & Lewis, 2016; Ward et al., 2019). Some species of oysters have been shown to have preferential selection of the particles they are consuming (Dutertre et al., 2007). The oyster particle selection mechanism is 100% efficient at selecting particles that are 5 to 6-μm in size (Ward & Shumway, 2004; Sussarellu et al., 2016). However, this can result in oysters and mussels (*Crassostrea virginica* and *Mytilus edulis*, respectively) preferentially feeding on certain microplastics as shown by Ward et al. (2019), with the number of rejected plastic spheres increasing with sphere size. The particles which were not selected, were packaged as pseudofaeces (Newell & Jordan, 1983). Oysters generally deposit these pseudofaeces to the sediment, further increasing the bioavailability of these rejected microplastics to benthic organisms and decomposers (Garrido et al., 2012).

Microplastic consumption in adult oysters can result in energetic depletion, impairing their reproductive output, reducing sperm motility, fecundity and oocyte size. Additionally, there can be significant reduction in the growth and larval yield of their offspring which had not been exposed to microplastic pollution (Sussarellu et al., 2016). Revel et al. (2020), found there was no significant effect on physiology and tissue integrity in adult Pacific oysters (*Crassostrea gigas*) from microplastics. However, in the Manila clam (*Ruditapes philippinarum*), there were histological alterations to the gills and the tissues of the digestive gland. Additionally, the filtration rate and therefore the feeding behaviour of Manila clams was reduced due to microplastic contamination (Sıkdokur et al., 2020). Similar impacts have been reported in the blue mussel (*Mytilus edulis*) (Van Cauwenberghe & Janssen, 2014; Van Cauwenberghe et al., 2015). Furthermore, on exposure to microplastic particles of polystyrene the lugworm (*Arenicola marina*) had a reduction in feeding, an increase in weight loss and in bioaccumulation of polychlorinated biphenyls (Besseling et al., 2013).

Nanoplastics, however, are more likely to be taken up by juvenile filter feeding organisms, wfacilitating the uptake of nanoplastics across cell membranes and the gut barrier (Galloway & Lewis, 2016). In the Mediterranean mussels (*Mytilus galloprovincialis*), there was a slight increase in cellular toxicity under short-term exposure to nanoplastics (Pittura et al., 2018). Manila clams (*Ruditapes philippinarum*) suffered oxidative stress, impacts to their immune system, and translocation of nanoplastics across the gill, the digestive glands, and the mantle, which were all of the studied tissues (Parolini et al., 2020; Sıkdokur et al., 2020). Conversely, the exposure of *C. gigas* to micro and nanoplastics had no significant effect on the feeding capacity of larvae, when exposed for eight days to plastic concentrations exceeding those detected in the marine environment (Cole & Galloway, 2015).

These results suggest that the omnipresence of plastics and plastic particles, where there should otherwise be food, can be associated with adverse biological impacts to both suspension and filter feeders. The daily clearance rates of suspension and filter feeding organisms can vary from microlitres (for unicellular organisms) to hundreds of litres or more (for large marine mammals). This feeding mechanism readily subjects these organisms to plastic consumption. The uptake of plastics by these suspension and filter feeders can lead to trophic transfers of the plastics themselves as well as the chemicals that the plastics may already contain or have absorbed from the seawater. It is clear that the sizes and shapes of plastic pollution are important factors when considering the impacts of plastic pollution to suspension and filter feeding organisms. The size of plastic pollution also plays a role in the transportation of these organisms in the ocean, as it provides a substrate for them to raft to. Further work is required to determine how chemical additives and polymer types impact these organisms, and what concentrations trigger the response to close their valves.

3.6. Predators

The first environmental observation of a marine organism having consumed plastic was in 1966 (Kenyon & Kridler, 1969). The carcasses of 100 layson albatrosses (*Phoebastria immutabilis*) were collected from the Hawaiian Islands National Wildlife Refuge, of these 100, 90 of them had consumed some form of plastic (Kenyon & Kridler, 1969). The first reports of plastic ingestion by fish (grubby, *Myoxocephalus aenus*; winter flounder, *Pseudopleuronectes americanus*; white perch, *Roccus americanus*; and silversides, *Menidia menidia*) followed shortly with a study published in 1972 (Carpenter et al., 1972). These samples were collected in Niantic Bay where polystyrene spherules were reportedly widespread (Carpenter et al., 1972). The phenomenon of plastic ingestion by marine predators became more researched from the 1970's onwards (Furness, 1983; Ryan, 1987; Pribanic et al., 1999).

In a study of 1337 marine fish 771 specimens (58%) contained microplastics in their stomaches and/or intestines (Güven et al., 2017). Fish, such as the marine medaka (*Oryzias melastigma*) showed the impacts of microplastics to decrease fecundity in female fish, delay the maturation of gonads, decrease both body length and hatching rate of the offspring and decrease heart rate (Wang et al., 2019). Additionally, the endocrine system of Japanese medaka (*Oryzias latipes*) was impaired by microplastics and the attached persistent organic pollutants resulting in abnormal reproductive cell proliferation (Rochman et al., 2014). These trends continue in other studied organisms with varying adverse effects. For example, the yellow seahorse (*Hippocampus kuda*), when exposed to microplastic contaminants, showed a reduction in both body weight and length, growth rates and survival rates (Jinhui et al., 2019). Zebrafish (*Danio rerio*), discus fish (*Symphysodon aequifasciatus*), Chinese mitten crab (*Eriocheir sinensis*) and goldfish (*Carassius auratus*) have all shown impairments which ranged from oxidative stress, decreased growth rates, liver and organ homeostasis, alterations to the intestine and circulatory system, and physical damages to the jaw through the act of chewing plastics (Jabeen et al., 2018; Rainieri et al., 2018; Wen et al., 2018; Yu et al., 2018). The impacts of microplastic ingestion on these secondary consumers are not specifically due to the plastics themselves. The associated exposure to heavy metals sorbed to microplastics showed a worse negative impact than microplastics alone in the yellow seahorse (Jinhui et al., 2019). The results suggest that the effect of microplastics on seahorse growth is caused by the accumulation of heavy metals, rather than by the microplastics alone. However, Rainieri et al., 2018 found that microplastics and sorbed chemicals had a greater effect on zebrafish than chemicals alone in feed treatments, highlighting the complexity of plastic pollution and their associated chemical additives in marine food webs.

Similarly in tertiary consumers, laboratory studies have considered altered behaviour, decreased swimming speed, altered ranges of movement and motility, changes in hiding responses, and predator–prey interactions such as hunting behaviour, with lower perception for food added in tanks paired with increased foraging activity as a result of exposure to microplastics (Guven et al., 2018; Yin et al., 2018; Barboza et al., 2020). In juvenile gobies (*Pomatoschistus microps*) predatory performance decreased by 65% paired with a reduction in feeding efficiency of 50% when organisms were concurrently exposed to microplastics (comparable in size and abundance to their prey) and *Artemia* spp. (de Sá et al., 2015). The food quality and quantity of marine species decreases as the nutritional quality of the organisms are influenced by plastic particles and their associated chemicals, resulting in lower growth, a decrease in protein and lipid contents, and histopathological changes in the gallbladder and liver (Espinosa et al., 2018; Yin et al., 2018; Mancia et al., 2020). These results were found in several different laboratory studied organisms such as jacopever (*Sebastes schlegelii*), catsharks (*Scyliorhinus canicular*), gilthead seabream (*Sparus aurata*), European sea bass (*Dicentrarchus labrax*), barramundi (*Lates calcarifer*) and Atlantic mackerel (*Scomber scombus*) (Espinosa et al., 2018; Yin et al., 2018; Mancia et al., 2020). Records of microplastic ingestion have been shown in environmental samples of European seabass (*Dicentrachus labrax*), Atlantic horse mackerel (*Trachurus trachurus*) (Rummel et al., 2016) and Atlantic chub mackerel (*Scomber colias*) (Barboza et al., 2020). However, there is limited knowledge on how microplastics impact wild fish stocks. Research by Barboza et al. (2020) has recently shown wild fish with microplastics present in their gastrointestinal tract, dorsal muscle, and gills, had significantly higher levels of lipid peroxidation in the dorsal muscle, gills, and the brain which showed increased acetylcholinesterase activity. This is linked with several brain disorders (Chen et al., 2018; Barboza et al., 2020). There is the potential for these negative impacts from microplastic and chemical contamination to effect ecological functioning, fisheries and food safety in the marine environment.

In quaternary consumers, the impact of plastic pollution is not well understood. As early as 1989, plastics made up to 39.1% of ingested foreign material found in the stomachs of whales (Walker & Coe, 1989). Although the first record of ingested plastic in sperm whales (*Physeter macrocephalus*) dates back to 1979 with the discovery of trawl nets and nylon rope (Walker & Coe, 1989; de Stephanis et al., 2013). Due to the difficult nature and ethical requirements to research these organisms studies were conducted opportunistically. An experimental study conducted on grey seals (*Halichoerus grypus*) examined the passage time of microplastics through the digestive system and found the average clearance rate to be six days, which was longer than that of the passage time of hard structures from natural prey (otoliths and cephalopod beaks) (Grellier & Hammond, 2006). However, the microplastics were recovered, suggesting that some microplastics can be easily egested in faeces. This study utilised uniform polystyrene balls with a 3-mm diameter, which is not representative of the diversity of environmental microplastics.

The presence of microplastics in wild marine predators were most commonly fibres, as was found in the bottlenose dolphin (*Tursiops truncatus*), small-spotted catshark (*Scyliorhinus canicula*), spiny dogfish (*Squalus acanthias*), starry smooth-hound (*Mustelus asterias*) and bull huss (*Scyliorhinus stellaris*) (Battaglia et al., 2020; Parton et al., 2020). In a study of 50 marine mammals, microplastics were found in ten of the 26 studied raptorial feeding species of cetaceans and pinnipeds around the coast of Britain (Nelms et al., 2019). Plastic consumption by wild caught catsharks (*Scyliorhinus canicula*) resulted in the expression of immune related genes (Mancia et al., 2020), suggesting a relationship with plastic consumption and adverse biological impacts. The potential for harmful impacts from plastic consumption remains unknown for apex predators; however, they are susceptible to biomagnification and bioaccumulation of persistent organic pollutants from plastics such as polychlorinated biphenyls which have been shown to adsorb onto plastics (Carpenter et al., 1972; Nelms et al., 2019). Due to the diversity of marine predators and their feeding mechanisms, the sizes, shapes, and chemical additives of plastic pollution could all contribute to the different ways they impact these organisms.

4. Trophic transfers

When plastic particles are retained in organisms through methods of direct consumption, or due to the adherence and/or entanglement to an organism, pathways arise for indirect consumption in organisms of higher trophic levels. These intake pathways can occur both selectively and accidently when a predator consumes an organism; these predators are also at risk of direct consumption of plastics. Laboratory based projects have facilitated and shown that trophic transfers across trophic levels are possible. Studies have shown that the grazing of herbivorous organisms, namely the common periwinkle (*Littorina littorea*) and parrotfish (Scaridae) on macrophytes can result in incidentally ingested microplastics (Gutow et al., 2016; Goss et al., 2018). This indicates that grazing on macrophytes by inhabitants is a viable pathway for microplastic intrusion into the food web at a basal level. It is possible that the presence of plastics in taxa which feed on macrophytes could have repercussions to organisms of higher trophic levels.

Studies have also shown the exchange of microplastic contamination passing from filter feeders to higher trophic levels (Farrell & Nelson, 2013; Watts et al., 2014; Santana et al., 2017). Microplastics were recorded in the hemolymph of mussels (*Perna perna*) and found to transfer across to their predators, crabs (*Callinectes ornatus*) and puffer fish (*Spheoeroides Greeley*) (Santana et al., 2017). Similar studies have found the indirect transfer of polystyrene microspheres from common mussels (*Mytilus edulis*) to shore crabs (*Callinectes maenas*) (Farrell & Nelson, 2013; Watts et al., 2014). These results continue with the progression of the food web as the predators, mysid shrimps (*Neomysis integer*), zebra fish (*D. rerio*) and three-spined stickleback (*Gasterosteus aculeatus*) consumed zooplankton (*Eurytemora affinis, Artemia* sp. and *Praunus* sp.) containing microplastics and their associated persistent organic pollutants (Setälä et al., 2014; Batel et al., 2016; Santana et al., 2017; Lehtiniemi et al., 2018). These microplastics were then transferred to the predators (Setälä et al., 2014; Batel et al., 2016; Santana et al., 2017). Predatory animals such as the Norway lobster (*Nephrops norvegicus*) retained plastics from a diet of whiting (*Merlangius merlangus*) and blue whiting (*Micromesistius poutassou*) embedded with strands of polypropylene, mimicking frayed fishing rope (Murray & Cowie, 2011).

The egestion of plastics from different species occurs at different rates, with some species not excreting plastics at all, making plastics accessible to predators when it is retained in prey (Murray & Cowie, 2011; Santana et al., 2017). Plastic consumption in humans can also be facilitated by trophic transfers. A study of canned tuna (*Thunnus tonggol* and *Thunnus albacare*) and mackerel (*Scombermorus commerson*) found 128 microplastics across 50 cans of fish, with approximately 80% of the cans containing microplastic contaminants (Akhbarizadeh et al., 2020).

Within food webs there are energy transfer efficiency limits. Energy transfer between trophic levels is inefficient, with around 10% transferred to the next trophic level. We do not understand what role plastic and the associated chemical contamination influences the success of these transfer limits. However, microplastic contamination is prevalent as 83% of the Norway lobsters (*N. norvegicus*) collected in the Clyde Sea had ingested plastics (Murray & Cowie, 2011), and 19.8% of 263 commercial fish from a sample of 26 different species contained one or more microplastic (Neves et al., 2015). The impacts of plastic contamination can transcend across trophic levels, to benthic communities and decomposers. All species at all levels within the marine food web, could be vulnerable to the impacts of plastic contamination. Trophic transfers of plastic pollution across or between species and trophic levels, can be predicted to increase with increasing pollution levels.

5. Conclusion & future research

The objectives of this review were to examine the complexity of impacts to marine organisms from the contamination of i) plastic pollution and ii) its associated chemicals. The published findings showed that facets of entire ecosystems can be affected by plastic intrusion, impacting how these systems support our economy. Plastics remain in the ecosystem for years as they only break-up and not down, therefore potentially harming thousands of sea creatures daily. Plastics of all shapes and sizes are impacting aquatic species (Fig. 2), and a sole piece of plastic can be responsible for reoccurring repercussions. Microplastics and nanoplastics in particular pose a risk to organisms across all stages of biological organisation, from sub-cellular to population level effects. This threat transcends individual organisms, as the impacts can be transferred within individuals to their offspring and across trophic levels both vertically and horizontally through predator-prey interactions. Marine organisms ingest these particles by various pathways such as filtration, confusion with prey and trophic transfers due to ingestion, entanglement, or surface adherence of plastics to prey. The consumptionof plastics has been shown to have negative effects on marine organisms through a reduction in fecundity, hindered motility, decreased feeding rates, decreased growth and survival, clogging of both digestive and gastrointestinal tracts; leading to internal perforations, and in some instances – death. These impacts also contribute to a reduction in future prey stock while decreasing food quality, with the implications to energy reserves still unknown.

We have limited knowledge on the implications of plastic litter on marine organisms, especially understanding the true extent of possible environmental impacts. The less alluring and small invertebrate species are even less understood as they evade attention but play vital roles in marine ecosystems. Certainly, negative consequences of plastic litter have been reported in laboratory-based settings, however, in contrast, the impact of plastics on environmental communities is rather less well researched. These laboratory-based studies provide valuable insights into the potential pathways and effects of plastic pollution. However, the concentrations used are not always reflective of what is present in the marine environment. Gaining accurate representation of trophic transfers of plastic particles is unachievable when the quantity of environmental plastics entering the food web and the chemical concentrations associated and leaching from them, are unknown. This is important as larval fish that feed on plankton are significantly more likely to ingest microplastic contaminated prey than they are to ingest uncontaminated prey. Research has focused on understanding plastic impacts to commercially profitable species however, we are lacking knowledge on the impacts of plastic pollution at the base of the food web. In order to develop effective environmental management, an appropriate understanding of ecological implications of plastic pollution at lower trophic levels, zooplankton in particular, are needed. For this to be enabled, consistent methodology across plastic research fields are required.

From this review it is apparent that the plastic size, polymer type, shape, and chemical composition all play important roles in their impact to organisms, When comparing sizes, shapes, longevity, density, origin, polymer composition, chemical leaching, and sorption potentials of microplastics it was found that the size of the polymer is one of the most important factors in determining the toxicity of plastics. However, in this review it was clear that the impacts to organisms were different based on the species, the plastic types, the plastic sizes and exposure to chemical additives. This is as plastics are a complex pollutant. To determine the risks and impacts plastics have to the marine environment we need to understand how the different shapes, sizes and associated chemicals effect marine organisms and ecosystems. Determining the impact of environmentally relevant sizes and abundances of plastics to organisms could potentially be an appropriate starting point. In most of the scenarios reported in this review the concentrations of plastics and associated chemicals were not environmentally relevant. However, the impacts still occurred to the organisms. This could be indicative that there may not be severe consequences in the ecosystem currently, but with the predicted increase in plastic pollutants in the ocean, these impacts could become the reality of the future.

Future research should utilise environmentally comparable plastics in size, shape, polymer composition and concentrations (of chemicals and abundances in mass and count). This will aid in understanding what and how each of these four factors impact marine organisms, ecosystems and the services it provides. Additionally, methods are often insufficiently described resulting in studies which are not comparable, reproductible, or transparent. Reproductible and comparable methods should be accompanied by multidisciplinary research, appropriate scientific advice, community and school education, and public outreach to curb the environmental issues imposed by marine plastic pollution.

Author statement

Elise M. Tuuri: Conceptualization; Investigation; Project administration; Visualization; Roles/Writing - original draft; Writing - review & editing. **Sophie C. Leterme:** Supervision; Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial

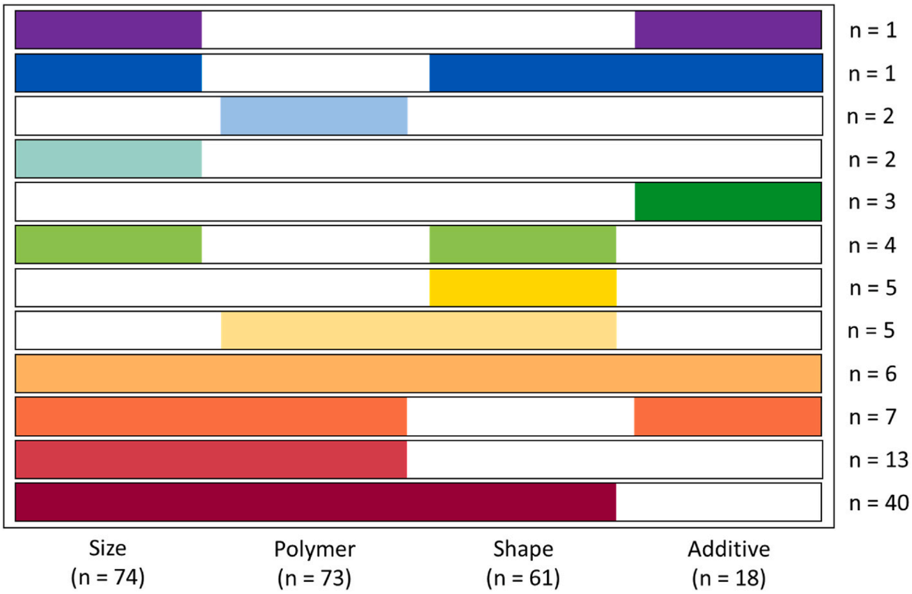

Fig. 2. Schematic diagram of the number of publications (n) which included a description of the plastic size, shape, polymer and/or additive, either observed to have impacted marine organisms environmentally or in a laboratory setting.

interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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