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A Risk Analysis of Microplastic Consumption in Filter Feeders

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By

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Abstract

Microplastics (plastic particles < 5 mm) pose a serious threat to marine organisms, as researchers have documented such particles in the gut contents of numerous species. In particular, filter feeders are at risk of consuming microplastics because they may accidentally consume the particulates when feeding or they may prey on species that have already consumed them. The goals of this research were to evaluate the risks that different filter feeders face in regards to microplastic consumption through the analysis of the calculated Microplastic Consumption Rates for numerous species of filter feeders. Factors that could potentially affect this risk were also considered, including ocean basin, environment type, salinity, life stage, IUCN status, and filtration technique. Initial analysis showed that body size greatly impacted a species' risk of microplastic consumption and further tests were completed to evaluate overall microplastic contamination for each species. Microplastic consumption and microplastic contamination values were evaluated and analyzed to determine which filter feeding species were most at risk of experiencing ecological effects from microplastic pollution. From a resource management perspective, this research highlights the filter feeding species most at risk, contributing to the development of more effective plastic waste management policies.

Keywords: microplastics, plastics, filtration, microplastic consumption, microplastic contamination, filter feeding species

I. Introduction

More than nine million tons of plastic fibers are produced every year, and microplastics (plastics < 5 mm) are now found in aquatic environments around the globe (Barrows et al. 2018). Plastics were first produced in the 1950s and became popular very quickly due to their durability and low production costs (Lusher et al. 2017). Although they offer many benefits to the average consumer, including lower prices and convenience, plastic materials have become a danger to the environment. When improperly managed, plastic waste is often allowed to reach freshwater and marine environments. There, the material is exposed to the sun's ultraviolet rays, causing it to degrade slowly (Lusher et al. 2017). This leads to the breakdown of the material and formation of small, microplastic particles, which have become such a prevalent problem today that they are now considered one of the greatest threats to the health of ecosystems and biodiversity on land and in marine and freshwater regions (Barrows et al. 2018, Lusher et al. 2017).

Microplastics can generally be categorized as either primary or secondary. Primary microplastics are fibers and beads manufactured to a small size, which are often used in the cosmetic industry. These particles might be used in soaps, shampoos, toothpastes, shaving cream, makeup, bubble bath, and other cosmetic products around the world (Leslie 2014). When consumers rinse off the product and wash it down the drain, these plastics find their way into wastewater. And while effective management facilities will retain a small portion of these microplastics, the rest flow into freshwater or marine environments (Leslie 2014). Secondary microplastics, on the other hand, are produced from the degradation of larger items (Lusher et al. 2017), such as plastic bottles, bags, and other forms of waste. This degradation occurs as a result of exposure to saltwater and ultraviolet sunlight (Lusher et al. 2017).

Plastics are known to include a variety of toxins, as they are often comprised of toxic chemicals and various additives that can have adverse effects on the health of marine organisms (Gallo et al. 2018). A variety of chemicals, such as monomers, plasticizers, and flame-retardants, are added to plastics during production (Lusher et al. 2017). The material can also adsorb contaminants like polychlorinated biphenyls (PCBS), polycyclic aromatic hydrocarbons (PAH), and persistent bioaccumulative toxic substances (PBTs) from the surrounding environment. Contaminants accumulate through predator-prey relationships and trophic transfers, potentially leading to adverse health effects, such as increased immune responses, decreased growth, and decreased fecundity (Gallo et al. 2018, Lusher et al. 2017).

Due to their popularity, long lifespan, process of degradation, and potential for toxicity, microplastics have become ubiquitous and a persistent pollutant. As such, it is increasingly important to understand their distribution and concentration around the globe (Barrows et al. 2018). In recent years, new research has expanded knowledge in this area, with much of the work being completed by citizen science initiatives (Barrows et al. 2018). A great example is the Global and Gallatin Microplastics Initiative, which launched a massive project that called for environmentally minded citizens who spend time on the water to take water samples and send it to their facilities for processing. The response was enormous, with samples collected from around the globe, encompassing marine and freshwater environments; this initiative has produced a large microplastic concentration dataset that can be used to bridge knowledge gaps (Global & Gallatin Microplastic Initiatives 2018).

It is widely known that many species, including filter feeders, consume microplastics as previous studies have found such particles in the stomachs and guts of various organisms (Cole et al. 2013, Taylor et al. 2016, Wieczorek et al. 2018). Even some of the smallest species, like copepods, bivalve larvae, and decapod larvae, ingest microplastics although the ability to uptake these particles may depend on size (Cole et al. 2013). Species that are larger in size or at higher trophic levels have also been documented interacting with microplastic pollution, whether directly or indirectly (Lusher et al. 2017). Although the direct ingestion of plastic particulates is more commonly studied, trophic transfer might also occur when an organism ingests a prey species that has already consumed the microplastics (Cole et al. 2013, Moore et al. 2001). Evidence even suggests that organisms in the deep sea have been exposed, as they frequently ingest microplastic fibers (Taylor et al. 2016)

Like most other marine species, filter feeding organisms ranging in size and complexity from sponges and jellyfish to whale sharks are also known to consume microplastics either directly if mistaken for food or indirectly as a result of prey consumption of plastic particles or fibers (Cole et al. 2013, Moore et al. 2001). Because filter feeders must filter small food items from the water, such as zooplankton and phytoplankton, they cannot always be selective and avoid the consumption of other particulates that may also be present (Cole et al. 2013). Some organisms have developed adaptations prevent the consumption of unwanted materials, such as the mesh size of gill rakers and other anatomical components that can prevent consumption of items larger than a specific size (Roesch et al. 2013). Microplastics can still easily be consumed, however, even if the filter feeder has such adaptations to prevent it. After all, these adaptations were developed over thousands of generations, but microplastics have only been an issue within our oceans for less than a century (Roesch et al. 2013, Lusher et al. 2017). In order to assess the risks that microplastics may pose to filter feeding organisms, it is thus necessary to determine how likely it is that a filter feeder might consume microplastics by considering their filtration rate and the concentration of microplastics in the water.

Most recent studies involving the interactions between living organisms and microplastics rely on the use of molluscs or crustaceans, though some may also focus on various fish species, both in the laboratory and in field observations (Lusher et al. 2017). In almost every niche environment, whether at the sea surface, on beaches, within the water column, or in the deep sea, microplastic uptake occurs among the organisms living there. Seabirds and marine mammals ingest microplastics regularly – an occurrence that can have significant consequences for both the organism and human health (Lusher et al. 2017, Taylor et al. 2016). However, little research has been done to better understand the ecological consequences of this phenomenon, particularly among filter feeders. Though some researchers believe the effects of microplastic consumption would not extend beyond the level of the individual, others have demonstrated that the trend might reduce primary productivity, either directly or indirectly (Lusher et al. 2017). In this study, the risk of microplastic consumption among filter feeders was assessed to bridge such knowledge gaps.

II. Statement of Purpose and Objectives

The goal of this research was to quantitatively assess the risks faced by different filter feeding organisms with regards to the consumption of microplastics based on three primary factors: the abundance of marine plastic debris across geographic locations, as demonstrated by recent studies (Global & Gallatin Microplastic Initiatives 2018, Barrows et al. 2018, Woodall et al. 2014); the location that filter feeding species primarily live and feed; and the different filtration rates utilized by filter feeders. Such information can be used to determine the likelihood filter feeders might consume microplastic particles.

In addition to the quantification of the microplastics consumed by these species while feeding, the study also determined if various factors had a significant impact on the estimated consumption of such particles. Perhaps most importantly, the study considered the impact of feeding location on these risks, potentially allowing conservation and waste managers in different areas to fully understand the risks filter feeding species face in their region. Feeding locations – including specific ocean basins, regions, types of environments, and whether the species feeds in marine or freshwater – provided insight into whether the specific variables could potentially impact a species' risk of microplastic consumption. Some species – such as basking sharks, jellyfish, and others – are globally distributed (Priede et al. 2008, Sims et al. 2003), leading to the expectation that they might be more likely to consume microplastics in areas with greater abundance of these particles than in those with less abundance. Other species are specific to smaller regions. The blue mussel, for instance, is generally found in the North Atlantic, in both the east and west regions of the basin (Boström & Bonsdorff 1997, Wildish & Miyares 1990).

The study also considered the vulnerability of each species by considering IUCN Red List status labels (IUCN 2019), as well as the effect of organism age. The filtration technique used by these species was also considered, as distinctive strategies result in differing filtration rates that affect the quantity of microplastics potentially consumed. Filtration technique was expected to have an effect on the quantity of microplastics potentially consumed by filter feeders. Most filter feeders rely on at least one of four primary techniques: ram filtration, suspension feeding, water pumping, and lunge feeding. Ram filtration occurs when a species, such as the whale shark *Rhincodon typus)*, swims forward slowly with an open mouth to capture food-laden water (Motta et al. 2010). Suspension feeding, however, occurs when an organism like the Pacific oyster *(Crassostrea gigas)* can capture and extract food items out of the surrounding water as it flows over the animal (Harris 2008). Water pumping occurs when an organism actively pumps water through the mouth to capture food (Wildish & Miyares 1990), while lunge feeding is frequently seen in large species, such as whales, to capture large quantities of food in one mouthful (Simon et al. 2012).

Involving a comparison of multiple representative filter feeders, this study hypothesized that: 1) filter feeders searching for food and feeding in geographic locations with higher microplastic abundance would be more likely to consume plastic; and 2) specific factors, such as filtration technique, could have a significant effect on the risk of microplastic consumption.

This study aimed to fill knowledge gaps by analyzing relevant datasets, including filtration rates and microplastic abundance worldwide. Altogether, this valuable information will enable managers to make informed environmental decisions and may aid in the development of more effective resource and waste management policies. Until now, little research has been done to attempt to quantify to what extent different species might consume such particles. After an extensive literature review was performed, a new database of 50 different species of filter feeding organisms was created to facilitate the evaluation of a wide range of filter feeders, from sea worms and bryozoans to whale sharks and fin whales.

II. Materials & Methods

Data Acquisition

This research study required a metadata analysis approach and a risk analysis framework, necessitating the use of various datasets to effectively characterize the risks associated with microplastics (Lusher et al. 2017). To accurately assess these risks, data was collated from a variety of sources, spanning decades of research.

a. Microplastic Abundance Data

The Global & Gallatin Microplastics Initiatives of Adventure Scientists conducted microplastic pollution surveys in aquatic environments around the globe from 2013 to 2017 (2018). This made it possible to assess and analyze where microplastics typically accumulate geographically. After the collection of 2,677 surface water samples in four years, this dataset demonstrates the ubiquity of microplastics in marine and freshwater environments worldwide (Global & Gallatin Microplastics Initiative, 2018).

The datasets provided from this research project included 1,394 samples of marine water and 1,009 samples of freshwater (Global & Gallatin Microplastics Initiative, 2018). Samples were taken from a broad range of water sources including coastal regions and open ocean areas of all ocean basins within the marine water dataset. In general, these data points only include surface water because all samples were obtained within the first 50 meters (Global & Gallatin Microplastics Initiative, 2018).

Microplastic abundance data was also confirmed with a study conducted by Kanhai et al. (2017). The researchers collated data from previously conducted studies to review microplastic abundance in various locations. They included data for each of the ocean basins, including the region from which samples were taken and the method used to collect water samples (Kanhai et al. 2017). Although this dataset was not directly used in the statistical analysis and calculations within this paper, it was useful in confirming the validity of the mean microplastic abundances determined in the Global & Gallatin Microplastics Initiative project.

b. Filter Feeder Species Selection

Next, datasets illustrating filtration rates for specific representative species was acquired. Because these studies typically focus on one species at a time, data points were gathered individually and collated for further analysis. It was necessary to acquire data for a large variety of filter feeding species, including cnidarians, sponges, bivalves, baleen whales, and fish, to accurately represent the diversity of such organisms. Because no filter feeder database currently exists in an easily accessible manner, one had to be created. Filtration rates for 50 species were collected from 44 published research papers (Table 1).

c. Species Characteristics

Other types of characteristic data were also collected for each filter feeding species because this information was necessary to determine which factors have a potentially significant effect on microplastic consumption in different species. This required a more in-depth review of literature for each of the 50 species. The information was included in the filter feeder database to allow for the tracking and analysis of each characteristic. These traits were: feeding locations and distribution, IUCN Red List Status, filtration techniques, whether the species lives in marine or freshwater areas, and whether the species tends to feed in coastal or open ocean areas. To obtain data for all these characteristics, the process entailed a review of an additional 190 papers (Table 1).

Table 1. *The different species reviewed in this paper, as well as all the sources from which filtration data and other characteristics were drawn.*

Species	**Sources of Data**
Whale Shark *(Rhincondon typus)*	Motta et al. (2010); Duffy (2002); Heyman et al. (2001); de la Parra Venegas et al. (2011); Taylor (2006); Graham et al. (2005)
Basking Shark *(Cetorhinus maximus)*	Sims (1999); Skomal et al. (2004); Sims et al. (2003); Priede & Miller (2008)
Blue mussels *(Mytilus edulis)*	Wildish et al. (1990); Bostrom & Bonsdorf (1996); Kotta & Orav (2001); Riisgard (1991)
Jellyfish *(Aurelia aurita)*	Linnaeus (1758); Segura-Puertas et al. (2009); Oleson (1995)
Bowhead whales *(Balaena mysticetus)*	Simon et al. (2009); Goldbogen et al. (2017); Laidre et al. (2007); Wursig et al. (1989); Moore et al. (2010); Ashjian et al. (2010); Schick & Urban (2000)
Humpback whale *(Megaptera novaeangliae)*	Simon et al. (2012); Clapham (2018); D'vincent (1985); Goldbogen et al. (2008); Hain et al (1982)
Blue whales *(Balaenoptera musculus)*	Doniol-Valcroze et al. (2011); Goldbogen et al. (2011); Acevedo-Gutierrez (2002); Watkins & Schevill (1979); Fiedler et al. (1998); Gill et al. (2011); Gill (2002);
Copepod *(Calanus finmarchicus)*	Fuller & Clark (1936); Prokopchuk & Sentyabox (2006); Speirs et al. (2006); Aksnes & Magnusen (1979); Marshall & Nicholls (1934)
Atlantic mackerel *(Scomber scombrus)*	Sutherland et al. (1995) Langoy et al. (2012); Overholtz & Keith (2011)
Antarctic minke whale *(Balaenoptera bonaerensis)*	Friedlaender et al. (2014); Thiele et al. (2004); Ohsumi et al. (1970); Goldbogen et al. (2017); Tamura & Konishi (2009);
Pacific Oyster *(Crassostrea gigas)*	Qiu et al. (2015); Gerdes (1982); Harris (2008); Fey et al. (2010); Cognie et al. (2006)
Tunicate *(Oikopleura dioica)*	Bochdansky & Deibel (1998); Gorsky et al. (1982); Tomita et al. (2019); Sato et al. (2001); Shelbourne (1953); Hopcroft & Roff (1995)
Silver Carp *(Hypophthalmichthys molitrix)*	Zhao et al. (2011); Lazarro (1987)
Manta Ray *(Manta birostis)*	Divi et al. (2018); Paig-Tran et al. (2013); Paig-Tran et al. (2011); Dewar et al. (2008); Braun et al. (2014); Stewart et al. (2016)
Pelagic Tunicate *(Pegea confederata)*	Harbison & Gilmer (1976); Harbison & Campenot (1979); Sutherland et al. (2010)
Fin whales *(Balaenoptera physalus)*	Goldbogen et al. (2010); Vikingsson et al. (2009); Mizroch et al. (1984); Monestiez et al. (2004); Panigada et al. (1999)

Glass sponge *(Aphrocallistes vastus)*	Leys et al. (2011); Kahn et al. (2015); Yahel et al. (2007); Austin et al. (2007); Buhl-Mortensen (2009)
Cockle *(Cardium edule)*	Riisgard et al. (2002); Richardson et al. (1993); Kater et al. (2006)
Soft-shell clam *(Mya arenia)*	Riisgard et al. (2002); Strasser (1999); Snelgrove et al. (1999); Seitz et al. (2001); Armonies & Reise (2003)
Atlantic menhaden *(Brevoortis tyrannus)*	Durbin & Durbin (1975); Love et al. (2006); Buchheister et al. (2016)
Mysid shrimp *(Rhopalophthalmus terranatalis)*	Jerling & Wooldridge (1994); Webb et al. (1997); Wooldridge (1986); Shlachler & Wooldridge (1995)
Mysid shrimp (*Mesopodopsis wooldridgei)*	Jerling & Wooldridge (1994); Webb et al. (1997); Paul & Calliari (2017); Froneman (2001)
Burrowing shrimp *(Upogebia deltaura)*	Lindahl & Baden (1997); Christiansen (2000); Tunberg (1985); Howe et al. (2004)
Antarctic Krill *(Euphausia superba)*	Boyd et al. (1984); Atkinson et al. (2008); Hill et al. (2013); Clarke & Tyler (2008); Schmidt et al. (2014)
Porcelain Crab *(Porcellana longicornis)*	Achituv & Pedrotti (1999); Lance (1964); Werding et al. (2003)
Ocean Quahog *(Arctica islandica)*	Winter (1969); Cargnelli et al. (1999); Witbaard & Bergman (2003)
Wrinkled Rockborer *(Hiatella arctica)*	Ali (1970); Gordillo (2001); Sejr et al. (2002); Wlodarska-Kowalczuk (2007)
Bay Scallop *(Pecten irradians)*	Chipman & Hawkins (1954); MacKenzie (2008); Smith et al. (1988)
Orange Sea Pen *(Ptilosarcus gurneyi)*	Best (1988); Stone (2006)
Feather star *(Oligometra serripinna)*	Leonard et al. (1988)); Holland et al. (1991); Tay et al. (2016); Hellal (2012)
Manila Clam *(Ruditapes philippinarum)*	Nakamura (2001); Velez et al. (2015); Dang et al. (2010); Lewis et al. (2007)
Yesso scallop (*Patinopecten yessoensis)*	Yamamoto (1968); Sato et al. (2004); Silina (1996)
Spaghetti Bryozoan *(Zoobotryon verticillatum)*	Bullivant (1967); Minchin (2012); Amat & Tempera (2009); McCann et al. (2015); Jebakumar et al. (2017)
Bryozoan *(Electra pylosa)*	Riisgard & Manriquez (1997); Nikulina et al. (2007); Hermansen et al. (2007)
Bryozoan *(Conopeum reticulum)*	Riisgard & Manriquez (1997)
Bryozoan *(Celleporella hyalina)*	Riisgard & Manriquez (1997); Hermansen et al. (2007)
Sea vase *(Ciona intestinalis)*	Randlov & Riisgard (1979); Runnstrom (1936); Havenhand (1991); Therriault & Herborg (2008)
Sea squirt *(Ascidella aspersa)*	Randlov & Riisgard (1979); Schmidt (1983); Chebbi et al. (2010); Mastrotaro (2008)
Polychaete worm *(Myxicola infundibulum)*	Dales (1957); Gotshall (2005); Greathead et al. (2011)
Peacock worm *(Sabella pavonina)*	Dales (1957); Greathead et al. (2011); Murray et al. (2011)
Keel worm *(Pomatoceros triqueter)*	Dales (1957); Kupriyanova & Badyaev (1998); Ponti et al. (2002); Southward (1957); Ekaratne et al. (1982)
Polychaete worm *(Hydroides norvegica)*	Dales (1957); Moen (2006); Southward (1957)
Sinistral spiral tubeworm *(Spirorbis borealis)*	Dales (1957); O'Connor & Lamont (1978)
Polychaete worm *(Salmacina dysteri)*	Dales (1957); Isaac (1974); Eldredge & Smith (2001); Nishi (1992); Parnell (2001)
Breadcrumb sponge *(Halichondria panicea)*	Riisgard et al. (1993); Hansen et al. (1995); Vethaak et al. (1982); Forester (1979); Peattie & Hoare (1981)
Common Bream *(Abramis brama)*	van den Berg (1993); Lammens (1986); Kuparinen et al. (2014); Lyons & Lucas (2002)

White Bream *(Blicca bjoerkna)*	van den Berg (1993); Lammens (1986)
Roach *(Rutilus rutilus)*	van den Berg (1993)
Gizzard shad *(Dorosoma cepedianum)*	van den Berg (1993); Drenner et al. (1984); Wuellner et al. (2008)
North Atlantic Right Whale *(Eubalaena glacialis)*	van der Hoop et al. (2019); Baumgartner & Mate (2005); Baumgartner et al. (2003); Baumgartner & Mate (2003)

Data Analysis

The sources reviewed to obtain these data points provided a more in-depth look at the risk each filter feeder faced regarding their consumption of microplastics. With the creation of the database, a risk assessment framework was used to evaluate the likelihood of adverse ecological effects as a result of filter feeder exposure to microplastics.

More than 2,000 data points illustrated global microplastic abundance. To simplify calculations, the values were categorized based on larger regions, encompassing specific locations as well as surrounding areas (Global & Gallatin Microplastics Initiative 2018). The relationship between microplastic abundance and geographic location were assessed based on two distinct factors: ocean basin and environment. The ocean basin variable had five fixed levels. Microplastic abundance in various ocean basins were not normally distributed ($p<0.05$, Shapiro-Wilkes) or homoschedastic ($p=0.01$, Bartlett's). A fixed factor One Way ANOVA of log-transformed data was thus used in the assessment. The environment variable had only two fixed levels, and the data were not normally distributed ($p<0.05$, Shapiro-Wilkes) or homoschedastic ($p=0.005$, Bartlett's). A two-tailed, two sample t-test of log-transformed data was used to assess any significant differences between microplastic abundance and environment.

Using the collated filtration rates, the Microplastic Consumption Rate (MCR) was then calculated in order to quantify how many microplastic particles are likely to be consumed by each filter feeding species. Calculation of the MCR required that filtration rates for each species be converted to mL s^{-1}. Additionally, each filter feeder needed an assigned estimated feeding location based on its known geographic distribution. Once filter feeders were assigned at least one location, the corresponding mean microplastic abundance for that region was multiplied by the species' filtration rate, as in the following equation:

Equation 1. *Determination of the Microplastic Consumption Rate*

Filtration Rate (mL/s) * Mean Microplastic Abundance (particles/mL) = Microplastic Consumption Rate (particles/s)

After calculating MCR values, the mean, median, and mode of microplastic consumption were determined. In total, 68 data points were considered for the 50 different filter feeding species, as some species were assessed at multiple feeding locations or life stages.

The significance of various factors, including salinity, IUCN status, filtration technique, life stage, ocean basin, and environment, in relation to MCR were assessed using R software. In determining the influence of salinity on MCR values, the factor was defined as a categorical variable, indicating whether each species feeds in marine or freshwater areas. Raw and transformed data were not normally distributed ($p<0.05$, Shapiro-Wilkes) or homoschedastic ($p<0.05$, Bartlett's), so the non-parametric two-tailed Mann-Whitney Wilcoxon test was used to compare MCR values between salinity levels.

Also defined as a categorical variable, the IUCN Red List Status included five levels at which the different filter feeding species were labeled: Not Evaluated, Least Concern, Near Threatened, Vulnerable, or Endangered (IUCN 2019). Raw and transformed data were not normally distributed ($p<0.05$, Shapiro-Wilkes) or homoschedastic ($p<0.05$, Bartlett's), so the non-parametric Kruskal-Wallis test was used to determine the significance of the relationship because the categorical factor had more than three levels in this assessment.

Filtration technique was defined as another categorical variable with four levels: lunging, suspension, pumping, and ram. The levels were determined through a review of literature, which indicated the typical techniques used by study species. Raw and transformed data were not normally distributed ($p<0.05$, Shapiro-Wilkes) or homoschedastic ($p<0.05$, Bartlett's), so the non-parametric Kruskal-Wallis test was used to assess the significance of filtration technique. This factor was also further reviewed to consider which species is most likely to experience higher MCR values at each of the four techniques by only analyzing each level at a time.

To determine whether filter feeders experienced significant differences in MCR as adults or juveniles, only those species that included data at different life stages were considered. In this case, life stage was defined as simply being Adult or Juvenile. Data were normally distributed ($p>0.05$, Shapiro-Wilkes) and homoschedastic ($p=0.075$, Bartlett's). Thus, a two-tailed, two sample t-test was used because this factor only had two levels.

To consider if the ocean basin influenced the MCR, the feeding locations for filter feeding species were estimated. For example, whale sharks are known to feed in coastal areas near Mexico (Motta et al. 2010, de la Parra Venegas et al. 2011). For this reason, the mean microplastic abundance value for Pacific Central America Coastal was used to calculate the whale shark's microplastic consumption rate. Like a few other species, whale sharks were assessed at multiple locations. Because they might also feed near the coast of New Zealand (Duffy 2002), they were also assessed using the mean microplastic abundance values from the Pacific West Coastal category.

Although basking sharks are known to be a global species, they are often found in waters near Scotland and thus their feeding location was estimated to be around the Atlantic East Coastal category for the purpose of this research study (Priede & Miller 2008, Sims et al. 2003, Skomal et al. 2004). Blue mussels were analyzed in both Atlantic NW Coastal and Atlantic NE Coastal regions (Bostrom & Bonsdorf 1996, Kotta & Orav 2001, Riisgard 1991, Wildish & Miyares 1990), and bowhead whales were also estimated to feed in multiple locations: Atlantic NW Coastal and Pacific SE Alaska Coastal (Ashjian et al. 2010, Goldbogen et al. 2017, Laidre et al. 2007, Moore et al. 2010, Schick & Urban 2000, Simon et al. 2009). Continuing through the database of 50 species, feeding locations for all filter feeders were estimated, and some relied on the analysis of more than one region.

Raw and transformed data for the ocean basin variable were not normally distributed ($p<0.05$, Shapiro-Wilkes) or homoschedastic ($p<0.05$, Bartlett's), so the non-parametric Kruskal-Wallis test was used to assess the significance of feeding location. Additionally, an unbalanced Two Way ANOVA was completed to analyze both filtration technique and ocean basin to determine if any significant interactions occurred between these variables. Because the same dataset was used, parametric assumptions were once again not met and a non-parametric Kruskal-Wallis test was used.

Finally, the significance of the environment in relation to MCR was assessed. Defined as another categorical variable, the environment indicated whether species fed in coastal or open ocean locations. Data were not normally distributed ($p<0.05$, Shapiro-Wilkes) or homoschedastic ($p<0.05$, Bartlett's). Thus, a two-tailed, two sample t-test of log-transformed data was used.

Analysis of the MCR values for each species indicated the possibility that organism size played a key role in a species' risk of microplastic consumption. To determine the nature of this relationship, further data regarding average bodyweight for each review species was collated. MCR values were then normalized as an MCR-to-bodyweight ratio with the values reported in units of particles/s/kg. After the data was normalized, analytical tests were run once again to determine if bodyweight affected the significant differences in MCR values for each of the six factors considered.

In the consideration of Normalized Microplastic Consumption Rates (or NMCR), data for salinity was once again not normal ($p<0.05$, Shapiro-Wilkes) or homoschedastic ($p<0.05$, Bartlett's). To analyze this factor, the non-parametric Mann-Whitney Wilcoxon test was used. Data for IUCN status was also found to be not normal ($p<0.05$, Shapiro-Wilkes) or homoschedastic ($p<0.05$, Bartlett's). The normalized data for this variable, then, required a non-parametric Kruskal-Wallis test for analysis.

Analysis of the normalized data for filtration technique indicated that data was still not normal ($p<0.05$, Shapiro-Wilkes) or homoschedastic ($p<0.05$, Bartlett's). The non-parametric Kruskal-Wallis ANOVA, thus, was used for analysis. The life stage factor once again required analysis of only data from relevant species. Normalized data were found to be normal ($p>0.05$, Shapiro-Wilkes) and homoschedastic ($p=0.614$, Barlett's), so analysis required a two-tailed two sample t-test.

After the normalized data for the ocean basin variable was transformed, however, the data was found to be normal ($p>0.05$, Shapiro-Wilkes) and homoschedastic ($p=0.08$, Bartlett's). For this variable, a One Way ANOVA could be used for the analysis. Similarly normalized data for the environment variable was found to be normal ($p>0.05$, Shapiro-Wilkes) and homoschedastic ($p=0.497$, Bartlett's) after a log transformation. Thus, analysis required the use of a two-tailed, two sample t-test.

The analysis also showed that there was a possible interaction between the two factors, filtration technique and ocean basin. To investigate further, an unbalanced two-way ANOVA was run to determine if interactions between the two factors had any significant effect on MCR. As previously noted, data was not normal or homoschedastic for either variable, so non-parametric tests were used in the analysis. Additionally, NMCR data was also considered and the test was run a second time to determine if taking body weight into consideration impacted the results.

As a final step in this project, the different filter feeding species were then divided into groups based on one factor found to be significant in the analysis: filtration technique. Once they were grouped as such, mean MCR and NMCR values were graphed to determine which species within each sub-category were most at risk of microplastic consumption or contamination. While it would be useful to determine if filtration technique had a significant impact on MCR and NMCR values for each of the subcategories, it was not possible to test with a One Way ANOVA because there were not enough data points for each species.

IV. Results and Discussion

Microplastic Abundance

Because several of the ocean basins are so large, spanning across different nations and localities, the microplastic abundance data were first categorized to make cross-referencing with filtration rates simpler. (Table 2). For example, coastal samples from the Atlantic Ocean were considered part of Caribbean, Gulf of Mexico, Mediterranean, Northwest (including North America, Bermuda, and Canada), Northeast (including United Kingdom, Europe, and Africa), and the South Atlantic regions. The Pacific coastal data points were also categorically divided into Central America, Gulf of Alaska, SE Alaska, SE Asia, West (including Australia, New Zealand, Niue, and Beveridge), and East (North and South America, Hawaii, Mexico, and Canada) regions (Figure 1). To analyze the factors affecting microplastic abundance, data was then further grouped by ocean basin.

The raw data shows that samples from the open ocean typically contain the greatest abundance of particles compared to coastal water samples (Table 2). The mean value of 54.57 ± 16.07 particles/L was found for open ocean samples from the Arctic basin, while coastal values of the same basin were 23.87 ± 6.46 particles/L (Table 2). Of the open ocean samples, highest mean values of microplastic abundance were found for the Arctic, Pacific (18.42 ± 3.47 particles/L), Atlantic (17.96 ± 1.22 particles/L), Southern (17.5 ± 1.22 particles/L), and Indian (16.87 ± 10.22 particles/L) oceans, respectively (Table 2) (Global & Gallatin Microplastic Initiative, 2018).

Table 2. *Microplastic abundance data calculated at ocean basins and environments.*

Ocean Basin	**Regional Sea**	**Coastal or Open Ocean**	**Mean Microplastic Abundance (particles / L)(± SE)**
Arctic		Coastal	23.8708 (± 6.4608)
Arctic		Open Ocean	54.5680 (± 16.0698)
Atlantic	Caribbean	Coastal	9.9372 (± 3.5674)
Atlantic	Gulf of Mexico	Coastal	3.0120 (± 1.4593)
Atlantic	Mediterranean	Coastal	2.1180 (± 0.8149)
Atlantic	NW (America, bermuda, canada)	Coastal	5.8342 (± 0.6392)
Atlantic	NE (UK, Europe, Africa)	Coastal	1.9975 (± 0.4088)
Atlantic	South	Coastal	2.2262 (± 0.6452)
Atlantic	Caribbean	Open Ocean	5.840 (± 3.7176)
Atlantic	Mediterranean	Open Ocean	9.0476 (± 1.3877)
Atlantic		Open Ocean	18.0176 (± 1.2235)
Indian		Coastal	2.9480 (± 0.5434)
Indian		Open Ocean	16.8722 (± 10.2184)
Pacific	Central America	Coastal	4.3898 (± 0.7205)
Pacific	Gulf of Alaska	Coastal	8.1858 (± 1.8316)
Pacific	SE Alaska	Coastal	5.6129 (± 1.2623)
Pacific	SE Asia	Coastal	5.3268 (± 1.4358)
Pacific	West (Australia, New Zealand, Niue, Beveridge)	Coastal	1.0850 (± 0.2545)
Pacific	East (America, Mexico, Canada, Hawaii, S. America)	Coastal	2.7056 (± 0.8773)
Pacific	Central America	Open Ocean	3.1231 (± 1.7898)
Pacific	SE Asia	Open Ocean	19.0741 (± 12.2426)
Pacific		Open Ocean	18.4176 (± 3.4670)
Southern		Coastal	15.29 (± 8.7241)
Southern		Open Ocean	17.5
Freshwater	North America		1.1493 (± 0.0858)
Freshwater	Europe		1.5720 (± 0.3808)

The analysis showed that ocean basins experience significant difference in mean microplastic abundance ($p = 0.0432$, $F_{4,19}=0.0323$, One-Way ANOVA). The Arctic had the highest mean and the Indian had the lowest mean compared to other sample locations (Figure 2). Furthermore, post-hoc analysis (Multiple Comparisons) indicated that microplastic abundance in the Arctic Ocean was significantly higher than abundance data in the Atlantic Ocean, while the Indian, Pacific, and Southern Oceans were not significantly different from each other.

The Open Ocean and coastal environments were also compared to determine if this factor affected microplastic abundance. Open ocean environments had a significantly higher mean microplastic abundance compared to coastal samples ($p = 0.005$, $t = -3.22$, two-tailed two sample t-test) (Figure 3). When considering the results from these analyses, it is important to know that the raw data was not evenly distributed throughout the global ocean. Rather, very few samples were taken from the Arctic and Southern Oceans, likely because data was collected on a volunteer basis and fewer individuals were able to visit these locations. The Atlantic and Pacific Oceans, however, had a far greater quantity of data points available. Such an unbalanced distribution could affect the reliability of these results.

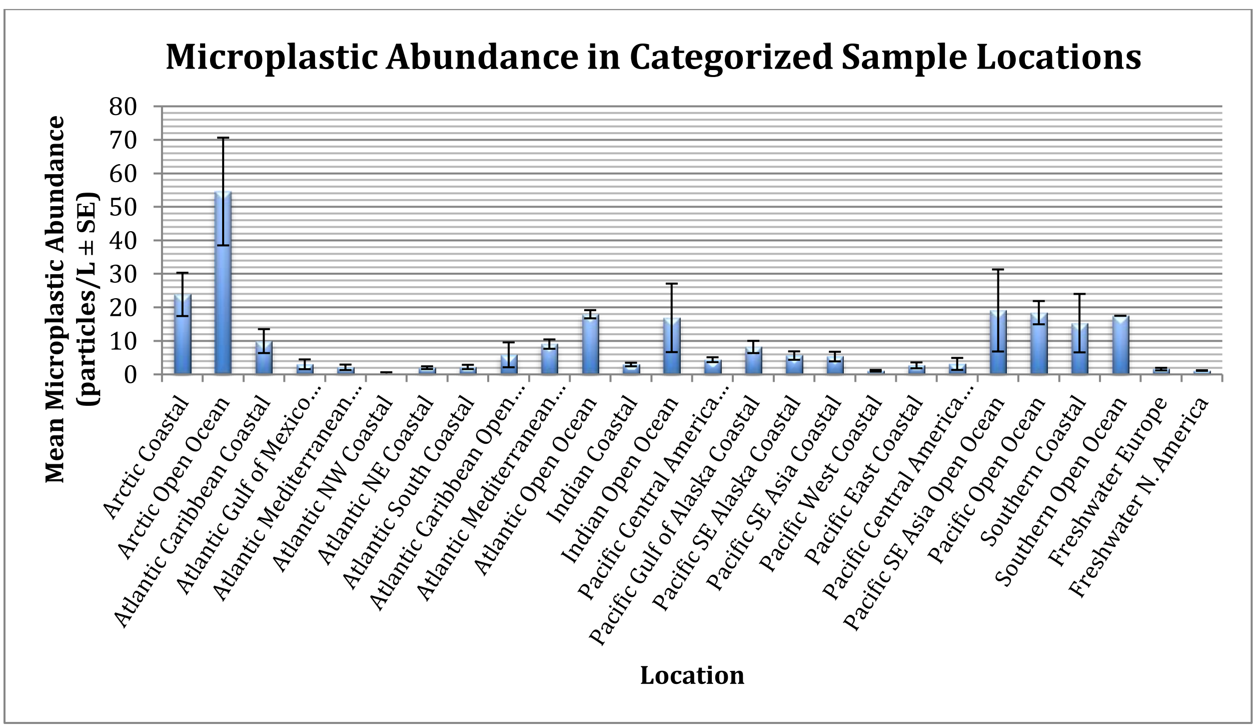

Figure 1. Mean microplastic abundance (particles/L ± SE) for each of the sample locations as categorized for further analysis.

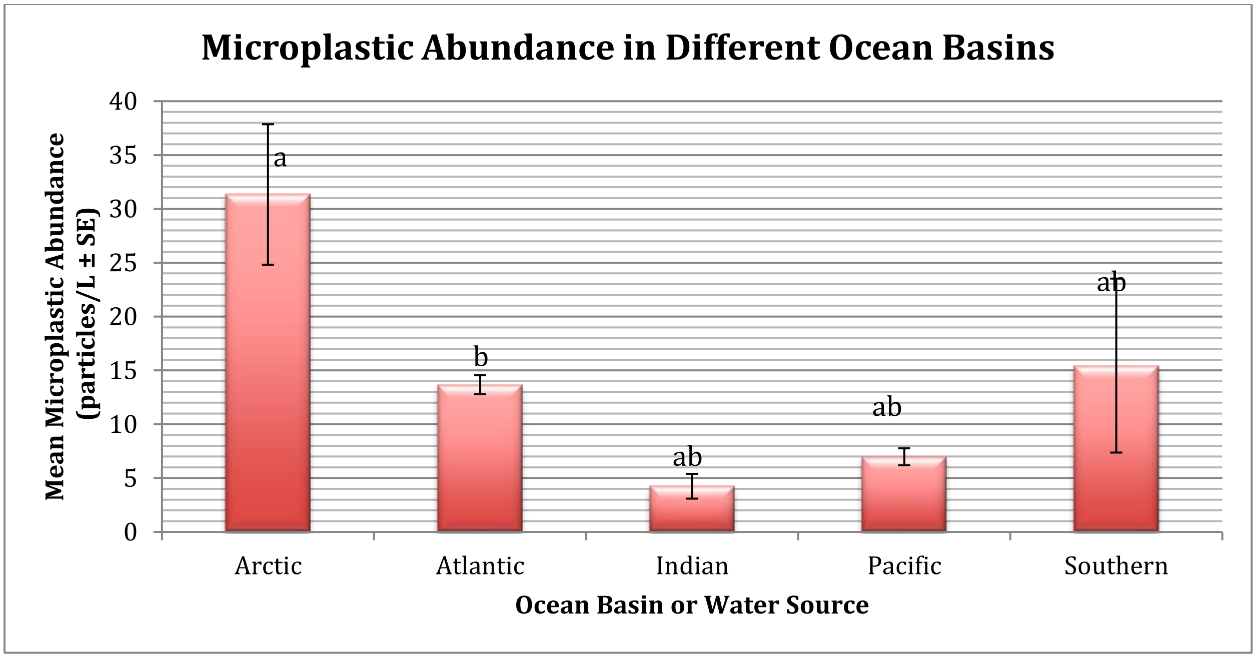

Figure 2. Mean microplastic abundance (particles/L ± SE) for each of the marine sample locations.

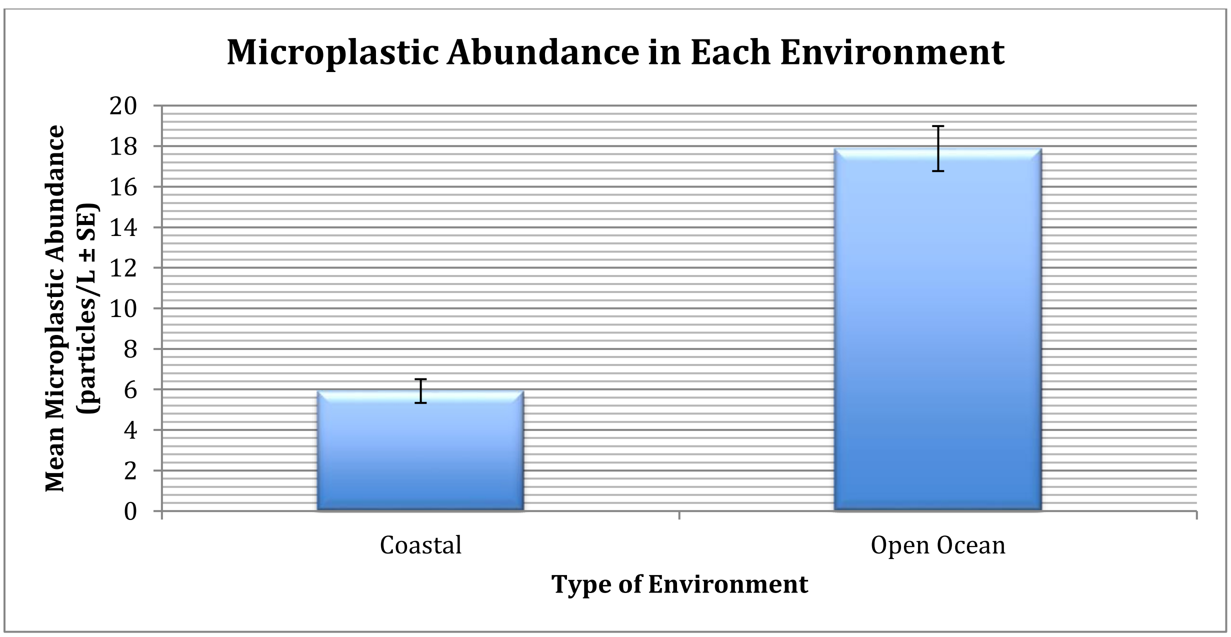

Figure 3. Mean microplastic abundance (particles/L ± SE) found in the two different types of environment, Coastal and Open Ocean.

Filtration Rates

In general, species of the smallest sizes, such as oyster larvae, bryozoans, copepods, seaworms, and tunicates, filter the least amount of water (Table 3). Larvae of Pacific oysters, for example, filter 1.39x10^{-6} mL water/second. Much larger – and therefore, stronger and faster – species, however, tend to filter greater quantities of water. Fin whales, for example, can filter volumes of water as large as 9.75x10^{6} mL/second (Table 3). Following this filtration rate would be that of bowhead whales (3.02x10^{-6} mL/s), then North Atlantic right whales (1.39x10^{6} mL/s), humpback whales (7.0x10^{5} mL/s), basking sharks (1.20x10^{-5} mL/s), and whale sharks (9.06x10^{4} mL/s).

Table 3. *Mean minimum and maximum filtration rates for each species (mL/s).*

Species Name *(Scientific)*	**Filtration Rate Minimum (mL/s)**	**Filtration Rate Maximum (mL/s)**	**Source**
Whale Shark *(Rhincondon typus)*	9.06E+04	1.71E+05	Motta et al. (2010)
Basking Shark *(Cetorhinus maximus)*	1.20E+05	1.20E+05	Sims (1999)
Blue mussels *(Mytilus edulis)*	6	38	Wildish et al. (1990); Riisgard et al. (2002)
Jellyfish *(Aurelia aurita)*	2.17E-03	7.56E-02	Oleson (1995)
Bowhead whales *(Balaena mysticetus)*	3.20E+06	3.20E+06	Simon et al. (2009); Goldbogen et al. (2017)
Humpback whale *(Megaptera novaeangliae)*	7.00E+05	7.00E+05	Simon et al. (2012)
Blue whales *(Balaenoptera musculus)*	5.85E+02	5.85E+02	Doniol-Valcroze et al. (2011); Goldbogen et al. (2011)
Copepod *(Calanus finmarchicus)*	5.21E-05	5.21E-05	Fuller & Clark (1936)
Atlantic mackerel *(Scomber scombrus)*	26.67	51.67	Sutherland et al. (1995)
Antarctic minke whale *(Balaenoptera bonaerensis)*	5.36E+04	5.36E+04	Friedlaender et al. (2014)
Oyster LARVAE *(Crassostrea gigas)*	1.39E-06	1.39E-06	Qiu et al. (2015)
Pacific Oyster ADULT *(C. gigas)* - smaller size	0.108	0.108	Gerdes (1982)
Pacific Oyster ADULT *(C. gigas)* - larger size	0.288	0.288	Gerdes (1982)
Tunicate *(Oikopleura dioica)*	2.31E-04	2.31E-04	Bochdansky & Deibel (1998)
Silver Carp *(Hypophthalmichthys molitrix* Val.)	9.58	10.42	Zhao et al. 2011
Manta Ray *(Manta birostis)*	1.51E+04	1.51E+04	Divi et al. (2018); Paig-Tran et al. (2013)
Pelagic Tunicate *(Pegea confederata)*	6.17E-03	7.77E-02	Harbison & Gilmer (1976)
Fin whales (*Balaenoptera physalus)*	9.75E+06	9.75E+06	Goldbogen et al. (2010)
Glass sponge *(Aphrocallistes vastus)*	17.25	1.73E+01	Leys et al. (2011)

Cockle *(Cardium edule)*	0.111	1.03	Riisgard et al. (2002)
Soft-shell clam *(Mya arenia)*	0.333	1.056	Riisgard et al. (2002)
Atlantic menhaden *(Brevoortis tyrannus)*	41.67	87.83	Durbin & Durbin (1975)
Mysid shrimp *(Rhopalophthalmus terranatalis) ADULTS*	2.36E-03	2.36E-03	Jerling & Wooldridge (1994)
(Rhopalophthalmus terranatalis) JUVENILES	3.75E-03	3.75E-03	Jerling & Wooldridge (1994)
Mysid shrimp (*Mesopodopsis wooldridgei) ADULTS*	9.50E-03	9.50E-03	Jerling & Wooldridge (1994)
(Mesopodopsis wooldridgei) JUVENILES	5.17E-03	5.17E-03	Jerling & Wooldridge (1994)
Burrowing shrimp *(Upogebia deltaura)*	0.972	9.72E-01	Lindahl & Baden (1997)
Antarctic Krill *(Euphausia superba)*	0.125	0.125	Boyd et al. (1984)
Porcelain Crab *(Porcellana longicornis)*	3.94E-02	7.42E-02	Achituv & Pedrotti (1999)
Ocean Quahog *(Arctica islandica)*	0.555	1.14E+00	Winter (1969)
Wrinkled Rockborer *(Hiatella arctica)*	1.53E-03	9.47E-03	Ali (1970)
Bay Scallop *(Pecten irradians)*	0.906	4.089	Chipman & Hawkins (1954)
Orange Sea Pen *(Ptilosarcus gurneyi)*	100	1000	Best (1988)
Feather star *(Oligometra serripinna)*	68	111.6	Leonard et al. (1988)
Manila Clam *(Tapes philippinarum)*	2.78E-02	0.278	Nakamura (2001); Hosokawa (1988)
Yesso scallop (*Patinopecten yessoensis)*	0.694	1.1	Yamamoto (1968)
Spaghetti Bryozoan *(Zoobotryon verticillatum)*	4.22E-05	2.92E-04	Bullivant (1967)
Bryozoan *(Electra pylosa)*	6.94E-05	7.78E-05	Riisgard & Manriquez (1997)
Bryozoan *(Conopeum reticulum)*	4.72E-05	5.56E-05	Riisgard & Manriquez (1997)
Bryozoan *(Celleporella hyalina)*	3.33E-05	4.17E-05	Riisgard & Manriquez (1997)
Sea vase *(Ciona intestinalis)*	0.05	0.2	Randlov & Riisgard (1979)
Sea squirt *(Ascidella aspersa)*	0.067	0.333	Randlov & Riisgard (1979)
Polychaete worm *(Myxicola infundibulum)*	7.90E-02	7.94E-02	Dales (1957)
Peacock worm *(Sabella pavonina)*	2.03E-02	2.03E-02	Dales (1957)
Keel worm *(Pomatoceros triqueter)*	7.50E-03	7.50E-03	Dales (1957)
Polychaete worm *(Hydroides norvegica)*	3.10E-03	3.10E-03	Dales (1957)
Sinistral spiral tubeworm *(Spirorbis borealis)*	6.39E-05	6.39E-05	Dales (1957)
Polychaete worm *(Salmacina dysteri)*	8.06E-04	8.06E-04	Dales (1957)
Breadcrumb sponge *(Halichondria panicea)*	7.17E-02	7.17E-02	Riisgard et al. (1993)
Common Bream *(Abramis brama)*	7.6389	7.6389	van den Berg (1993)
White Bream *(Blicca bjoerkna)*	6.389	6.389	van den Berg (1993)
Roach *(Rutilus rutilus)*	9.833	9.833	van den Berg (1993)
Gizzard shad *(Dorosoma cepedianum)*	20.833	20.833	van den Berg (1993) & Drenner et al. (1984)
North Atlantic Right Whale *(Eubalaena glacialis)*	1.39E+06	1.39E+06	van der Hoop et al. (2019)

Microplastic Consumption Rates

With filtration rates and microplastic abundance data collated, the estimated microplastic abundance was determined for each species' location categories and the MCR (in particles/s) was calculated (Table 4). The species with the highest maximum microplastic consumption rate (MCR) while feeding was the fin whale in the Pacific Open Ocean ($1.79x10^5$ particles/s). Among the species reviewed in this paper, the lowest maximum MCR occurred in larvae of Pacific Oysters ($1.51x10^{-9}$ particles/s). However, among only the adults (and thus, excluding juveniles), the lowest maximum MCR occurred in the bryozoan, *E. pylosa* ($8.48x10^{-8}$ particles/s).

The minimum mean MCR was found to be $1.51x10^{-09}$ particles/s, while the maximum mean MCR was found to be $6.235x10^3$. The variance and standard deviation values, $9.21x10^8$ and $3.03x10^4$, respectively, further indicated that the data was very spread out.

The MCR data indicated a strong increasing trend with increasing body weight (Figure 4), suggesting that an organism's size played a significant role in MCR values. For this reason, the data was further analyzed to create a new dataset of with these values reported as a MCR-to-bodyweight ratio in units of particles/s/kg (Table 4). While MCR values provide information regarding a species' risk of microplastic consumption, these Normalized MCR (or NMCR) values provide information regarding a species' risk of microplastic contamination because the values are reported in terms of body weight. Analysis of the data showed that the pelagic tunicate (*P. confederata*) actually experiences the highest risk of microplastic contamination, as it had a NMCR value of $5.17x10^4$ particles/s/kg. The bryozoan *(E. pylosa*), however, experiences the lowest risk of microplastic contamination with a NMCR value of $1.88x10^{-07}$ particles/s/kg (Figure 5).

Analysis of the relationship between body size and MCR showed that bodyweight does have a significant relationship with MCR values (p=1.92x10-11, z=6.71, tau=0.563, Non-parametric correlation). This relationship indicates that smaller organisms are more at risk of microplastic contamination, as they appear to consume larger quantities of microplastics on a per-kg basis.

Table 4. *Mean minimum and maximum MCR (particles/s) for each species.*

Species	**Microplastic Abundance Sample Locations**	**Mean MCR (particles/s)**	**Mean Normalized MCR (particles/s/kg)**
Antarctic Krill *(Euphausia superba)*	Southern, Coastal	1.91E-03	3.35E+00
Antarctic minke whale *(Balaenoptera bonaerensis)*	Southern, Open Ocean	9.38E+02	9.90E-02
Atlantic mackerel *(Scomber scombrus)*	Atlantic, NW, Coastal	3.01E-01	9.77E-01
Atlantic mackerel *(Scomber scombrus)*	Atlantic, NE, Coastal	1.03E-01	3.34E-01
Atlantic mackerel *(Scomber scombrus)*	Atlantic, Mediterranean, Coastal	3.39E-02	1.10E-01
Atlantic menhaden *(Brevoortis tyrannus)*	Atlantic, NW, Coastal	5.12E-01	8.53E-01
Basking Shark *(Cetorhinus maximus)*	Pacific, East, Coastal	3.25E+02	8.13E-02
Bay Scallop *(Pecten irradians)*	Atlantic, NW, Coastal	2.38E-02	9.52E-02
Blue mussels *(Mytilus edulis)*	Atlantic, NW, Coastal	2.22E-01	3.36E+01
Blue mussels *(Mytilus edulis)*	Atlantic, NE, Coastal	7.59E-02	1.15E+01
Blue whales *(Balaenoptera musculus)*	Pacific, East, Coastal	1.59E+00	2.00E-05
Bowhead whales *(Balaena mysticetus)*	Atlantic, NW, Coastal	1.87E+04	2.49E-01
Bowhead whales *(Balaena mysticetus)*	Pacific, SE Alaska, Coastal	1.80E+04	2.40E-01
Breadcrumb sponge *(Halichondria panicea)*	Atlantic, NE, Coastal	1.43E-04	2.20E-03
Breadcrumb sponge *(Halichondria panicea)*	Pacific, West, Coastal	7.82E-05	1.20E-03
Bryozoan *(Celleporella hyalina)*	Atlantic, NW, Coastal	2.43E-07	5.40E-07
Bryozoan *(Celleporella hyalina)*	Pacific, East, Coastal	1.13E-07	2.41E-07
Bryozoan *(Conopeum reticulum)*	Atlantic, NE, Coastal	1.11E-07	2.46E-07
Bryozoan *(Electra pylosa)*	Pacific, West, Coastal	8.48E-08	1.88E-07
Burrowing shrimp *(Upogebia deltaura)*	Atlantic, Mediterranean, Coastal	2.06E-03	1.03E+00
Cockle *(Cardium edule)*	Atlantic, NE, Coastal	2.06E-03	2.58E-01
Common Bream *(Abramis brama)*	Freshwater, Europe	1.17E-02	1.95E-03
Copepod *(Calanus finmarchicus)*	Atlantic Open Ocean (surface)	9.37E-07	2.86E+00
Feather star *(Oligometra serripinna)*	Pacific, SE Asia, Coastal	2.13E+00	7.10E+02
Fin whales (*Balaenoptera physalus)*	Pacific Open Ocean	1.79E+05	3.58E+00
Fin whales (*Balaenoptera physalus)*	Atlantic, Open Ocean	1.76E+05	3.52E+00
Gizzard shad *(Dorosoma cepedianum)*	Freshwater, North America	2.40E-02	1.26E-02
Glass sponge *(Aphrocallistes vastus)*	Pacific, Gulf of Alaska, Coastal	1.41E-01	1.57E-01
Humpback whale *(Megaptera novaeangliae)*	Atlantic, NW, Coastal	4.08E+03	1.41E-01
Humpback whale *(Megaptera novaeangliae)*	Pacific, West, Coastal	7.63E+02	2.63E-02
Jellyfish *(Aurelia aurita)*	Atlantic, NW, Coastal	4.41E-04	6.35E-03
Keel worm *(Pomatoceros triqueter)*	Atlantic, NE, Coastal	1.50E-05	3.75E+00
Keel worm *(Pomatoceros triqueter)*	Arctic, Coastal	1.79E-04	4.48E+01
Manila Clam *(Tapes philippinarum)*	Indian, Coastal	8.20E-04	7.13E-02

Manta Ray *(Manta birostis)*	Atlantic, Caribbean, Coastal	1.50E+02	9.10E-02
Manta Ray *(Manta birostis)*	Pacific, SE Asia, Coastal	8.05E+01	4.88E-02
Mysid shrimp (*Mesopodopsis wooldridgei) ADULTS*	Indian, Coastal	2.80E-05	1.18E+02
Mysid shrimp *(Mesopodopsis wooldridgei)* JUVENILES	Indian, Coastal	1.53E-05	3.19E+02
Mysid shrimp *(Rhopalophthalmus terranatalis) ADULTS*	Indian, Coastal	6.96E-06	2.32E+00
Mysid shrimp *(Rhopalophthalmus terranatalis)* JUVENILES	Indian, Coastal	1.11E-05	1.11E+01
North Atlantic Right Whale *(Eubalaena glacialis)*	Atlantic, Open Ocean	2.50E+04	1.09E+00
Ocean Quahog *(Arctica islandica)*	Atlantic, NW, Coastal	6.64E-03	2.92E-02
Orange Sea Pen *(Ptilosarcus gurneyi)*	Pacific, East, Coastal	2.71E+00	1.81E+01
Pacific Oyster ADULT *(C. gigas)* - larger size	Pacific, West, Coastal	3.14E-04	7.85E-04
Pacific Oyster ADULT *(C. gigas)* - smaller size	Pacific, West, Coastal	1.18E-04	5.10E-04
Pacific Oyster LARVAE *(Crassostrea gigas)*	Pacific, West, Coastal	1.51E-09	7.55E-02
Peacock worm *(Sabella pavonina)*	Atlantic, Mediterranean, Coastal	4.30E-05	1.08E+01
Pelagic Tunicate *(Pegea confederata)*	Atlantic, NE, Coastal	1.55E-04	5.17E+04
Polychaete worm *(Hydroides norvegica)*	Atlantic, Mediterranean, Coastal	6.57E-06	1.64E+00
Polychaete worm *(Myxicola infundibulum)*	Atlantic, Open Ocean	1.43E-03	3.58E+02
Polychaete worm *(Myxicola infundibulum)*	Pacific Open Ocean	1.45E-03	3.63E+02
Polychaete worm *(Salmacina dysteri)*	Pacific Open Ocean	1.48E-05	3.70E+00
Porcelain Crab *(Porcellana longicornis)*	Atlantic, NE, Coastal	1.48E-04	5.92E+00
Roach *(Rutilus rutilus)*	Freshwater, Europe	1.50E-02	8.33E-03
Sea squirt *(Ascidella aspersa)*	Atlantic, NE, Coastal	6.65E-04	4.43E-03
Sea vase *(Ciona intestinalis)*	Atlantic, Open Ocean	3.60E-03	1.76E-04
Silver Carp *(Hypophthalmichthys molitrix* Val.)	Freshwater, Asia	2.34E-02	4.68E-04
Sinistral spiral tubeworm *(Spirorbis borealis)*	Atlantic, NE, Coastal	1.28E-07	3.20E-02
Sinistral spiral tubeworm *(Spirorbis borealis)*	Pacific, East, Coastal	1.73E-07	4.33E-02
Soft-shell clam *(Mya arenia)*	Atlantic, NW, Coastal	6.16E-03	1.81E-01
Soft-shell clam *(Mya arenia)*	Atlantic, NE, Coastal	2.11E-03	6.20E-02
Spaghetti Bryozoan *(Zoobotryon verticillatum)*	Atlantic, Caribbean, Coastal	2.90E-06	4.83E-04
Tunicate *(Oikopleura dioica)*	Atlantic, NE, Coastal	4.62E-07	1.54E+02
Whale Shark *(Rhincondon typus)*	Pacific, Central America, Coastal	7.51E+02	2.20E-02
Whale Shark *(Rhincondon typus)*	Pacific, West, Coastal	1.86E+02	5.50E-03
White Bream *(Blicca bjoerkna)*	Freshwater, Europe	9.78E-03	9.78E-03
Wrinkled Rockborer *(Hiatella arctica)*	Atlantic, South, Coastal	2.13E-05	1.42E-02
Yesso scallop (*Patinopecten yessoensis*)	Pacific, West, Coastal	1.20E-03	9.23E-04

Figure 4. Mean microplastic consumption rate (particles/s ± SE) for each filter feeding species in order of bodysize. Multiple columns indicate data at different geographic locations for a single species, as described in Table 8.

Figure 5. Mean normalized microplastic consumption rate (particles/s/kg ± SE) for each filter feeder in order of body size. Multiple columns indicate data at different geographic locations for a single species, as described in Table 8.

Filter Feeder Characteristics

a. Salinity

Salinity was analyzed to allow for comparison between marine and freshwater species. Only a few freshwater species were considered in this review, including silver carp *(Hypophthalamichthys molitrix)*, common bream *(Abramis brama)*, white bream *(Blicca bjoerkna)*, roach *(Rutilus rutilus)*, and gizzard shad *(Dorosoma cepedianum).* The remaining 49 were marine species (Table 4).

Table 4. *The salinity type (Marine or Freshwater) to which each species belongs.*

Species	**Salinity**
Whale Shark *(Rhincondon typus)*	Marine
Basking Shark *(Cetorhinus maximus)*	Marine
Blue mussels *(Mytilus edulis)*	Marine
Jellyfish *(Aurelia aurita)*	Marine
Bowhead whales *(Balaena mysticetus)*	Marine
Humpback whale *(Megaptera novaeangliae)*	Marine
Blue whales *(Balaenoptera musculus)*	Marine
Copepod *(Calanus finmarchicus)*	Marine
Atlantic mackerel *(Scomber scombrus)*	Marine
Antarctic minke whale *(Balaenoptera bonaerensis)*	Marine
Pacific Oyster LARVAE *(Crassostrea gigas)*	Marine
Pacific Oyster ADULT *(C. gigas)* - smaller size	Marine
Pacific Oyster ADULT *(C. gigas)* - larger size	Marine
Tunicate *(Oikopleura dioica)*	Marine
Silver Carp *(Hypophthalmichthys molitrix* Val.)	Freshwater
Manta Ray *(Manta birostis)*	Marine
Pelagic Tunicate *(Pegea confederata)*	Marine
Fin whales (*Balaenoptera physalus)*	Marine
Glass sponge *(Aphrocallistes vastus)*	Marine
Cockle *(Cardium edule)*	Marine
Soft-shell clam *(Mya arenia)*	Marine
Atlantic menhaden *(Brevoortis tyrannus)*	Marine
Mysid shrimp (Rhopalophthalmus terranatalis) ADULTS	Marine
Mysid shrimp (Rhopalophthalmus terranatalis) JUVENILES	Marine
Mysid shrimp (Mesopodopsis wooldridgei) ADULTS	Marine
Mysid shrimp (Mesopodopsis wooldridgei) JUVENILES	Marine

Burrowing shrimp *(Upogebia deltaura)*	Marine
Antarctic Krill *(Euphausia superba)*	Marine
Porcelain Crab *(Porcellana longicornis)*	Marine
Ocean Quahog *(Arctica islandica)*	Marine
Wrinkled Rockborer *(Hiatella arctica)*	Marine
Bay Scallop *(Pecten irradians)*	Marine
Orange Sea Pen *(Ptilosarcus gurneyi)*	Marine
Feather star *(Oligometra serripinna)*	Marine
Manila Clam *(Tapes philippinarum)*	Marine
Yesso scallop (*Patinopecten yessoensis)*	Marine
Spaghetti Bryozoan *(Zoobotryon verticillatum)*	Marine
Bryozoan *(Electra pylosa)*	Marine
Bryozoan *(Conopeum reticulum)*	Marine
Bryozoan *(Celleporella hyalina)*	Marine
Sea vase *(Ciona intestinalis)*	Marine
Sea squirt *(Ascidella aspersa)*	Marine
Polychaete worm *(Myxicola infundibulum)*	Marine
Peacock worm *(Sabella pavonina)*	Marine
Keel worm *(Pomatoceros triqueter)*	Marine
Polychaete worm *(Hydroides norvegica)*	Marine
Sinistral spiral tubeworm *(Spirorbis borealis)*	Marine
Polychaete worm *(Salmacina dysteri)*	Marine
Breadcrumb sponge *(Halichondria panicea)*	Marine
Common Bream *(Abramis brama)*	Freshwater
White Bream *(Blicca bjoerkna)*	Freshwater
Roach *(Rutilus rutilus)*	Freshwater
Gizzard shad *(Dorosoma cepedianum)*	Freshwater
North Atlantic Right Whale *(Eubalaena glacialis)*	Marine

Salinity was assessed to have no significant relationship with microplastic consumption rates ($p = 0.3719$, $w = 196$, Mann-Whitney Wilcoxon test). Although marine species had a higher mean MCR than freshwater species (Figure 4), the difference was not significant. The differences seen are likely due to the Marine outliers, which are above 1.5×10^5 particles/s. However, it is important to note that the differences are likely results of the few data points collected for freshwater species. Only five species out of the 50 live in freshwater environments, and the sample size can easily impact the reliability and precision of the non-parametric test used to analyze the relationship.

When taking bodyweight into consideration, however, significant differences did occur in NMCR values between salinity levels ($p = 0.026$, $w=62$, Mann-Whitney Wilcoxon test). Marine species had a significantly higher NMCR than freshwater species (Figure 7). This suggests that species in marine water would experience higher risks of microplastic contamination.

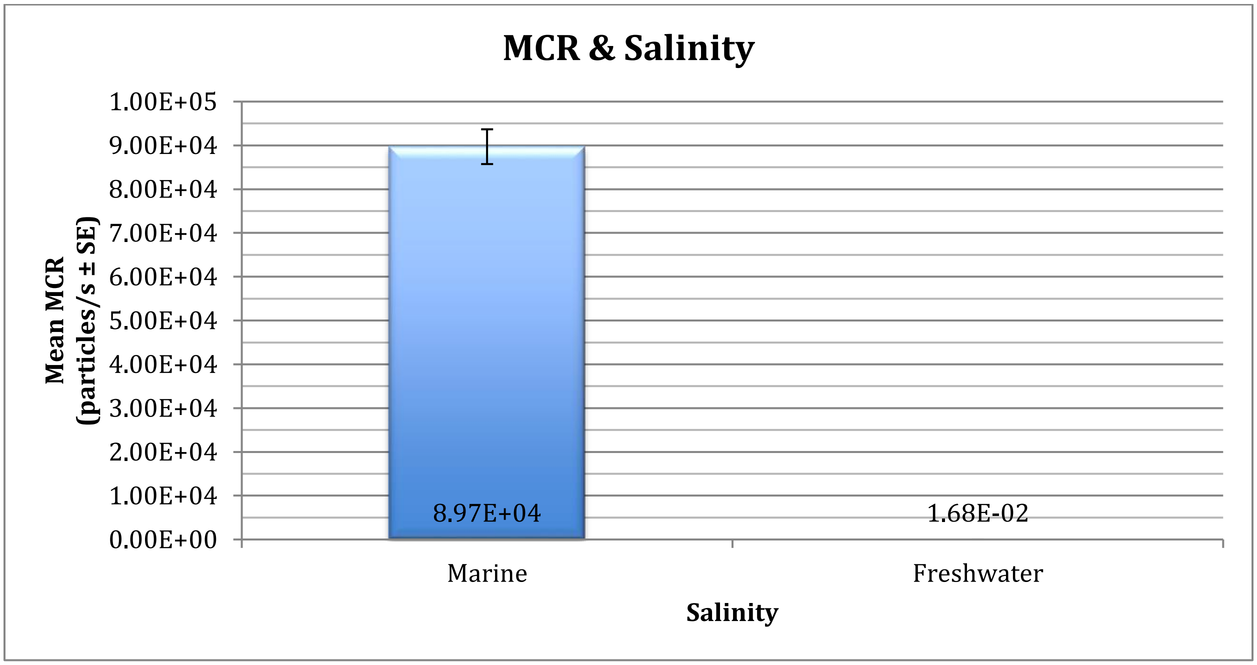

Figure 6. The calculated MCR (particles/s ± SE) at both types of salinity, freshwater and marine.

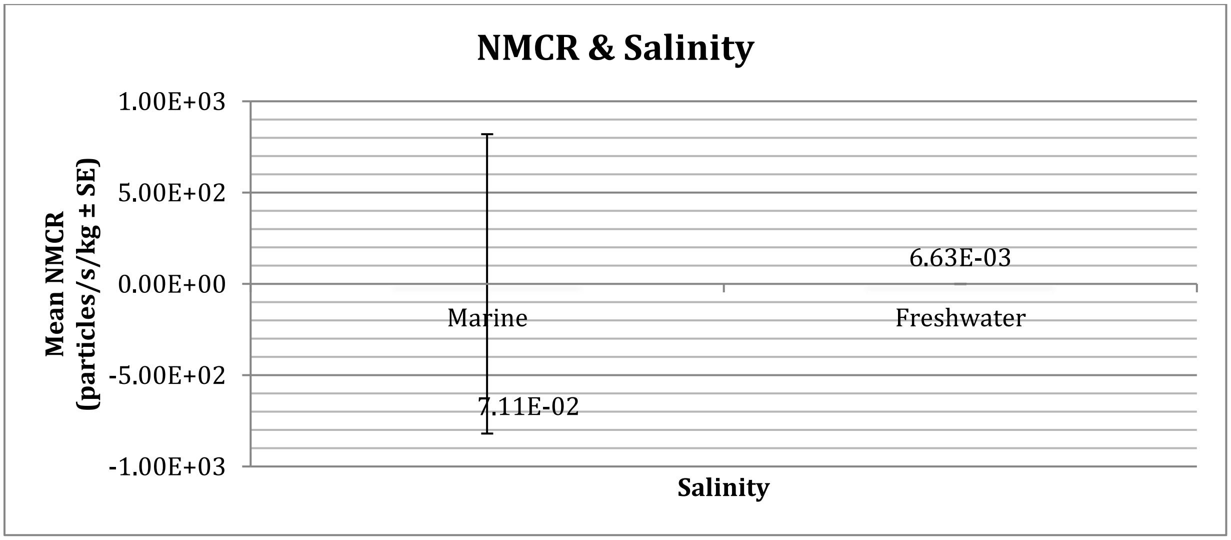

Figure 7. The calculated NMCR (particles/s/kg ± SE) at both types of salinity, freshwater and marine.

b. IUCN Red List Status

To effectively determine which species are most at risk of experiencing harmful ecological impacts from microplastics, the IUCN Red List status for each species was also collected (Table 5) (IUCN 2019). The IUCN generally categorizes species based on the vulnerability status, including labels that range from Least Concern to Vulnerable, Endangered, Critically Endangered, Extinct in the Wild, and Extinct. For those species on which very little data has been collected, the organization generates the default label, Not Evaluated (IUCN 2019). Of the 50 different filter feeding species, most have yet to be evaluated and are thus given the label "NE." Of the evaluated species, only three were considered endangered (EN) –whale sharks *(Rhindondon typus)*, blue whales *(Balaenoptera musculus)*, and North Atlantic right whales *(Eubalaena glacialis)* (IUCN 2019).

Those labeled Least Concern (LC) include bowhead whales *(Balaena mysticetus)*, humpback whales *(Megaptera novaeangliae)*, Atlantic mackerel *(Scomber scombrus)*, Atlantic menhaden *(Brevoortis tyrannus)*, Antarctic krill *(Euphausia superba)*, common bream *(Abramis brama)*, white bream *(Blicca bjoerkna)*, roach *(Rutilus rutilus)*, and gizzard shad *(Dorosoma cepedianum)* (IUCN 2019). A few were considered to be vulnerable (VU) species, including the basking shark *(Cetorhinus maximus)*, the manta ray *(Manta birostis)*, and fin whales *(Balaenoptera physalus)*. Antarctic minke whales *(Balaenoptera bonaerensis)* and silver carp *(Hypophthalmichthys molitrix)* were considered near threatened (NT), while only the whale sharks *(Rhincondon typus)*, blue whales *(Balaenoptera musculus)*, and North Atlantic right whales *(Eubalaena glacialis)* were considered endangered (EN) species (IUCN 2019).

Table 5. *IUCN Red List Status of study species (IUCN 2019).*

Species	**IUCN Red List Status**
Whale Shark *(Rhincondon typus)*	EN
Basking Shark *(Cetorhinus maximus)*	VU
Blue mussels *(Mytilus edulis)*	Not Evaluated
Jellyfish *(Aurelia aurita)*	Not Evaluated
Bowhead whales *(Balaena mysticetus)*	LC
Humpback whale *(Megaptera novaeangliae)*	LC
Blue whales *(Balaenoptera musculus)*	EN
Copepod *(Calanus finmarchicus)*	Not Evaluated
Atlantic mackerel *(Scomber scombrus)*	LC
Antarctic minke whale *(Balaenoptera bonaerensis)*	NT
Pacific Oyster JUVENILES *(Crassostrea gigas)*	Not Evaluated
Pacific Oyster ADULT *(C. gigas)* - smaller size	Not Evaluated
Pacific Oyster ADULT *(C. gigas)* - larger size	Not Evaluated
Tunicate *(Oikopleura dioica)*	Not Evaluated
Silver Carp *(Hypophthalmichthys molitrix* Val.)	NT
Manta Ray *(Manta birostis)*	VU
Pelagic Tunicate *(Pegea confederata)*	Not Evaluated
Fin whales (*Balaenoptera physalus)*	VU
Glass sponge *(Aphrocallistes vastus)*	Not Evaluated
Cockle *(Cardium edule)*	Not Evaluated
Soft-shell clam *(Mya arenia)*	Not Evaluated
Atlantic menhaden *(Brevoortis tyrannus)*	LC
Mysid shrimp *(Rhopalophthalmus terranatalis) ADULTS*	Not Evaluated
Mysid shrimp *(Rhopalophthalmus terranatalis)* JUVENILES	Not Evaluated
Mysid shrimp (*Mesopodopsis wooldridgei) ADULTS*	Not Evaluated
Mysid shrimp *(Mesopodopsis wooldridgei)* JUVENILES	Not Evaluated
Burrowing shrimp *(Upogebia deltaura)*	Not Evaluated
Antarctic Krill *(Euphausia superba)*	LC
Porcelain Crab *(Porcellana longicornis)*	Not Evaluated
Ocean Quahog *(Arctica islandica)*	Not Evaluated
Wrinkled Rockborer *(Hiatella arctica)*	Not Evaluated
Bay Scallop *(Pecten irradians)*	Not Evaluated
Ornage Sea Pen *(Ptilosarcus gurneyi)*	Not Evaluated
Feather star *(Oligometra serripinna)*	Not Evaluated
Manila Clam *(Tapes philippinarum)*	Not Evaluated
Yesso scallop (*Patinopecten yessoensis)*	Not Evaluated
Spaghetti Bryozoan *(Zoobotryon verticillatum)*	Not Evaluated
Bryozoan *(Electra pylosa)*	Not Evaluated
Bryozoan *(Conopeum reticulum)*	Not Evaluated

Bryozoan *(Celleporella hyalina)*	Not Evaluated
Sea vase *(Ciona intestinalis)*	Not Evaluated
Sea squirt *(Ascidella aspersa)*	Not Evaluated
Polychaete worm *(Myxicola infundibulum)*	Not Evaluated
Peacock worm *(Sabella pavonina)*	Not Evaluated
Keel worm *(Pomatoceros triqueter)*	Not Evaluated
Polychaete worm *(Hydroides norvegica)*	Not Evaluated
Sinistral spiral tubeworm *(Spirorbis borealis)*	Not Evaluated
Polychaete worm *(Salmacina dysteri)*	Not Evaluated
Breadcrumb sponge *(Halichondria panicea)*	Not Evaluated
Common Bream *(Abramis brama)*	LC
White Bream *(Blicca bjoerkna)*	LC
Roach *(Rutilus rutilus)*	LC
Gizzard shad *(Dorosoma cepedianum)*	LC
North Atlantic Right Whale *(Eubalaena glacialis)*	EN

The quantitative analysis of the IUCN status for each species allowed determination of whether a significant relationship exists with the corresponding MCR for the species. VU-labeled species had a significantly higher mean MCR than any other status ($p<<0.000$, $\chi^2= 38.195$, df = 4, Kruskal-Wallis test). Not Evaluated species, however, had a significantly lower mean MCR than any other status (Figure 8). The significance of these results indicate that IUCN status could be used as a potential indicator of a species' microplastic consumption risk. However, similar biological characteristics must be met when drawing similar conclusions for other species. Post-hoc analysis (Multiple Comparisons) found that species categorized as endangered, least concern, near threatened, and vulnerable were not significantly different from each other. Species categorized as endangered and near threatened were also not significantly different from each other.

Once bodyweight was taken into account and NMCR values were calculated, the statistical tests were re-run to determine if this impacted the results. It was determined that no significant differences occurred in NMCR values between IUCN statuses ($p = 0.51$, $\chi 2=3.29$, df=4, Kruskal-Wallis Test). This suggests that IUCN status does not indicate whether a species is at more or less risk of microplastic contamination (Figure 9).

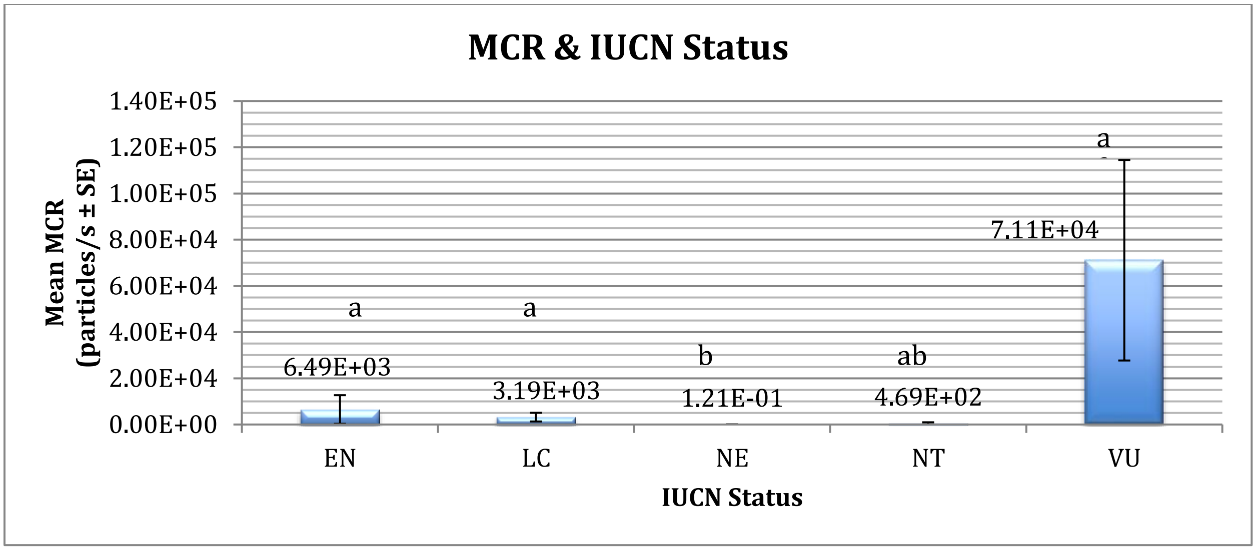

Figure 8. Mean MCR (particles/s ± SE) for each IUCN Red List Status labels, including EN, LC, NE, NT, and VU.

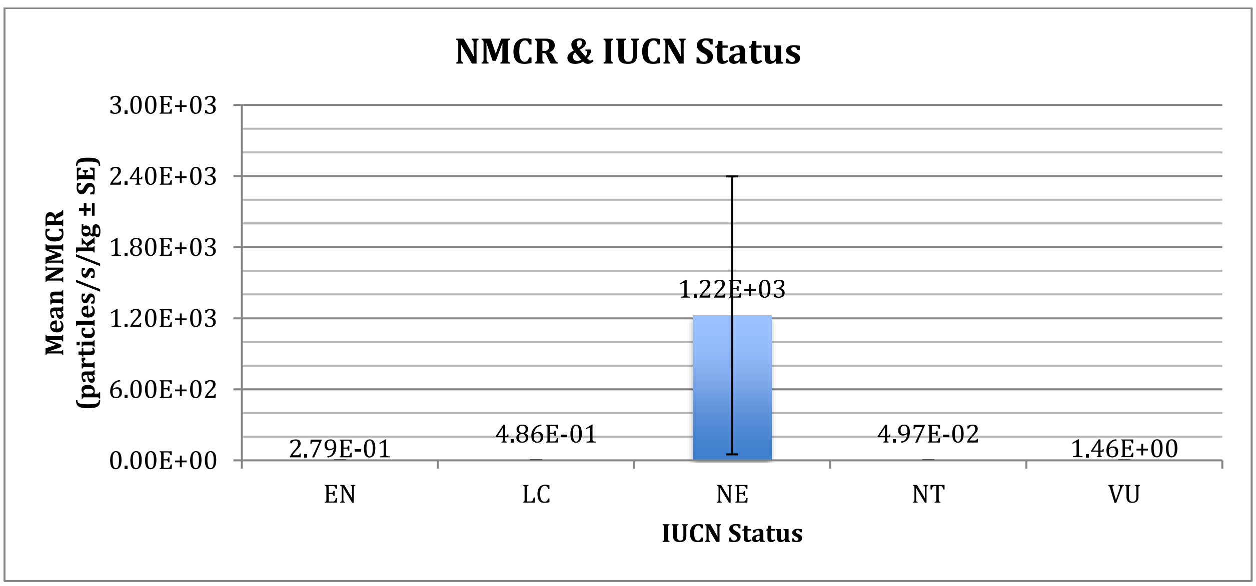

Figure 9. Mean NMCR (particles/s/kg ± SE) for each IUCN Red List Status labels, including EN, LC, NE, NT, and VU.

c. Filtration Technique

Of the 50 marine species reviewed, most relied on at least one of four main techniques: ram filtration, suspension feeding, water pumping (or suction feeding), and lunge feeding. For the purposes of this study, whale sharks, basking sharks, bowhead whales, Atlantic mackerel, manta rays, Atlantic menhaden, and North Atlantic right whales are primarily considered to use ram filtration techniques. Humpback whales, blue whales, Antarctic minke whales, and fin whales typically rely on lunge feeding methods, while blue mussels, copepods, tunicates, and pelagic tunicates use water-pumping methods (Table 6). The remaining species, including jellyfish, Pacific oysters, glass sponges, cockles, soft-shell clams, porcelain crabs, ocean quahogs, wrinkled rockborers, bay scallops, orange sea pens, feather stars, Manila clams, Yesso scallops, bryozoans, sea vase, sea squirts, polychaete worms, peacock worms, and keel worms, are considered suspension feeders (Table 6).

In some cases, a species might be known to use more than one technique, such as whale sharks. Although these gentle giants primarily rely on ram filtration techniques by swimming forward at slow speeds, they have also been documented using an active suction feeding method. To do this, they frequently position themselves vertically just below the water's surface and use a powerful buccal pump to create a suction, trapping their prey in gill rakers (Heyman et al. 2001). Despite multiple techniques, the mean filtration rate obtained for this review corresponds with the whale shark's use of ram filtration, and the species is considered a ram filter feeder.

Although some species may use highly specialized methods to obtain prey, their overall technique is still considered to fall into one of these four categories. For example, tunicates *(Pegea confederata and Oikopleura doica)* are considered to use the water pumping technique, accomplishing filtration by creating a "house" and pumping water through it (Bochdansky & Deibel 1998, Tomita et al. 2019). Antarctic krill *(Euphausia superba)* offer another excellent example, as these suspension feeders frequently create a feeding apparatus with the use of their front legs (Boyd et al. 1984, Clark & Tyler 2014). Manta rays are also unique in that, although they use a ram filtration technique, their specific strategy is known as ricochet filtration (Divi et al. 2018). Despite the unique methods and adaptations these species use in water filtration, an overall assessment required the categorization of their techniques into one of the four primary methods.

Table 6. *Filtration technique (ram, suspension, lunge, or pumping) used by study species.*

Species	**Filtration Technique**
Whale Shark *(Rhincondon typus)*	Ram filtration
Basking Shark *(Cetorhinus maximus)*	Ram filtration
Blue mussels *(Mytilus edulis)*	Suspension
Jellyfish *(Aurelia aurita)*	Suspension
Bowhead whales *(Balaena mysticetus)*	Ram filtration
Humpback whale *(Megaptera novaeangliae)*	Lunge feeding
Blue whales *(Balaenoptera musculus)*	Lunge feeding
Copepod *(Calanus finmarchicus)*	Suspension feeding
Atlantic mackerel *(Scomber scombrus)*	Ram Filtration
Antarctic minke whale *(Balaenoptera bonaerensis)*	Lunge feeding
Oyster JUVENILES *(Crassostrea gigas)*	Suspension feeding
Pacific Oyster ADULT *(C. gigas)* - smaller size	Suspension feeding
Pacific Oyster ADULT *(C. gigas)* - larger size	Suspension feeding
Tunicate *(Oikopleura dioica)*	Water pumping
Silver Carp *(Hypophthalmichthys molitrix* Val.)	Water pumping
Manta Ray *(Manta birostis)*	Ram Filtration
Pelagic Tunicate *(Pegea confederata)*	Water pumping
Fin whales (*Balaenoptera physalus)*	Lunge feeding
Glass sponge *(Aphrocallistes vastus)*	Suspension feeding
Cockle *(Cardium edule)*	Suspension feeding
Soft-shell clam *(Mya arenia)*	Suspension feeding
Atlantic menhaden *(Brevoortis tyrannus)*	Ram Filtration
Mysid shrimp (Rhopalophthalmus terranatalis) ADULTS	Suspension feeding
Mysid shrimp (Rhopalophthalmus terranatalis) JUVENILES	Suspension feeding
Mysid shrimp (Mesopodopsis wooldridgei) ADULTS	Suspension feeding
Mysid shrimp (Mesopodopsis wooldridgei) JUVENILES	Suspension feeding
Burrowing shrimp *(Upogebia deltaura)*	Suspension feeding
Antarctic Krill *(Euphausia superba)*	Suspension feeding
Porcelain Crab *(Porcellana longicornis)*	Suspension feeding
Ocean Quahog *(Arctica islandica)*	Suspension feeding
Wrinkled Rockborer *(Hiatella arctica)*	Suspension feeding
Bay Scallop *(Pecten irradians)*	Suspension feeding
Ornage Sea Pen *(Ptilosarcus gurneyi)*	Suspension feeding
Feather star *(Oligometra serripinna)*	Suspension feeding
Manila Clam *(Tapes philippinarum)*	Suspension feeding
Yesso scallop (*Patinopecten yessoensis)*	Suspension feeding
Spaghetti Bryozoan *(Zoobotryon verticillatum)*	Suspension feeding
Bryozoan *(Electra pylosa)*	Suspension feeding
Bryozoan *(Conopeum reticulum)*	Suspension feeding

Bryozoan *(Celleporella hyalina)*	Suspension feeding
Sea vase *(Ciona intestinalis)*	Suspension feeding
Sea squirt *(Ascidella aspersa)*	Suspension feeding
Polychaete worm *(Myxicola infundibulum)*	Suspension feeding
Peacock worm *(Sabella pavonina)*	Suspension feeding
Keel worm *(Pomatoceros triqueter)*	Suspension feeding
Polychaete worm *(Hydroides norvegica)*	Suspension feeding
Sinistral spiral tubeworm *(Spirorbis borealis)*	Suspension feeding
Polychaete worm *(Salmacina dysteri)*	Suspension feeding
Breadcrumb sponge *(Halichondria panicea)*	Suspension feeding
Common Bream *(Abramis brama)*	Ram or Suction
White Bream *(Blicca bjoerkna)*	Ram or Suction
Roach *(Rutilus rutilus)*	Ram or Suction
Gizzard shad *(Dorosoma cepedianum)*	Ram or Suction
North Atlantic Right Whale *(Eubalaena glacialis)*	Ram Filtration

In assessing the effect of filtration technique on Microplastic Consumption Rates, significant differences occurred in MCR values at the different levels of filtration technique. ($p = 2.015e\text{-}08$, $\chi^2 = 38.694$, df = 3, Kruskal-Wallis test This is likely due to the tendency that such species, including whales, are often much larger than other filter feeders and can therefore filter far greater quantities of particulates from water (Figure 10).

Furthermore, a post-hoc analysis (Multiple Comparisons) determined that species using lunge and ram filtration techniques had significantly higher MCR values than the others. Species that relied on water pumping and ram filtration were not significantly different from each other, while those that relied on suspension feeding and water pumping were had significantly lower MCR values than the techniques.

However, the results appeared to change when taking bodyweight into account. No significant differences occurred in NMCR values between filtration techniques ($p = 0.185$, $\chi2=4.83$, df=3, Kruskal-Wallis ANOVA). Thus, the different filtration techniques used by filter feeders are not associated with higher risks of microplastic contamination (Figure 11).

The filter feeding species were also further separated into groups based on their filtration techniques to determine which species of each category faced the greatest risks. When bodyweight was not taken into account, this analysis showed that of the lunge feeding species, fin whales experience the highest MCR values, while blue whales *(B. musculus*) experienced the lowest MCR values (Figure 12). Taking bodyweight into consideration did not cause any change to this result in regards to NMCR values (Figure 13). Of the water pumping filter feeders, blue mussels (*M. edulis*) had the highest MCR values but copepods (*C. finmarchicus*) had the lowest MCR values when bodyweight was not considered (Figure 14). When considering bodyweight, however, the pelagic tunicate *(P. confederata*) had the highest NMCR values, while the silver carp (*H. molitrix*) had the lowest NMCR values (Figure 15). Of ram filter feeders, the North Atlantic right whale (*E. glacialis*) had the highest MCR values, while the white bream (*B. bjoerkna*) had the lowest MCR values (Figure 16). When taking bodyweight into account, the North Atlantic right whale still has the highest NMCR values, but the common bream (*A. brama*) has the lowest NMCR values (Figure 17). Finally, among suspension feeders, the orange sea pen (*P. gurneyi*) had the highest MCR values but Pacific oyster larvae (*C. gigas*) had the lowest MCR values when bodyweight was not considered (Figure 18). When organism size was considered, the feather star (*O. serripinna*) had the highest NMCR values but the bryozoan (*E. pylosa*) had the lowest NMCR values (Figure 19). While this analysis provides new insight into the filtration technique categories, it was not possible to test for significant differences because only one data point existed for each species.

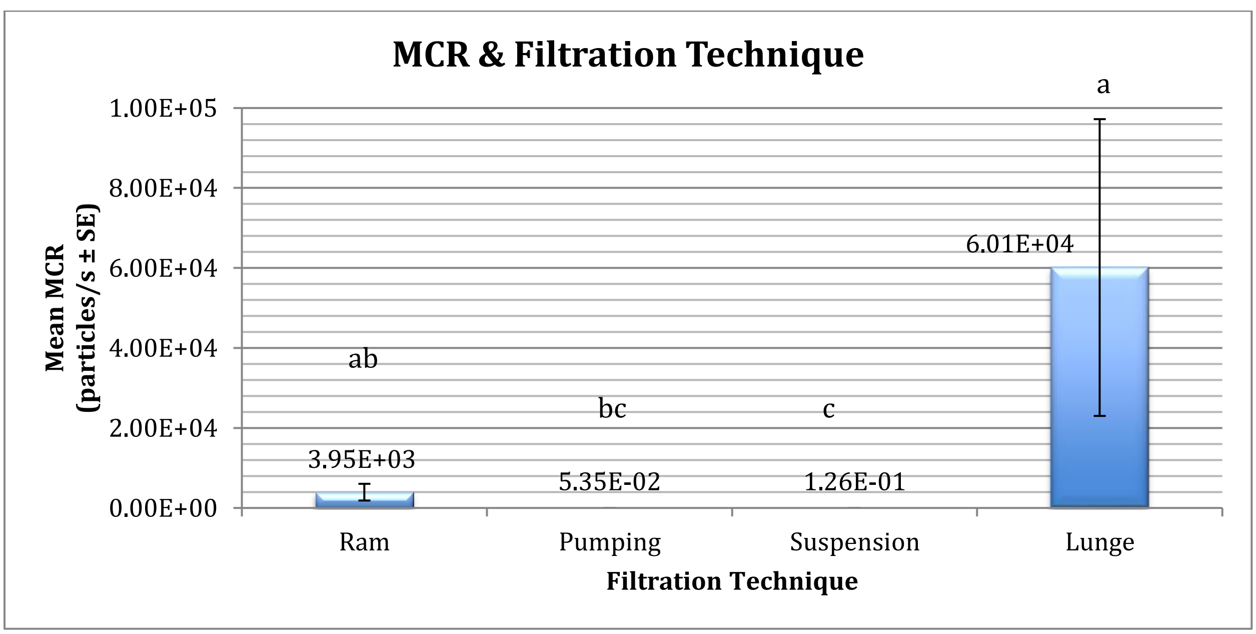

Figure 10. Calculated MCR (particles/s ± SE) for each of the four types of filtration technique: lunge feeding, water pumping, ram filtration, and suspension feeding.

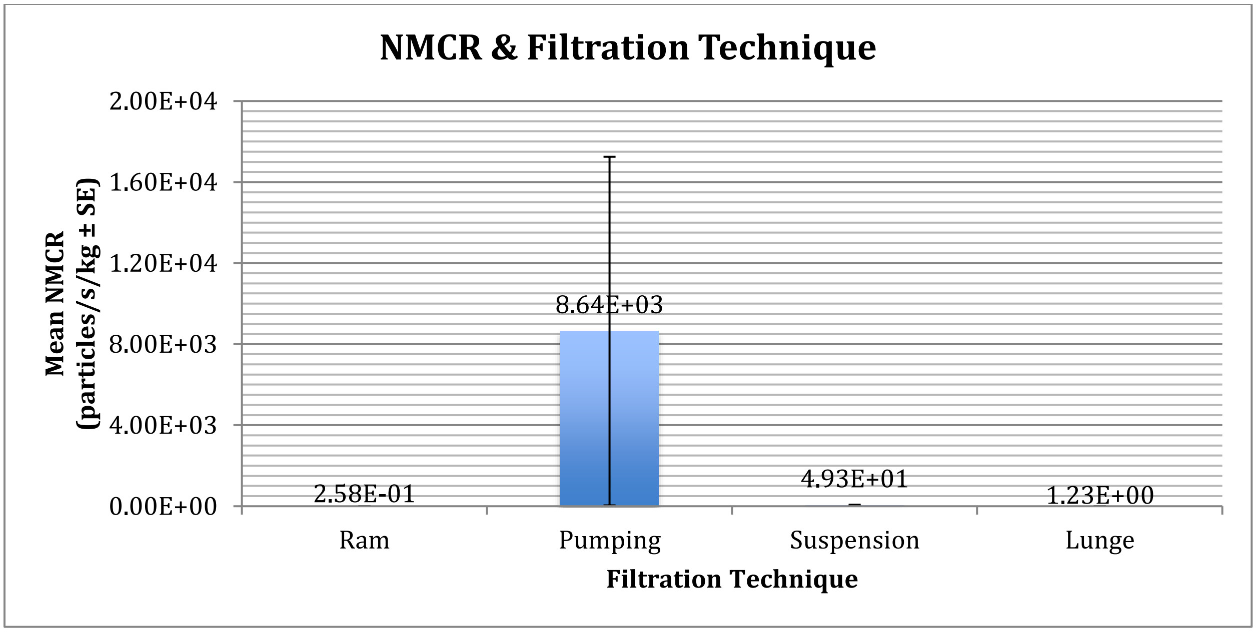

Figure 11. Calculated NMCR (particles/s/kg ± SE) for each of the four types of filtration technique: lunge feeding, water pumping, ram filtration, and suspension feeding.

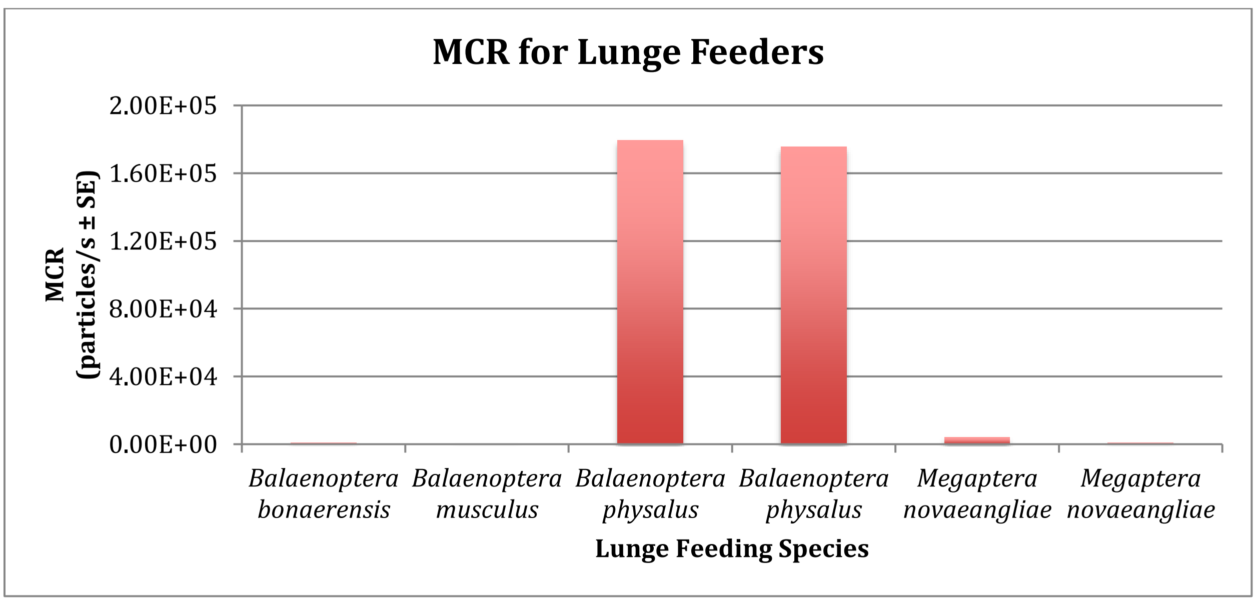

Figure 12. Calculated MCR (particles/s ± SE) for lunge feeders. Multiple columns indicate data at different geographic locations for a single species, as described in Table 8.

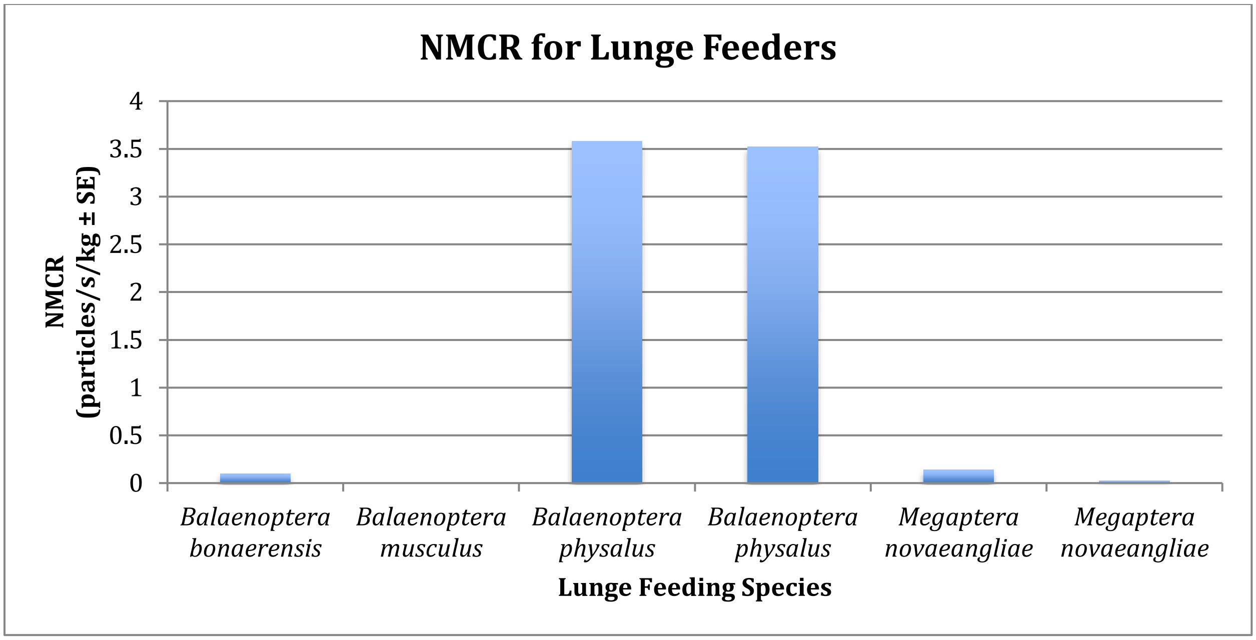

Figure 13. Calculated NMCR (particles/s/kg ± SE) for lunge feeders. Multiple columns indicate data at different geographic locations for a single species, as described in Table 8.

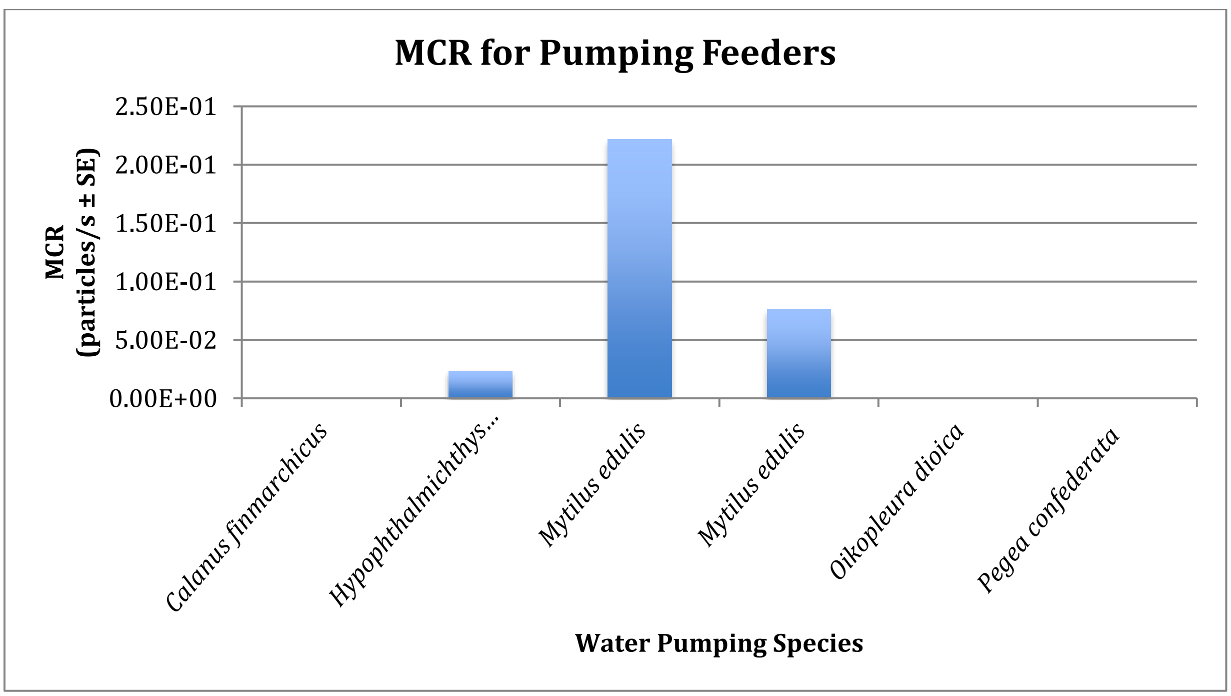

Figure 14. Calculated MCR (particles/s ± SE) for pumping feeders. Multiple columns indicate data at different geographic locations for a single species, as described in Table 8.

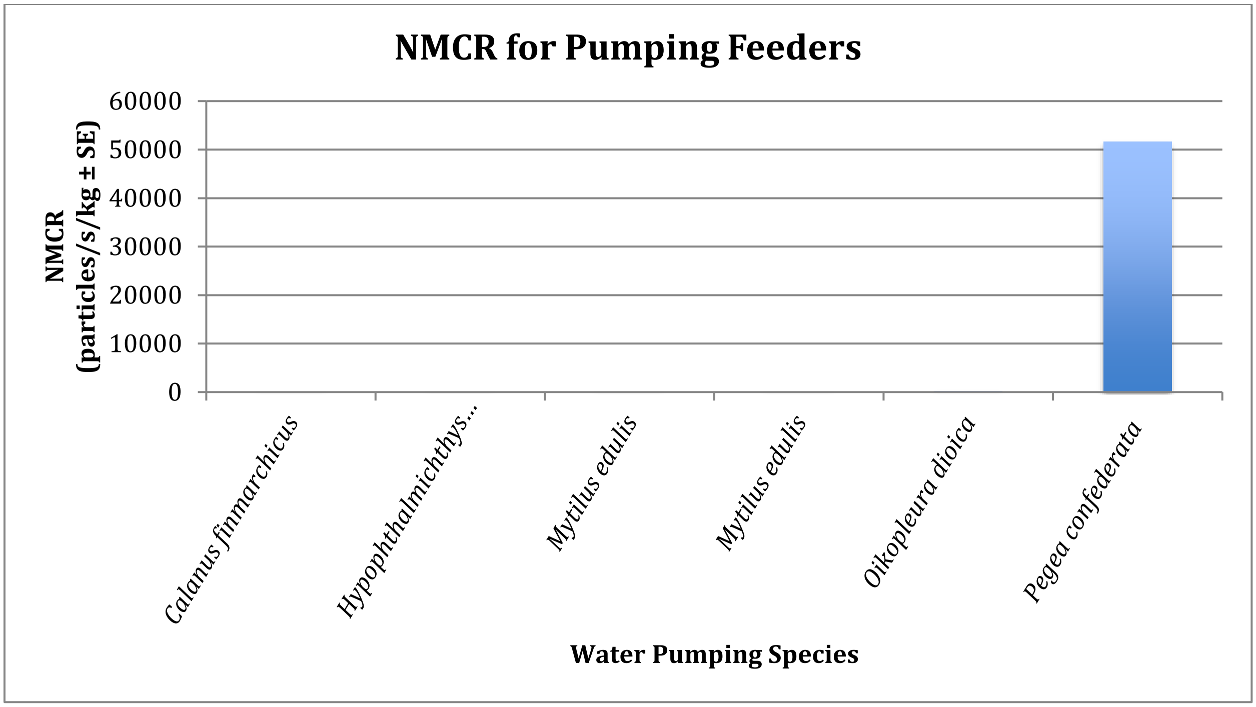

Figure 15. Calculated NMCR (particles/s/kg ± SE) for pumping feeders. Multiple columns indicate data at different geographic locations for a single species, as described in Table 8.

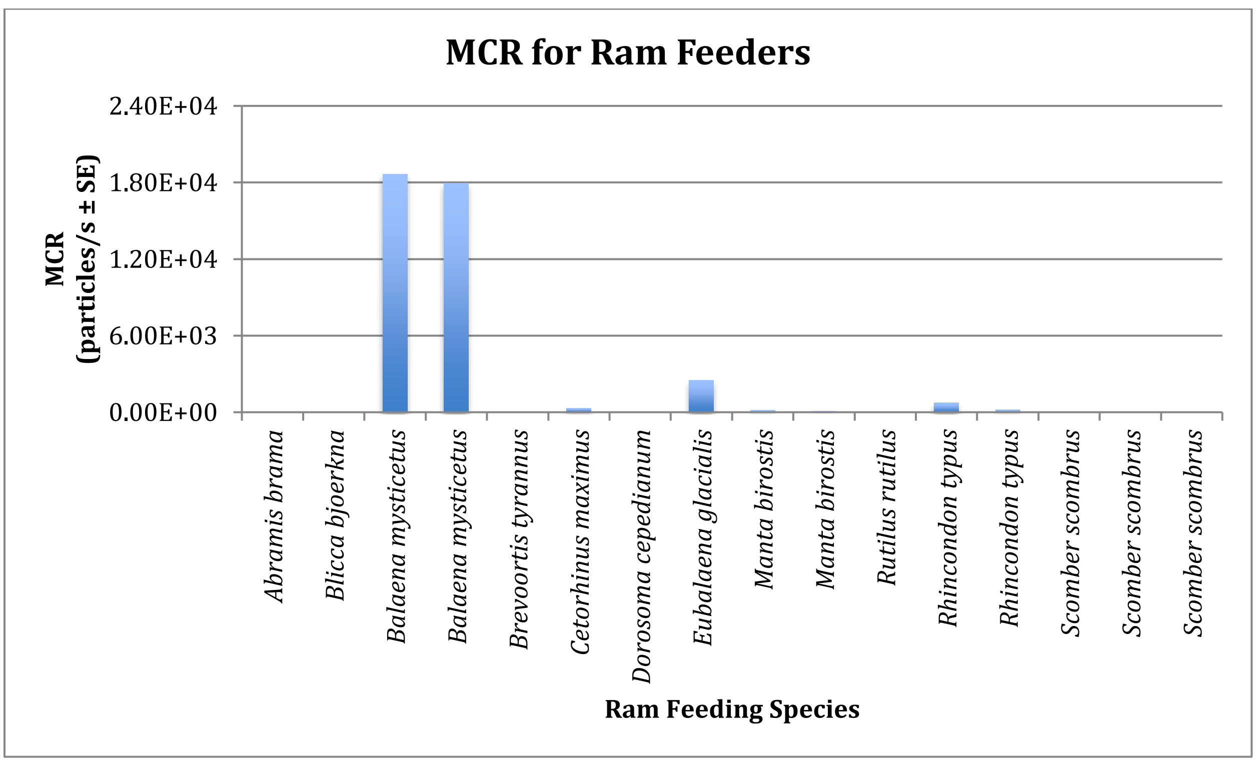

Figure 16. Calculated MCR (particles/s ± SE) for ram feeders. Multiple columns indicate data at different geographic locations for a single species, as described in Table 8.

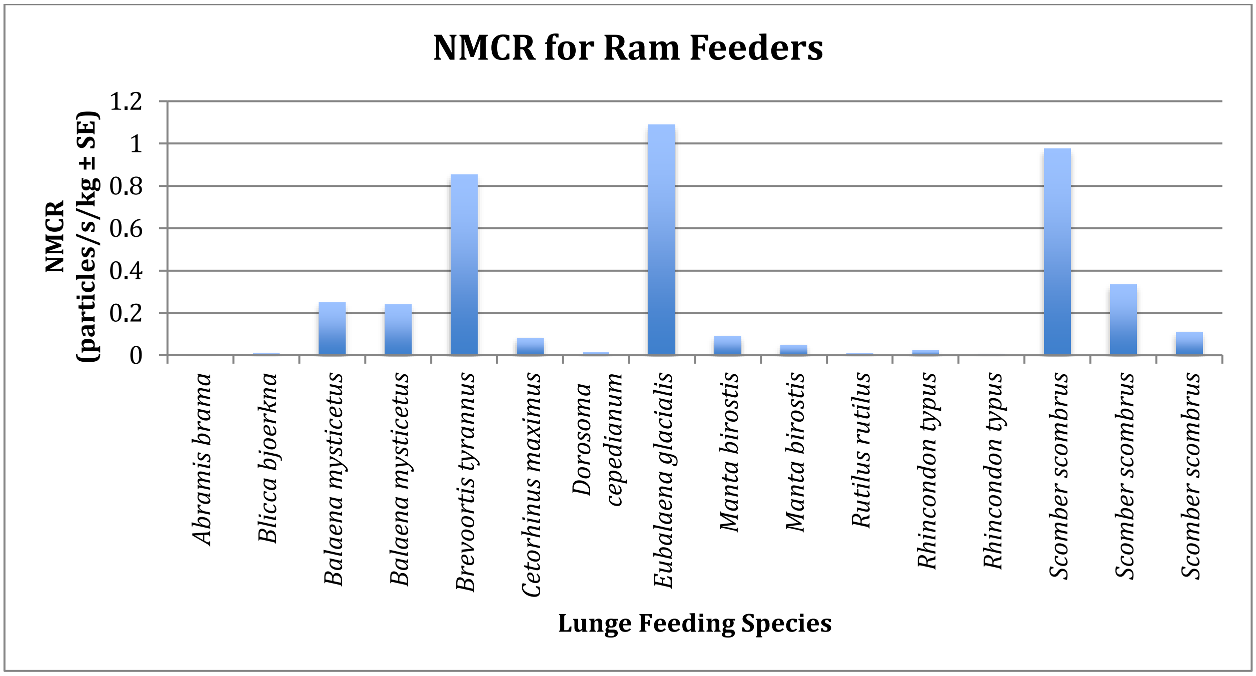

Figure 17. Calculated NMCR (particles/s/kg ± SE) for ram feeders. Multiple columns indicate data at different geographic locations for a single species, as described in Table 8.

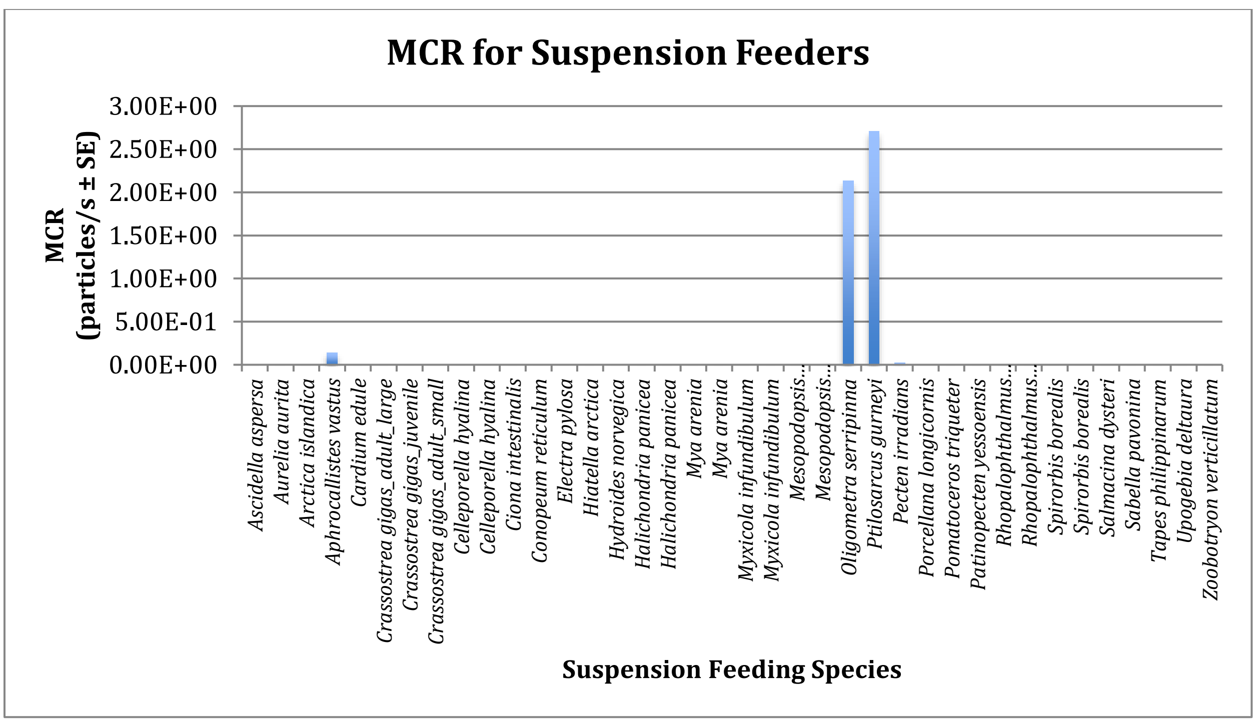

Figure 18. Calculated MCR (particles/s ± SE) for suspension feeders. Multiple columns indicate data at different geographic locations for a single species, as described in Table 8.

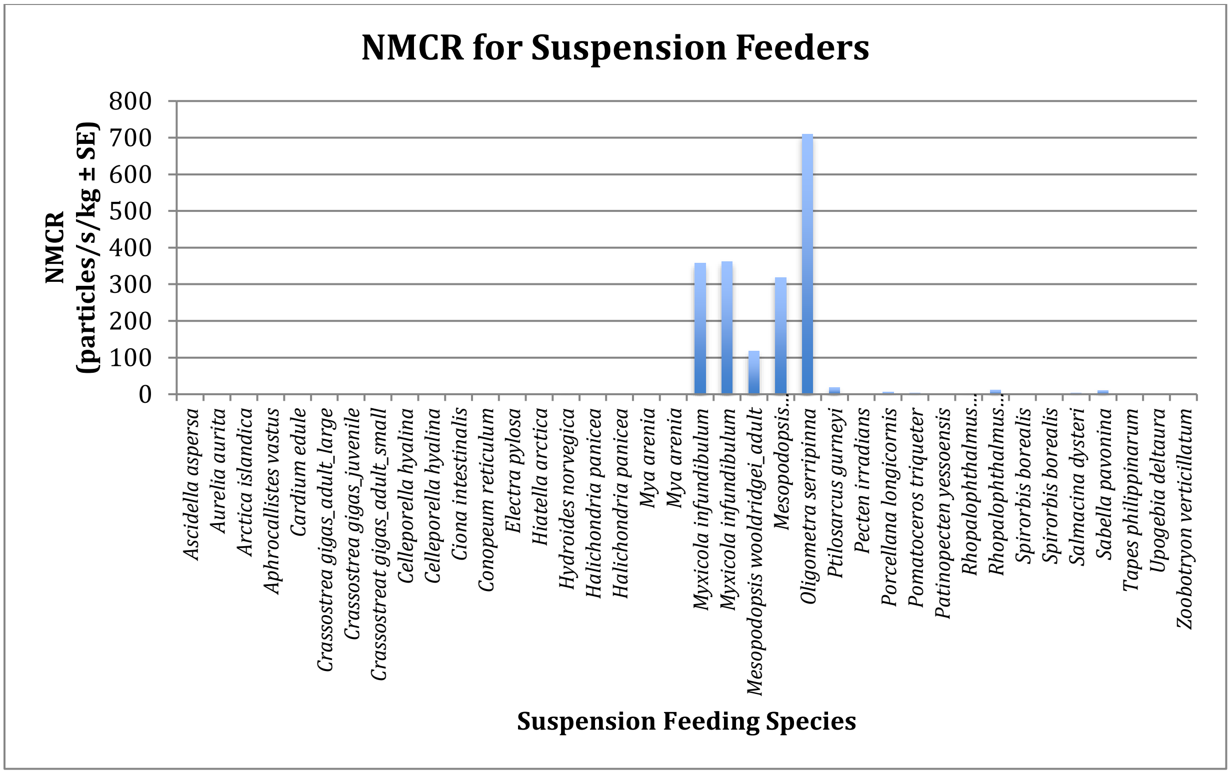

Figure 19. Calculated NMCR (particles/s/kg ± SE) for suspension feeders. Multiple columns indicate data at different geographic locations for a single species, as described in Table 8.

d. Life Stage

Filtration rates of three species were also considered at different life stages, as either Adults or Juveniles. Only data for species that included filtration rates at both life stages were considered in the review (Table 7). These were the blue mussel, *Crassostrea gigas,* and two species of mysid shrimp, *Rhopalophthalmus terranatalis* and *Mesopodopsis wooldridgei* (Wildish et al. 1990, Riisgard et al. 2002, Jerling & Wooldridge 1994).

Table 7. *The life stages (Adult or Juvenile) at which they each of the three species were considered and their MCR (particles/s)*

Species	LifeStage	Mean Microplastic Consumption Rate (particles/s)
Blue mussel (*Crassostrea gigas)*	Juvenile	1.51E-09
Blue mussel (*Crassostrea gigas) – small size*	Adult	1.18E-04
Blue mussel (*Crassostrea gigas) – large size*	Adult	3.14E-04
Mysid shrimp *(Rhopalophthalmus terranatalis)*	Adult	2.36E-03
Mysid shrimp *(Rhopalophthalmus terranatalis)*	Juvenile	3.75E-03
Mysid shrimp *(Mesopodopsis wooldridgei)*	Adult	9.50E-03
Mysid shrimp *(Mesopodopsis wooldridgei)*	Juvenile	5.17E-03

Life stage was assessed to have no significant relationship with microplastic consumption rates ($p = 0.2209$, $t = 1.5382$, Welch two-sample t-test). The adult group has a higher mean MCR (Figure 20), though the difference is not significant. This difference likely occurs because only a few species were considered at both life stages, constricting the sample size. It might also occur as a result of the juveniles being less efficient at water filtration.

Similarly, significant differences still did not occur in NMCR values between the life stages when bodyweight was taken into account ($p = 0.336$, $t = 1.06$, $df = 4.997$, two-tailed two-sample t-test). This result suggests both adults and juveniles organisms experience equal risks of microplastic contamination (Figure 21).

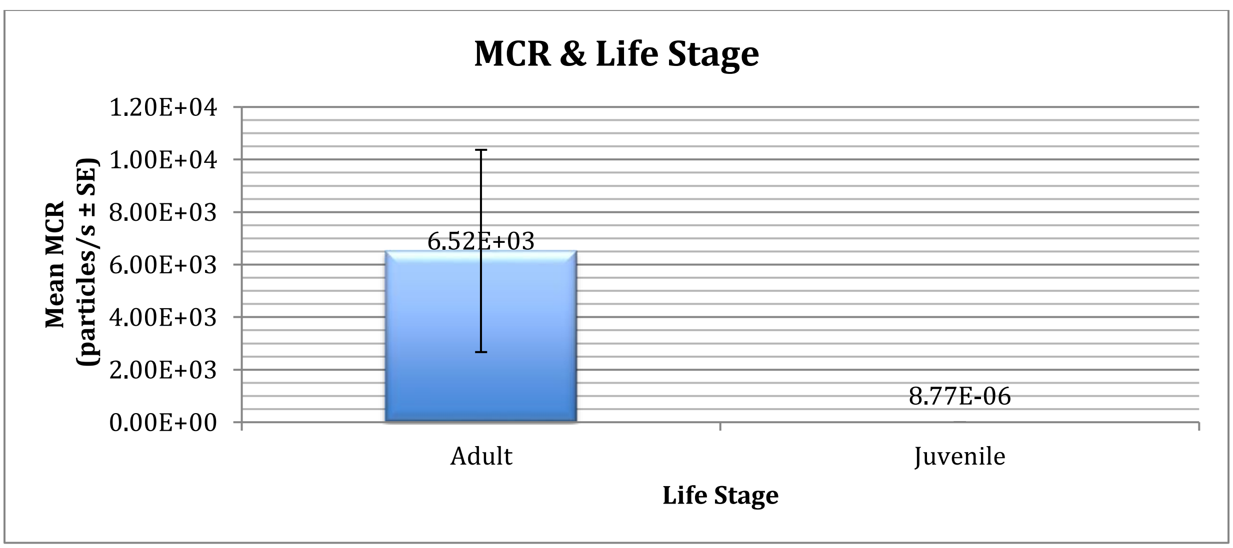

Figure 20. The calculated MCR value (particles/s ± SE) at both types of life stages, Adult or Juvenile.

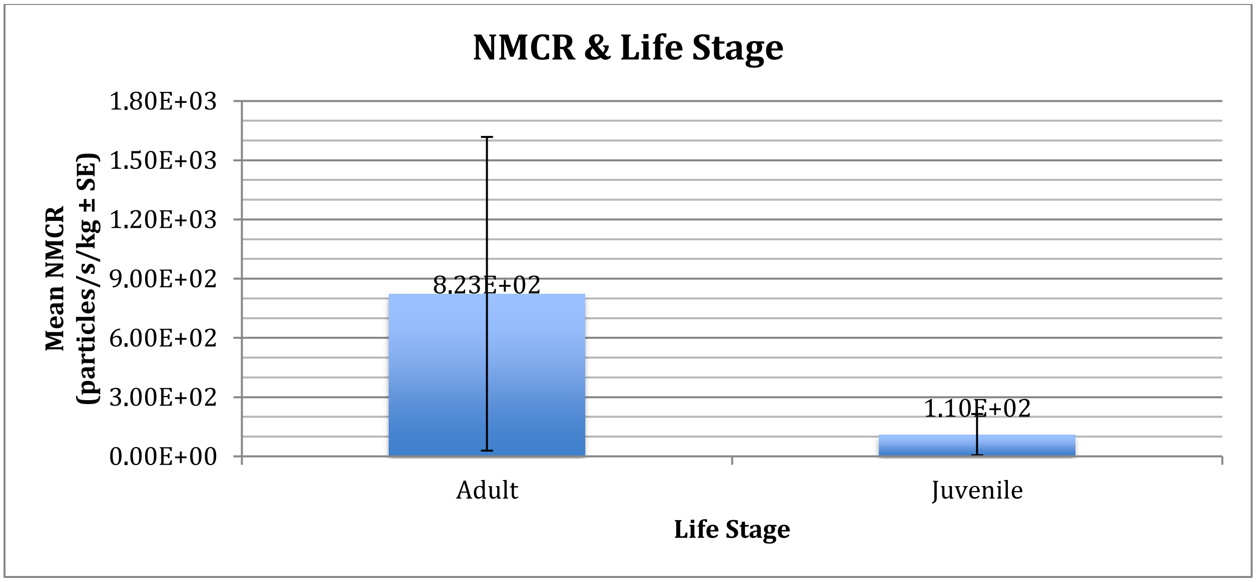

Figure 21. The calculated NMCR value (particles/s/kg ± SE) at both types of life stages, Adult or Juvenile.

e. Ocean Basin

Locations were generalized so that filter feeders could be placed into one of several categories (Table 8): Pacific, Central America, Coastal (PCC); Pacific, West, Coastal (PWC); Pacific, East, Coastal (PEC); Pacific, Southeast Alaska, Coastal (PSAC); Pacific, Southeast Asia, Coastal (PSC); Pacific, Open Ocean (PO); Pacific, Gulf of Alaska, Coastal (PGC); Atlantic, Northwest, Coastal (ANWC); Atlantic, Northeast, Coastal (ANEC); Atlantic, Open Ocean (AO); Atlantic, Mediterranean, Coastal (AMC); Atlantic, Caribbean, Coastal (ACC); Atlantic, South, Coastal (ASC); Southern, Open Ocean (SO); Indian, Coastal (IC); Arctic, Coastal (AC); Freshwater, Asia (FA); Freshwater, Europe (FE); and Freshwater, North America (FNA).

Some species required than one category, particularly for those that are globally distributed. For example, the whale shark is commonly found in PCC waters as well as PWC waters; blue mussels can be found in ANWC waters and in ANEC waters; bowhead whales are found in ANWC and PSAC waters; humpback whales are found in ANWC and PWC locations; Atlantic mackerel can be found in ANWC, ANEC, and AMC waters; manta rays are found in ACC and PSC locations; fin whales are located in PO and AO waters; soft-shell clams are located in ANWC and ANEC waters; bryozoans *(Celleporella hyaline)* are generally found in ANWC and PEC waters; polychaete worms *(Myxicola infundibulum)* are found in AO and PO waters; keel worms are in ANEC and AC waters; sinistral spinal tubeworms are found in ANEC and PEC locations; and, finally, breadcrumb sponges have been documented in ANEC and PWC waters.

Table 8. *Estimated geographic distribution and sampling locations (indicating ocean basin and environment) for each species. Cross-referenced with the microplastic abundance data to be used in calculation of MCR.*

Species	**Estimated Geographic Distribution (Microplastic Abundance Sample Locations)**	**Ocean Basin**	**Environment**
Whale Shark *(Rhincondon typus)*	Pacific, Central America, Coastal	Pacific	Coastal
Whale Shark *(Rhincondon typus)*	Pacific, West, Coastal	Pacific	Coastal
Basking Shark *(Cetorhinus maximus)*	Pacific, East, Coastal	Pacific	Coastal
Blue mussels *(Mytilus edulis)*	Atlantic, NW, Coastal	Atlantic	Coastal
Blue mussels *(Mytilus edulis)*	Atlantic, NE, Coastal	Atlantic	Coastal
Jellyfish *(Aurelia aurita)*	Atlantic, NW, Coastal	Atlantic	Coastal
Bowhead whales *(Balaena mysticetus)*	Atlantic, NW, Coastal	Atlantic	Coastal
Bowhead whales *(Balaena mysticetus)*	Pacific, SE Alaska, Coastal	Pacific	Coastal
Humpback whale *(Megaptera novaeangliae)*	Atlantic, NW, Coastal	Atlantic	Coastal
Humpback whale *(Megaptera novaeangliae)*	Pacific, West, Coastal	Pacific	Coastal
Blue whales *(Balaenoptera musculus)*	Pacific, East, Coastal	Pacific	Coastal
Copepod *(Calanus finmarchicus)*	Atlantic Open Ocean (surface)	Atlantic	Open Ocean
Atlantic mackerel *(Scomber scombrus)*	Atlantic, NW, Coastal	Atlantic	Coastal
Atlantic mackerel *(Scomber scombrus)*	Atlantic, NE, Coastal	Atlantic	Coastal
Atlantic mackerel *(Scomber scombrus)*	Atlantic, Mediterranean, Coastal	Atlantic	Coastal
Antarctic minke whale *(Balaenoptera bonaerensis)*	Southern, Open Ocean	Southern	Open Ocean

Pacific Oyster JUVENILES *(Crassostrea gigas)*	Pacific, West, Coastal	Pacific	Coastal
Pacific Oyster ADULT *(C. gigas)* - smaller size	Pacific, West, Coastal	Pacific	Coastal
Pacific Oyster ADULT *(C. gigas)* - larger size	Pacific, West, Coastal	Pacific	Coastal
Tunicate *(Oikopleura dioica)*	Atlantic, NE, Coastal	Atlantic	Coastal
Silver Carp *(Hypophthalmichthys molitrix*)	Freshwater, Asia	Freshwater	Coastal
Manta Ray *(Manta birostis)*	Atlantic, Caribbean, Coastal	Atlantic	Coastal
Manta Ray *(Manta birostis)*	Pacific, SE Asia, Coastal	Pacific	Coastal
Pelagic Tunicate *(Pegea confederata)*	Atlantic, NE, Coastal	Atlantic	Coastal
Fin whales (*Balaenoptera physalus)*	Pacific Open Ocean	Pacific	Open Ocean
Fin whales (*Balaenoptera physalus)*	Atlantic, Open Ocean	Atlantic	Open Ocean
Glass sponge *(Aphrocallistes vastus)*	Pacific, Gulf of Alaska, Coastal	Pacific	Coastal
Cockle *(Cardium edule)*	Atlantic, NE, Coastal	Atlantic	Coastal
Soft-shell clam *(Mya arenia)*	Atlantic, NW, Coastal	Atlantic	Coastal
Soft-shell clam *(Mya arenia)*	Atlantic, NE, Coastal	Atlantic	Coastal
Atlantic menhaden *(Brevoortis tyrannus)*	Atlantic, NW, Coastal	Atlantic	Coastal
Mysid shrimp *(Rhopalophthalmus terranatalis) ADULTS*	Indian, Coastal	Indian	Coastal
Mysid shrimp *(Rhopalophthalmus terranatalis)* JUVENILES	Indian, Coastal	Indian	Coastal
Mysid shrimp (*Mesopodopsis wooldridgei) ADULTS*	Indian, Coastal	Indian	Coastal
Mysid shrimp *(Mesopodopsis wooldridgei)* JUVENILES	Indian, Coastal	Indian	Coastal
Burrowing shrimp *(Upogebia deltaura)*	Atlantic, Mediterranean, Coastal	Atlantic	Coastal
Antarctic Krill *(Euphausia superba)*	Southern, Coastal	Southern	Coastal
Porcelain Crab *(Porcellana longicornis)*	Atlantic, NE, Coastal	Atlantic	Coastal
Ocean Quahog *(Arctica islandica)*	Atlantic, NW, Coastal	Atlantic	Coastal
Wrinkled Rockborer *(Hiatella arctica)*	Atlantic, South, Coastal	Atlantic	Coastal

Bay Scallop *(Pecten irradians)*	Atlantic, NW, Coastal	Atlantic	Coastal
Orange Sea Pen *(Ptilosarcus gurneyi)*	Pacific, East, Coastal	Pacific	Coastal
Feather star *(Oligometra serripinna)*	Pacific, SE Asia, Coastal	Pacific	Coastal
Manila Clam *(Tapes philippinarum)*	Indian, Coastal	Indian	Coastal
Yesso scallop (*Patinopecten yessoensis)*	Pacific, West, Coastal	Pacific	Coastal
Spaghetti Bryozoan *(Zoobotryon verticillatum)*	Atlantic, Caribbean, Coastal	Atlantic	Coastal
Bryozoan *(Electra pylosa)*	Pacific, West, Coastal	Pacific	Coastal
Bryozoan *(Conopeum reticulum)*	Atlantic, NE, Coastal	Atlantic	Coastal
Bryozoan *(Celleporella hyalina)*	Atlantic, NW, Coastal	Atlantic	Coastal
Bryozoan *(Celleporella hyalina)*	Pacific, East, Coastal	Pacific	Coastal
Sea vase *(Ciona intestinalis)*	Atlantic, Open Ocean	Atlantic	Open Ocean
Sea squirt *(Ascidella aspersa)*	Atlantic, NE, Coastal	Atlantic	Coastal
Polychaete worm *(Myxicola infundibulum)*	Atlantic, Open Ocean	Atlantic	Open Ocean
Polychaete worm *(Myxicola infundibulum)*	Pacific Open Ocean	Pacific	Open Ocean
Peacock worm *(Sabella pavonina)*	Atlantic, Mediterranean, Coastal	Atlantic	Coastal
Keel worm *(Pomatoceros triqueter)*	Atlantic, NE, Coastal	Atlantic	Coastal
Keel worm *(Pomatoceros triqueter)*	Arctic, Coastal	Arctic	Coastal
Polychaete worm *(Hydroides norvegica)*	Atlantic, Mediterranean, Coastal	Atlantic	Coastal
Sinistral spiral tubeworm *(Spirorbis borealis)*	Atlantic, NE, Coastal	Atlantic	Coastal
Sinistral spiral tubeworm *(Spirorbis borealis)*	Pacific, East, Coastal	Pacific	Coastal
Polychaete worm *(Salmacina dysteri)*	Pacific Open Ocean	Pacific	Open Ocean
Breadcrumb sponge *(Halichondria panicea)*	Atlantic, NE, Coastal	Atlantic	Coastal
Breadcrumb sponge *(Halichondria panicea)*	Pacific, West, Coastal	Pacific	Coastal
Common Bream *(Abramis brama)*	Freshwater, Europe	Freshwater	Coastal

White Bream *(Blicca bjoerkna)*	Freshwater, Europe	Freshwater	Coastal
Roach *(Rutilus rutilus)*	Freshwater, Europe	Freshwater	Coastal
Gizzard shad *(Dorosoma cepedianum)*	Freshwater, North America	Freshwater	Coastal
North Atlantic Right Whale *(Eubalaena glacialis)*	Atlantic, Open Ocean	Atlantic	Open Ocean

No significant difference in microplastic consumption rates was found among species feeding in the different ocean basins ($p = 0.1512$, $\chi^2 = 0.5$, df = 1, Kruskal-Wallis test). Although no significant difference occurs, species feeding in the Pacific Ocean had the highest mean microplastic consumption rates compared to other ocean basins (Figure 14). Those feeding in freshwater, the Indian Ocean, and Arctic Ocean had the lowest mean microplastic consumption rates (Figure 22).

When considering how bodyweight might affect these results, the analysis showed that still no significant differences occurred in NMCR values at the different ocean basins ($p = 0.09$, $F_{5,62}=2.01$, Kruskal-Wallis Test). Thus, it can be concluded that the ocean basin is not associated with higher risks of microplastic contamination in different filter feeders (Figure 23).

Additionally, both ocean basin and filtration technique were further tested to determine if any interactions between these two variables significantly affected MCR or NMCR values. Analysis showed that when bodyweight was not considered, no significant interactions occurred between ocean basin and filtration technique to affect MCR values ($p = 0.1$, $F_{10,55}=4.0$, Kruskal-Wallis Test). When bodyweight was taken into consideration, the analysis determined that significant interactions still did not occur between the two variables to affect MCR values ($p = 0.967$, $F_{10,55}=4.0$, Kruskal-Wallis Test).

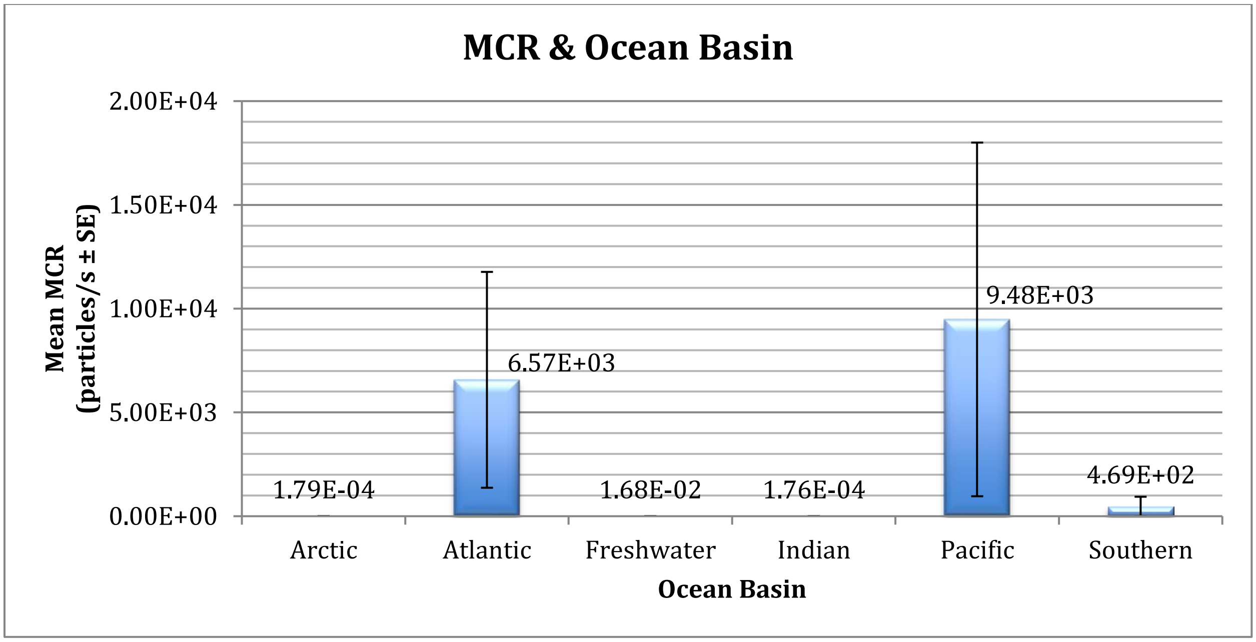

Figure 22. Calculated MCR value (particles/s ± SE) for the six different ocean basins/water sources: Arctic, Atlantic, Freshwater, Indian, Pacific, Southern.

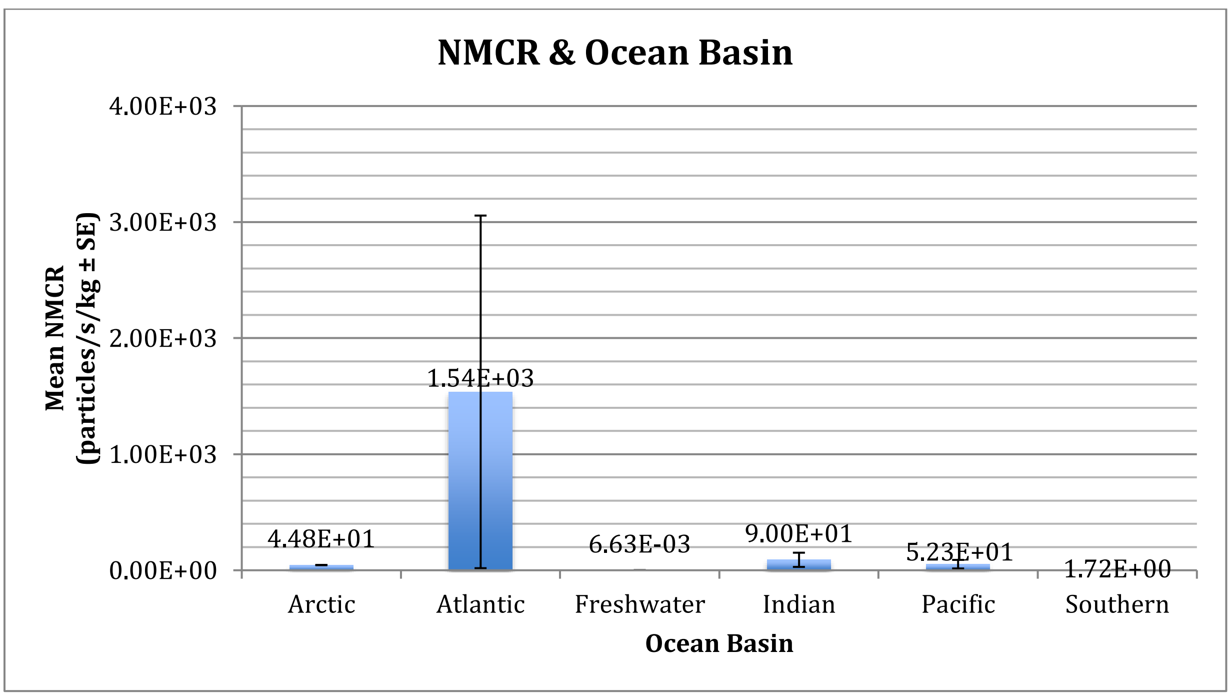

Figure 23. Calculated NMCR value (particles/s/kg ± SE) for the six different ocean basins/water sources: Arctic, Atlantic, Freshwater, Indian, Pacific, Southern.

f. Environment

Each species was determined to feed in one of two types of environment: coastal or open ocean (Table 8). Analysis showed that the different environments do not have significant differences in regards to MCR for study species ($p = 0.173$, $t = -1.48$, Welch two sample t-test). Despite the lack of a significant difference, species in the open ocean had a higher mean MCR compared to those in the coastal areas (Figure 24), which supports similar values found in previous studies (Barrows et al. 2018).

Additional analysis considered bodyweight and showed that no significant differences in NMCR values occurred at the different environments ($p = 0.173$, $t = -1.48$, two-tailed two sample t-test). This result suggests that filter feeders in either environment experience equal risks of microplastic contamination (Figure 25).

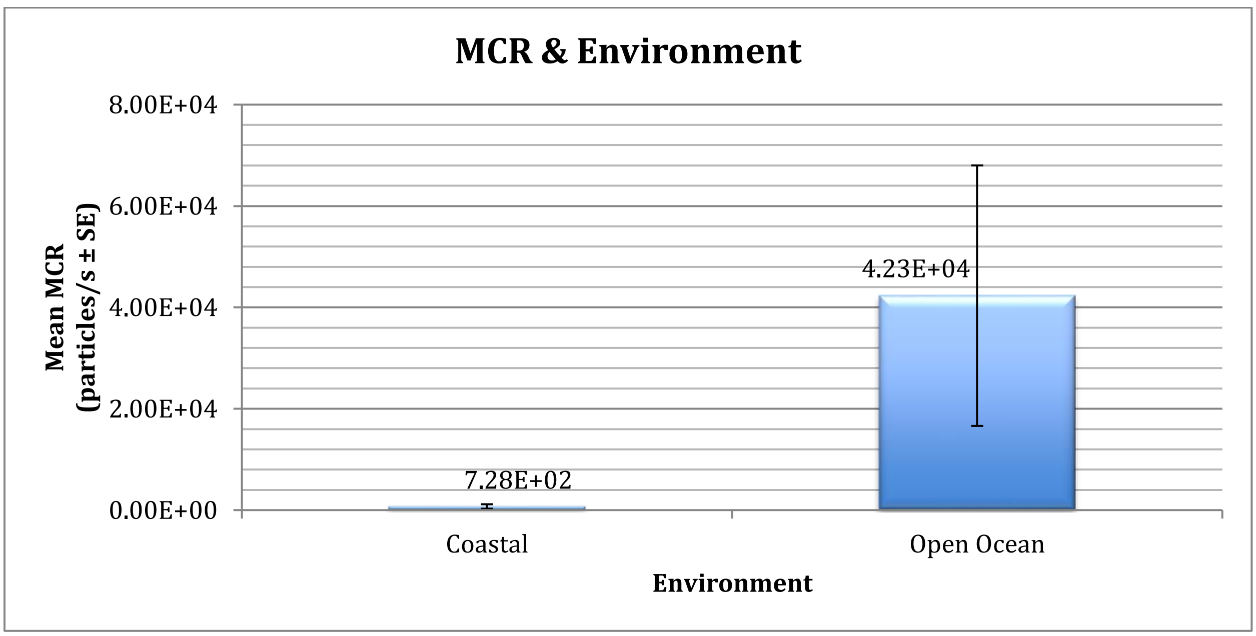

Figure 24. Calculated MCR (particles/s ± SE) for each environment, coastal or open ocean.

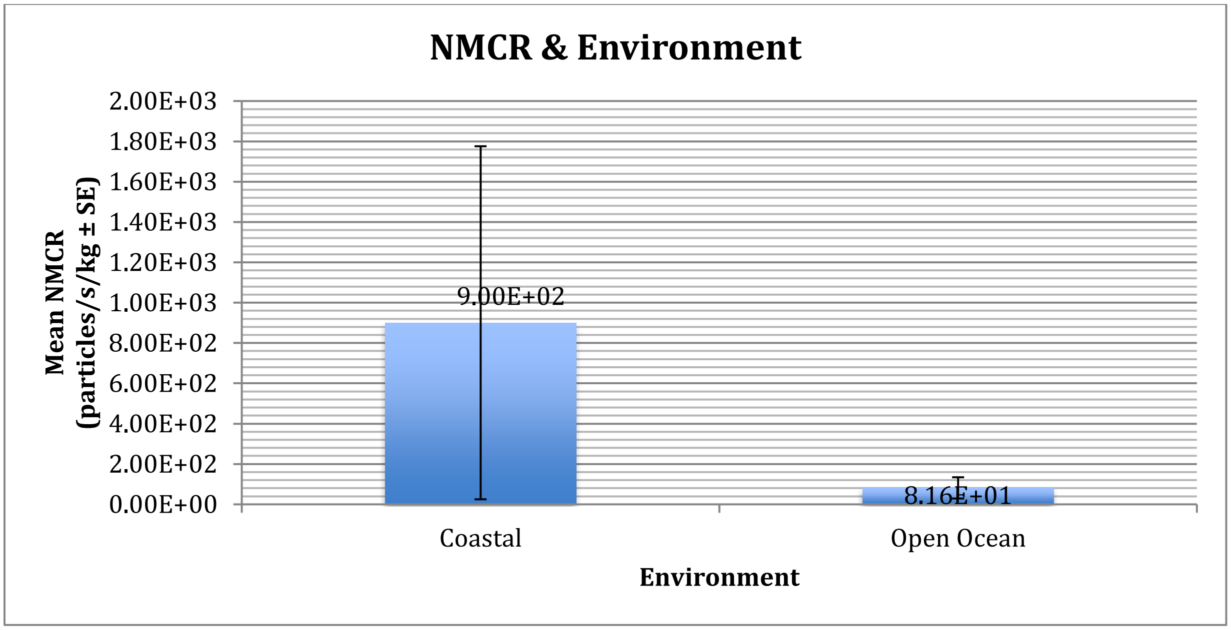

Figure 25. Calculated NMCR (particles/s/kg ± SE) for each environment, coastal or open ocean.

V. Summary and Conclusions

Overall Risk Assessment

This study estimated the quantity of microplastics likely consumed by filter feeders and analyzed the factors that affected that statistic. When bodyweight was not taken into account, it was found that fin whales *(Balaenoptera physalus)* consume the highest mean quantity of microplastics per second of feeding. Given that this species can consume 10 kilograms of krill in 70,000 liters of water, this conclusion is well supported in the literature (Goldbogen et al. 2010). Relying on lunge techniques, feeding among rorqual whales (Balaenopteridae) is energetically costly (Goldbogen et al. 2008, Goldbogen et al. 2011) and inadvertently consuming microplastic particulates could potentially take a major toll on even these massive organisms. The larger species are also at risk of consuming other types of debris, including macroplastics, which could potentially block the digestive system if consumed. Globally, fin whale populations are on the rise. They are no longer considered endangered, but are still labeled as vulnerable on the IUCN Red List (2019). Although this provides a better outlook than their estimated MCR values might suggest, caution must be taken to ensure that these organisms are exposed to plastics as minimally as possible.

Pacific oyster larvae *(Crassostrea gigas)* and bryozoans *(Electra pylosa),* on the other hand, consumed the lowest mean quantity of microplastics per second of feeding when bodyweight was not considered. Unfortunately, neither of these species is evaluated by the IUCN (2019) and it is difficult to infer how microplastics might affect their overall population. Yet, their comparatively small MCR indicates that they likely experience lesser risk of microplastic consumption compared with most other filter feeding species, including fin whales. Similar to other species, feeding in *E. pilosa* and other bryozoans is expected to incur some energetic costs, as the organisms actively filter with the use of a mechanical laterofrontalfilter (Riisgard & Manriquez 1997). It is possible that some inorganic particles may be filtered out post-capture by these species, but more research is required to determine if they are actually capable of removing any sediment or debris as has been previously described (Riisgard & Manriquez, 1997).

The factors found to have significant differences in mean MCR values were IUCN Red List status and filtration technique. The species with higher levels of vulnerability according to the IUCN Red List statuses (i.e. vulnerable and endangered species) had higher mean Microplastic Consumption Rates compared to those that were not evaluated or threatened. Species that had not yet been evaluated tended to be small and widely distributed, including crabs, scallops, bryozoans, sea worms, tunicates, and copepods (IUCN 2019). Such organisms are generally incapable of filtering massive quantities of particulates from the water regardless of the microplastic abundance in their location. This result can be beneficial to resource managers IUCN could potentially be used as a predictor, as it shows that vulnerable species are more likely to consume higher quantities of microplastics over time. Effective strategies, then, could be implemented to protect these species. It is important to note, however, that reasonable biological characteristics must be met to use this factor as a predictor for specific species. The variable has only been considered in terms of marine filter feeding species and thus, conclusions should only be drawn for similar organisms.

Species that filter water with lunge feeding techniques, such as humpback whales and bowhead whales, had significantly higher mean MCR values compared with those that rely on other techniques, like suspension feeding or water pumping. Lunge feeding is energetically expensive and, as such, it is a method frequently used by larger and stronger species, which are also capable of filtering greater quantities of particulates in water (Acevedo-Gutiérrez et al. 2002, Watkins & Schevill 1979).

The remaining variables considered – ocean basin, environment, life stage, and salinity – were not found to have significant differences in Microplastic Consumption Rates. These factors, then, do not increase or decrease the risk that individuals will experience higher risks of microplastic consumption. Although fin whales – the species with highest mean MCR in this study – are known to feed in offshore, subpolar marine waters (Vikingsson et al. 2009), for example, it is impossible to conclude from this knowledge that they are at risk of consuming high quantities of microplastics. Instead, it is much more valuable to consider the population's vulnerability and filtration technique. Similarly, Pacific oyster larvae and bryozoans are known to feed in coastal marine waters of the Atlantic and Pacific Oceans (Harris 2008, Fey et al. 2010, Cognie et al. 2006). Though these areas tend to have a lower abundance of microplastics, conclusions cannot be drawn without first considering vulnerability and filtration techniques. Both of these species are not yet evaluated by the IUCN (2019) and rely on suspension feeding techniques (Gerdes 1982, Harris 2008, Riisgard & Manriquez 1997), factors that support the conclusion that such species are not at great risks of microplastic consumption.

When bodyweight is factored into the analysis, results showed that pelagic tunicates (*P. confederata*) had the highest NMCR values. As one of the smallest species studied in this review, this result is likely caused by the species' incredible efficiency and high filtration rate in relation to its size. No other factors considered here would have had a significant effect on the NMCR, so it would be important for future studies to take this into account. The only factor that had a significant relationship with NMCR was salinity, while the remaining variables did not experience significant differences. Bryozoans (*E. pylosa*) still experienced the smallest NMCR values. Thus, it can be concluded that pelagic tunicates experience the highest risk of microplastic contamination, while bryozoans experience the lowest risk of contamination.

Understanding the species most at risk of consuming microplastics – including fin whales *(Balaenoptera physalus)*, North Atlantic right whales *(Eubalaena glacialis)*, and bowhead whales *(Balaena mysticetus)* – is critical because these particles are known to contain toxic chemicals and pose serious dangers to the species that consume them (Gallo et al. 2018). Chemicals commonly associated with microplastics include Persistent Organic Pollutants, polychlorinated biphenyls, and Persistent, Bioaccumulative, and Toxic Compounds, are found in marine plastic litter (Gallo et al. 2018, Lusher et al. 2017). Some of these chemicals and additives have endocrine disrupting properties (Lusher et al. 2017). And PBTs are known to bioaccumulate, leading to the dangerous hazards that plastics pose (Lusher et al. 2017). Toxins and chemicals frequently associated with microplastics are often either added during the manufacturing process or absorbed from the surrounding environment. These harmful additives are expected to have significant and detrimental effects on entire populations and ecosystems, as they can reduce an individual's ability to survive in their environment (Gallo et al. 2018). The whale species found to be most at risk of consuming microplastic are thus more likely to be exposed to such toxins and chemicals, providing them with yet another human-caused challenge to overcome and recover from their statuses as endangered or vulnerable species.

This study also considered factors that affect microplastic abundance. It was determined there are significant differences in microplastic abundance among the ocean basins and between the different environments. The open ocean had higher mean microplastic abundance in surface waters compared to coastal environments. Furthermore, the Arctic and Southern Oceans had significantly higher mean levels of microplastic abundance than other basins. This can pose a potentially substantial problem in the Arctic Ocean, because researchers expect that climate change may lead to the release of even greater quantities of microplastics from melting sea ice in the region (Lusher et al. 2017). When drawing conclusions from these results, however, caution must be taken because data was not equally distributed between the different oceans. Far fewer water samples existed in the Arctic and Southern Oceans than in the Pacific, Atlantic, and Indian Oceans, and this disparity could cause the results to be slightly unreliable.

The presence of marine litter has been a problem for decades in the open ocean, as solid waste was frequently discarded from ships prior to the 1980s (Lusher et al. 2017), most likely due to ghost fishing gear or shipping container losses. Yet, even as international regulations and conservation efforts attempt to reduce the quantity of microplastics in offshore waters today, the findings in this study show that open ocean environments continue to harbor vast quantities of litter. Due to continuous ocean currents, improper waste disposal, and dramatic events, such as floods and cyclones, it can be extremely difficult to manage the levels of marine litter found ((Lusher et al. 2017).

Future Considerations

In future studies, it would be beneficial for researchers to focus on individual species and consider their specific and unique risks in terms of microplastic consumption. Here, it was necessary to make generalizations and estimates of geographic distribution for each species simply as a result of the quantity of species considered throughout the review. Although the mean filtration rates would remain the same for each species, geographic distribution greatly determines the quantity of microplastics to which filter feeders are exposed. It was extremely beneficial to take an overall assessment of the many different filter feeders to better understand which are most at-risk of consuming toxic particulates and which factors affect that risk. But focusing future studies on specific species – particularly those that are commercially and ecologically important – could further this understanding.

Additionally, consumption of macroplastics is an important topic to highlight in future studies. Communities around the globe are familiar with widely publicized news articles concerning the occurrence of beached animals (Lusher et al. 2015). Many of the necropsies that result from these incidents indicate that macroplastics are consumed, particularly in whales, sharks, seabirds, and other species that are vital to the ecosystem (Lusher et al. 2015, Bråte et al. 2017). It would be beneficial to develop a broader understanding of the risks associated with macroplastic consumption in conjunction with the risks of microplastic consumption, as reviewed in this paper. Such an understanding could illuminate the different ecological impacts associated with plastics of varying sizes.

Previous studies have also shown that mesh size and the size of microplastic particulates should be considered when evaluating microplastic consumption (Roesch et al. 2013, Zhao et al. 2014). Thus, it would be beneficial if future studies consider how specific mesh sizes of gill rakers in each species, as well as the average microplastic particle size, could potentially affect the quantity of microplastics consumed. This paper aimed to determine how likely it is that different filter feeding species will consume microplastics, and while this complex problem was simplified to estimate risks of consumption and contamination for many different species for the purposes of this review, it did not provide concrete quantities of microplastics actually consumed. With the use of ever emerging technologies and techniques, it is expected that actual consumption data will be provided for many of these species, allowing researchers to consider these risks further and more accurately predict their ecologically and environmental impacts.

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