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1 Introduction

Microplastics (MP) are plastics smaller than 5 millimeters which have either primary or secondary origins. Primary microplastics were deliberately created for uses in cosmetics, artificial clothing fibers (such as polar fleece and rayon), commercial uses, or other products. Secondary microplastics are those that break down from larger plastic items such as water bottles, rope, straws, balloons, and other materials. Primary plastics are degraded into secondary microplastics through physical and chemical processes such as photodegradation (Coyle et al. 2020) and also through biological processes such as colonization by marine organisms (Jang et al. 2018).

Primary and secondary microplastics are now ubiquitous in marine water and sediment samples, and many marine organisms have been shown to consume them (van Sebille et al. 2015; Lusher et al. 2017). Microplastics occur at all ocean depths. Polymers denser than sea water typically sink, while many polymers less dense than sea water float, sink, or remain mixed in the water column due to a variety of mechanisms (Coyle et al. 2020). The health effects of microplastics on marine organisms and humans who consume marine products are still being assessed (Lusher et al. 2017; Baechler et al. 2020, Shumway et al. 2023).

The study of marine microplastics is still a relatively new field, especially given that plastic was not produced at industrial levels until the 1950s (Lusher et al. 2017). Methods for identification of plastic debris are still under development and in most cases it is impossible to determine the origin of marine microplastic (Martinelli et al. 2020, Shumway et al. 2023). In fact, in some cases, due to weathering and digestion, it is impossible to determine the original type of plastic found (Bendell et al. 2020; Martinelli et al. 2020).

Currently, most research is occurring in the academic community in highly directed, and often flawed, studies (Shumway et al. 2023). A review report conducted by the Food and Agriculture Organization of the United Nations (FAO) in 2017 compiled the state of knowledge at that time about microplastics in fisheries and aquaculture to determine the implications for aquatic organisms and food safety (Lusher et al. 2017). This FAO report relied upon two reports by the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) for much of the research on the sources, fate, and effects of microplastics in marine environments (GESAMP 2015; GESAMP 2016). GESAMP is an organization composed of scientists from the FAO, the United Nations Educational, Scientific and Cultural Organization (UNESCO) and many other organizations; their reports are designed to provide scientific advice to the sponsoring agencies.

The GESAMP reports determined that there was still too little research at the time to determine the largest sources for marine microplastics (GESAMP 2015; GESAMP 2016). However, newer studies, including the report by the FAO, found that aquaculture gear had not been identified as a significant source of marine microplastic pollution (Lusher et al. 2017; Monteiro et al. 2018; Li et al. 2021). Other studies found that the primary source of marine plastic pollution is land based (Lambert et al. 2014; Coyle et al. 2020). For example, microfibers from clothing are a large component of marine microplastics (Lusher et al. 2017). De Falco et al. (2019) found that washing clothes released up to 308 milligrams per kilogram (mg/kg) of microfibers into the wastewater treatment system. Unfortunately, wastewater treatment systems were only able to filter 85% to 98% of the microplastics from effluent which left between 2 to 28 particles per liter in outgoing water (Conley et al. 2019). Additionally, Conley et al. (2019) found that 75% of microplastics in the wastewater treatment effluent were fibers.

The lack of impacts of shellfish aquaculture gear on marine microplastic pollution are reinforced in a massive review focused on microplastics in shellfish by five scientists at the Department of Marine Sciences of the University of Connecticut (Shumway et al. 2023). This review, titled "A Critical Assessment of Microplastics in Molluscan Shellfish with Recommendations for Experimental Protocols, Animal Husbandry, Publication, and Future Research", is highly critical of much of the recent published literature on this topic, noting "*Over the past two decades, this haste [to publish] has resulted in a chaotic and cluttered literature rife with inappropriate methodologies, poor experimental protocols, misinterpreted results, overstated significance, and subsequent damaging media stories*". Their review critically assessed more than 750 publications. They conclude that "*[T]he data to date clearly demonstrate extremely low numbers (<10 per individual) of MP in filter-feeding bivalve molluscs globally. There are no data demonstrating presence of MP in these molluscs is a serious risk to human health, and few data to demonstrate negative impacts on the shellfish at environmentally relevant concentrations*".
In this memo, we discuss the prevalence of microplastics in seafood and their sources, the potential for shellfish aquaculture to contribute to microplastic pollution, and the potential leaching of harmful substances from shellfish aquaculture plastics.

2 Potential for microplastics to contaminate the marine environment via degradation and fragmentation of plastic farm gear

There is concern that the degradation and fragmentation of plastic products associated with shellfish aquaculture could potentially contaminate marine systems with secondary microplastics (GESAMP 2016; Lusher et al. 2017). Unfortunately, it is difficult to study the production of microplastics from marine shellfish aquaculture gear because it is difficult to definitively ascribe origins of microplastics to specific sources (Bendell et al. 2020; Martinelli et al. 2020). A report by the FAO found that macroplastic debris from shellfish aquaculture can be a significant source of pollution in some places in the world, but the associated financial cost leads most producers to recover gear and to appropriately dispose of it (Lusher et al. 2017). Unrecovered macroplastic debris can degrade into microplastics over time, so loss of gear is a concern. As described in Section 2.4, several experimental studies about microplastic pollution from marine shellfish aquaculture disagree about the contribution of aquaculture to microplastic pollution. Shumway et al. (2023) state "[G]enerally speaking, there are no data to support a claim that shellfish aquaculture increases the presence of MP [microplastics] in the cultured animals."

2.1 Types of plastics used in aquaculture

The degradation potential of plastic differs by type; therefore, it is important to understand what types of plastic are used in aquaculture gear. Six types of plastic dominate global plastic production: *"polyethylene (PE, high and low density), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS, including expanded EPS), polyurethane (PUR) and polyethylene terephthalate (PET)"* (GESAMP 2015). Of these plastic polymers, several are used in shellfish aquaculture in the Pacific Northwest. PVC tubes have been used in geoduck farming, while high density polyethylene (HDPE) is used in bags and nets for oysters and clams (Schoof and DeNike 2017).HDPE is also increasingly being used for geoduck farming. Buoys and ropes can be manufactured from many different substances and likely vary by aquaculture operator. Ropes are often made from PE, PP or nylon (polyamide; PA), while buoys are often made from PS or PE (GESAMP 2016). Buoys can also be made from other materials including metal (GESAMP 2016).

2.2 Durability of plastic aquaculture products

Plastics are preferred materials for aquaculture because they are typically cheaper, more durable, and easier to handle than gear made from natural materials (Lusher et al. 2017). Plastic gear used for shellfish aquaculture is obtained from manufacturers who design and produce it specifically for use in the marine environment so that it will maintain its integrity and not degrade (e.g., see Smart Net Systems: http://www. https://www.smart-net-systems.com). In fact, many plastics used in shellfish farming in the Pacific Northwest are decades old (Schoof and DeNike 2017). Nets and bags made from HDPE and PVC tubes used for geoduck have been used and reused for over 20 years with little sign of degradation (Schoof and DeNike 2017). A study that directly tested durability of plastics to ultraviolet (UV) light and abrasion found that polyethylene (PE) pellets produced around 20 microplastic particles per pellet after twelve months of UV light exposure and two months of abrasion (Song et al. 2017). Polypropylene (PP) performed fairly well for six months of UV exposure and abrasion, producing fewer than 200 microplastic particles per pellet, but produced over 5,000 particles per pellet after twelve months (Song et al. 2017). Expanded polystyrene (EPS), however, produced up to 15,000 particles per pellet after six months and some of it turned into nanoplastic powder (Song et al. 2017).

2.3 Control of loss of shellfish aquaculture gear

The National Marine Debris Monitoring Program (NMDMP), conducted by Ocean Conservancy, surveyed marine debris on U.S. beaches during a five-year period from 2001-2006 (Ocean Conservancy 2007), finding that plastic items dominated debris collected. For debris found (not limited to plastics), land-based debris made up 48.8% of all collected items, with 33.4% of items from general sources (not specifically land- or marine-based) and only 17.7% of items were ocean-based. For the 40 monitoring locations along the west coast, the contribution from ocean-based items was lower, only 11.3%. Land-based debris and debris from general sources was dominated by plastic straws, balloons, plastic bottles and plastic bags. The ocean-based debris included rope, floats and buoys, fishing line, traps/pots and pipe-thread protectors. None of these items is uniquely associated with shellfish aquaculture.

There are several types of shellfish farmed in Washington State, and geoduck production has specifically been opposed by some as an activity that causes plastic pollution. Geoduck farmers in Washington State may use one of two types of netting: (1) net caps secured to individual tubes by UV-resistant bands; or (2) area nets secured to the substrate by rebar. While predator protection tubes and individual net caps have come loose and drifted from farm sites in some instances, this is not true for area nets. Area nets are secured to the substrate at regular intervals with rebar, growers utilize best management practices to regularly patrol and ensure farm gear is secured, and they follow similar permit conditions requiring patrols and maintenance. Area nets are also effective at containing PVC tubes and preventing off-site escapement. In addition, tubes that do come free are likely to migrate up the beach and be collected during routine inspections (SHB 2013). No instances of area nets escaping a farm site have been reported. But even if area nets were to come free, they do not pose an entrapment concern. Unlike fishing nets, geoduck netting is visible and would sink, rather than hang vertically in the water column (SHB 2013).

While most of the research we found suggests that shellfish farming is unlikely to result in significant marine debris and could even result in a net reduction, we are aware of one opinion piece suggesting that shellfish gear in British Columbia escapes in high quantities (Bendell Undated). This opinion piece is cited in a scientific paper by the same author (Bendell et al. 2020) along with a webpage from a non-governmental organization (NGO) that has a photo gallery of discarded shellfish aquaculture gear (Association for Denman Island Marine Stewards 2021). The author of the scientific paper and opinion piece is a professor of marine conservation and ecotoxicology at Simon Fraser University, Leah Bendell. Her opinion piece states: "An astonishing four to six tonnes of plastic debris, including anti-predator netting, plastics trays, ropes and styrofoam, is collected from the beaches annually. Now polyvinyl chloride (PVC) piping, used for the farming of geoducks is also being washed ashore." The author does not provide data or citations for this number. Other allegations in the opinion piece are either uncited or linked to NGO websites.

In contrast to the assertions of Bendell et al., industry practices in Washington and British Columbia to limit loss of aquaculture gear ensure that it will not contribute substantially to marine plastic debris in the future through the use of codes of practice and penalties for noncompliance. Both the Pacific Coast Shellfish Growers Association and the British Columbia Shellfish Growers' Association have developed codes of practice for shellfish farmers (PCSGA 2011, BCSGA 2013). Standards on the use and maintenance of gear in these codes of practice include routinely inspecting gear, designing and constructing equipment to withstand extreme weather conditions, and repairing and replacing gear as needed. Similar requirements to use appropriate gear, frequently monitor gear, replace damaged gear, and remove gear when it is no longer needed or not actively being used are typically included in regulatory conditions for approval of aquaculture operations (United States Army Corps of Engineers; USACE 2015).

Although it is possible that individual items of plastic gear may be lost from a farm, the application of these codes of practice assures that shellfish aquaculture operations as a whole will not have cumulative impacts to increase the load of plastic debris in Washington or British Columbia waters. The management practices and conditions that are applied during geoduck farm permitting have been recognized by the SHB as effective for avoiding and minimizing the potential for gear escapement and adverse impacts to receiving waters (Schoof and DeNike 2017). Noncompliance of codes is no longer tolerated by the BCSGA, which launched the Shellfish Farm Environmental Plan (SHEP) in 2021 (BCSGA 2021). SHEP requires shellfish farms to complete a self-assessment task based on exposed foam flotation, non-seabed debris, and wildlife protection measures; the self-assessment will be followed by inspections in 2023 with loss of insurance coverage or lost membership among the consequences for noncompliance.

In addition to following best management practices and complying with permit conditions, shellfish farmers in Washington have organized bi-annual beach cleanups to remove all forms of marine debris from the environment. Since these cleanups were first initiated over a decade ago, growers have seen a sharp downward trend in the amount of aquaculture-related marine debris, demonstrating the effectiveness of management practices and permit conditions (SHB 2013). The vast majority of marine debris collected during these cleanups is from non-aquaculture sources (SHB 2015). Accordingly, shellfish aquaculture operations may be responsible for a net reduction of marine debris.

2.4 Experimental studies of secondary microplastics from shellfish aquaculture gear

There are very few studies that directly test whether microplastics from farm gear are contaminating shellfish or nearby sediment, and it is usually difficult to tell what type of plastic the microplastic originated from. Experimental studies on this topic may sample shellfish, sediment, and/or water associated with aquaculture sites. For this review, we found several studies that explore microplastic loads in shellfish and sediment near to and away from shellfish farms. Our focus is on bivalves grown in open marine environments, but several studies of other forms of aquaculture are also noted. Indirect evidence of the influence of aquaculture gear on microplastics in the environment may be gleaned from studies comparing microplastic content of wild vs. farmed shellfish.

A recent review of the global literature on microplastics in oysters conducted by Wootton et al. (2022) provides the most comprehensive comparison of microplastics in farmed vs. wild oysters. Wootton et al. conducted a systematic review of 628 potentially relevant studies from which 49 studies were identified and selected as investigating microplastic presence in oyster species. Of these, 29 studies met the criteria for data extraction. These studies showed that wild-caught oysters contained more than double the amount of microplastics than aquaculture-raised oysters (2.18 ± 0.77 microplastic particles per gram of organism wet weight [MPs/g] and 1.03 ± 0.33 MPs/g, respectively), although the differences were not statistically significant. The authors believed that these data likely reflect the clean/pristine water conditions where aquaculture oysters are commonly cultivated. This study included examination of microplastics in 196 pacific oysters (Crassostrea gigas and Saccostrea glomerata) collected from aquaculture farms from six main oyster growing regions in South Australia. Microplastic presence and polymer type were quantified. Microplastics were present in 49.4% of all sampled oysters, including oysters from all eight locations sampled. On average, whole oysters contained 0.83 ± 0.08 microplastics per individual or 0.09 ± 0.01 microplastics per gram of organism wet weight. Using fourier-transform infrared spectroscopy, a low-density polyethylene from vexar plastic netting commonly used in aquaculture production was found to be the source of 62% of the verified microplastics.

Several studies report on microplastics in bivalves from the Salish Sea, with differing conclusions.

A study by Covernton et al. (2019) in British Columbia, sampled both Pacific oysters (*Crassostrea gigas*) and sediment from commercial oyster beds and from nearby areas that were not farmed. The authors only found small differences in numbers of microplastics between the farmed and unfarmed locations. Covernton et al. (2019) attributed the small differences found to differing body weights between farmed and non-farmed oysters (non-farmed oysters had larger body weights). Additionally, the microplastics they found were largely fibers from textiles which are not used in shellfish aquaculture. The lead author of this paper is a Ph.D. student at the University of Victoria. According to the author's website[1], this research was conducted in collaboration with the Department of Fisheries and Oceans Canada Aquaculture Collaborative Research and Development Program, the BCSGA, the University of Victoria, and Vancouver Island University.

Conversely, Bendell et al. (2020) found that aquaculture in British Columbia did increase microplastic concentrations in shellfish. In this study, the authors measured microplastic in clams from different areas and attempted to match the plastic with discarded aquaculture gear using Fourier Transform Infrared Spectroscopy (FTIR) analysis. FTIR is a method that uses infrared light to observe chemical properties in different materials. The authors created a pattern library for different plastics from the literature and from discarded fishing gear then compared the spectral imagery with microplastics in clams. The authors plotted the spectra and visually assigned them to types of plastics. Bendell et al. (2020) found a statistically significant higher number of microplastics in an area reportedly used most heavily in aquaculture, and they identified some of these plastics as coming from shellfish aquaculture gear. They specifically called out the Covernton et al. (2019) study as erroneous, because Covernton et al. (2019) used oysters and did not report on the health of the clams used in their study. Bendell et al. (2020) stated that oysters should not be used as biomonitors because they selectively consume particles and therefore do not ingest as much plastic as clams, which feed indiscriminately. Bendell et al. (2020) also stated that Covernton et al. (2019) had low clam survival and did not report on the health of the survivors so there was no guarantee that they were actively filter feeding. Shumway et al. (2023) do not share these concerns about the study by Converton et al. (2019).

Indeed, Shumway et al. (2023) are highly critical of the Bendell et al. (2020) study. Due to its relevance, their entire critique is quoted below:

> *"Bendell et al. (2020) went on to carry out a study with two species of clams (Manila clam Venerupis = Ruditapes philippinarum and varnish clam, Nutallia obscurata) under the incorrect premise that "They are non-discriminatory feeders that don't egest excess food through pseudofeces." Unfortunately, this is patently untrue as these and all other bivalves produce pseudofeces under certain conditions. Bendell et al. (2020) cite Gillespie et al. (1999) who say nothing about pseudofeces production or lack thereof. In fact, pseudofeces production by Ruditapes has been reported previously (see Defossez and Hawkins 1997). They also stated that the diversity in size and shape of particles found in the clams indicated that they are non-discriminatory in their feeding. This statement is also not necessarily true, that is, there is no evidence to show what particles were or may have been rejected during the feeding process. Based upon the erroneous assumption that no pseudofeces are produced by these clams, Bendell et al. (2020) incorrectly concluded that both clams might be suitable biomonitors for tracking MP in the field."*

[1] https://garthcovernton.wordpress.com/

Additionally, we note that the visual assignment of spectral images into different groups as reported in Bendell et al. (2020) would likely have been open to personal bias. The authors do not discuss whether the person grouping the images was blind to the study design, suggesting that they were not. The tone of this article is clearly biased against shellfish aquaculture. For example, the authors state: "*Despite its ecological importance, Baynes Sound is also a region that experiences an expanding and unregulated shellfish aquaculture industry.*" In the next sentence the authors give the number of shellfish tenures, which clearly shows that the industry is regulated. These authors are in a group that has published other scientific articles, books, and opinion pieces decrying the microplastic pollution in and from shellfish aquaculture (Kazmiruk et al. 2018; Bendell et al. 2019; Bendell Undated).

An additional relevant study did not specifically explore locations with or without shellfish aquaculture and instead studied microplastic load in oysters in the Puget Sound. In their study, Martinelli et al. (2020) found that oysters accumulated very few microplastics. The authors found polyester, rayon, poly(t-butyl acrylate), and poly(bisphenol A carbonate) along with other compounds that were not clearly identified. The identified microplastics likely came from fibers found in textiles, paints, adhesives, fuel, and thermoplastics. This result agrees with the findings of Covernton et al. (2019) that microplastic concentrations in British Columbia shellfish are low (average of less than 1 particle per shellfish). Given that Washington State is the highest producer of shellfish by sales in the United States according to the U.S. Department of Agriculture (USDA and NASS 2019), it is reasonable to assume more aquaculture-specific plastics would have been found in the Martinelli et al. (2020) study if aquaculture was a major source of microplastic contamination in the Puget Sound.

Other available studies of microplastics and various forms of aquaculture are less relevant to growing conditions of bivalves in the Salish Sea.

A study in South Korea found that the amount of microplastics from an aquaculture area contributed as many microplastics as an urban area (Jang et al. 2019). The study found a higher diversity of plastics near the urban area, while the plastics from the aquaculture area were largely due to the extensive use of EPS aquaculture buoys (Jang et al. 2019) which are known to shed debris (Jang et al. 2018). The authors of this study have published several other papers cited in this memo on marine microplastic debris, sources of microplastic, and leaching (Jang et al. 2016; Song et al. 2017; Jang et al. 2018; Jang et al. 2019). All of the authors have appointments at both the Korea University of Science and Technology Ocean Science program and at the Korea Institute of Ocean Science and Technology Oil and Persistent Organic Pollutants (POPs) Research Group.

Chen et al. (2021) summarized literature studies comparing microplastic abundance in aquaculture species and captured species and found that concentrations of microplastics detected in aquaculture products (e.g., mussels, oysters) are generally higher than those in their wild counterparts from surrounding environments. In addition to plastic gear and equipment, the authors emphasized that microplastics in aquaculture environments may come from an extensive list of sources, such as plastic waste and debris from the land, disposal plastic waste from tourism, shipping transportation, atmospheric deposition, and aquaculture feed and health products. Further, aquaculture areas are mostly enclosed or semi-enclosed aquatic environments, which prevent the transport of microplastics to other areas and contribute to a higher accumulation of microplastics in the water and sediment. Like other studies, the source contributions to the microplastic abundances in aquaculture environments were not quantitatively evaluated in this study.

In addition to shellfish, two literature studies were identified which evaluated microplastic abundances in the aquaculture ponds for other aquatic species, especially crabs. In these two studies crabs (bottom feeders) were raised in the aquaculture ponds with formulated diets, while shellfish (filter feeders) are fed wildly in the aquaculture farms in the Pacific Northwest. Such differences in the feeding mechanisms may greatly impact the amount of microplastics accumulated in the organism tissues. Nevertheless, these two crab studies are summarized below to provide some insights on the potential sources of microplastics in the aquaculture environment.

Yu et al. (2023) studied the abundance and characteristics of microplastics in water, sediment, and crab tissue samples collected from aquaculture ponds in the Yangtze Estuary of China. Results indicated that the crabs in the aquaculture ponds had a higher abundance of microplastics than the wild crabs, with accumulation mostly in intestinal tissue. Microplastics found in the water, sediments, and crab tissues all had a certain degree of aging. The authors believed that the two major potential sources of microplastics in artificial breeding ponds may be: 1) dissolution of microplastics in crab feed; 2) aging and breakage of plastic aquaculture tools, because the types of microplastics found in crab tissues were also detected in crab feed and aquaculture tools. In crab tissues, PE was found to be the main polymer type, followed by PET, PP, and PS. In crab meals, PE and PET are the most dominant polymer types. Among the aquaculture tools used in the ponds, the floor film, floor net, floor cage, and water pipe were identified as PE, the strapping tape was identified as polyamide, and the water pants were identified as PP and PVC. In summary, HDPE and PVC used for shellfish aquaculture in the Pacific Northwest were not found in the crab tissues in this study, given that the authors did not specify whether PE detected in any sample matrix was HDPE or LDPE. Further, the authors did not quantitatively evaluate the contribution from each source to the microplastic concentrations in the crab tissues.

Xiong et al. (2021) investigated the occurrence of microplastics in the water of aquaculture ponds for fish, crayfish, and crab, as well as in the natural lake near the aquaculture area around the Honghu Lake in China. Results indicated that the crab and crayfish ponds contained higher microplastic abundances than the fish ponds and the nearby natural lake. The authors found that plastic fencing was used in the crab and crayfish ponds to prevent the escape of animals, but not used in the fish ponds. It was considered by the authors as a key contributor to the higher levels of microplastic abundance in the crab and crayfish ponds, given that other plastic products used in different types of aquaculture ponds were almost similar. The authors further concluded that direct exposure of plastic fencing to sunlight, as well as abrasion due to the climbing of crabs and crayfish on the fencing, might also promote the generation of microplastics in the crab and crayfish ponds. This study did not provide direct evidence on the microplastic generation process, and therefore it is difficult to attribute the higher levels of microplastic abundance solely to plastic fencing used in the crab and crayfish ponds. Other factors may also play an important role, such as the smaller areas and volumes of the crab and crayfish ponds (concentration effect) and the higher nutrient levels in the fish ponds (promoting microplastic deposition out of water) as described by the authors. Further, crab feed, which has been considered as a potential source of microplastics by other studies in the literature (Yu et al. 2023, Chen et al. 2021), was not evaluated in Xiong et al. (2021). Finally, the polymer type of plastic fencing used in the crab and crayfish ponds was not reported in this study and therefore cannot be compared with the aquaculture gear used for shellfish in the Pacific Northwest.

3 Potential leaching of harmful substances from aquaculture gear and microplastics

Concerns have been raised about the possibility that toxic chemicals may be released from ingested microplastics and pose a health risk to seafood consumers, both from primary components and from pollutants that may sorb to microplastic particles in the environment. Although there is evidence to support leaching of plastic constituents and sorption of pollutants to microplastics, recent research does not generally support concerns that these processes pose health risks. Research in this area has been conducted primarily by individual academic researchers, although some of it has been reviewed as part of a larger FAO study (Lusher et al. 2017).

Plastics and microplastics are made from a mix of chemicals to create characteristics useful for the desired plastic product. Characteristics vary depending on the product but can include flexibility, rigidity, and shock absorption. The FAO review noted that plastics in the marine environment can be a source of chemical leaching but can also pull contaminants out of the water through adsorption or absorption (Lusher et al. 2017). Research by Bhagwat et al. (2021) demonstrated that plastics that were in the marine system for over 10 years accumulated plastic-associated inorganic and organic matter which harbored high concentrations of metal(loid)s, polyaromatic hydrocarbons (PAHs), and per- and polyfluoroalkyl substances (PFAS) and appeared to be acting as a sink for contamination. There is some evidence that plastics that have sorbed contaminants from the water column could then pass them on to marine organisms that use the plastic as a matrix (Jang et al. 2016).

3.1 Leaching from plastic components

Recent studies suggest that plastics commonly used in marine shellfish aquaculture did not adversely affect organism survival through leaching when used as a growth substrate, after exposure in a closed system, or when directly consumed. An algal aquaculture study determined that PVC, HDPE, and other polymers did not affect algal growth through leaching when used as the growth substrate; in fact, PVC, polymethyl methacrylate (PMA) and polypropylene carbonate (PPC) all positively influenced growth (Kerrison et al. 2017). A study of daphnia found that rigid PVC did not change body morphology or mortality after 31 days of exposure, while flexible PVC did change morphology and reproduction to some extent (Schrank et al. 2019). In an extreme example, one study found that PVC itself was not inherently toxic. Mealworms, *Tenebrio molitor* larvae, were able to survive on a diet of only rigid PVC for over 5 weeks with 80% survival in a study that attempted to depolymerize and biodegrade PVC in an alternative way from landfills or incineration (Peng et al. 2020). The PVC used in the study was pure PVC powder less than 150 µm in size. The authors found that if the mealworm's PVC diet was supplemented with feed, survival increased and the larvae were able to complete their life cycles (Peng et al. 2020).

In the sections below, we discuss different types of plastics and their potential for leaching. Some plastics leach main components of the plastic in the form of monomers or oligomers, and others leach additives such as plasticizers or flame retardants. The type of plastic and the age of the plastic determines the likelihood of leaching, with newer plastics leaching more heavily than older plastics (Gardon et al. 2020).

3.1.1 Plasticizers and flame retardants

Plasticizers are used to make plastic more flexible, elastic, and shatter resistant, and flame retardants lower the danger from fire. Plasticizers like phthalates and bisphenol A (BPA) are known to migrate from polymers and may act as endocrine disruptors (Lusher et al. 2017). Flame retardants, especially brominated flame retardants, also readily leach out of plastics; these include polybrominated diphenyl ethers (PBDEs) and hexabromocyclododecane (HBCD) which can accumulate in aquatic environments due to their high environmental persistence (Hermabessiere et al. 2017; Lusher et al. 2017; UN Environment Programme 2019). A recent study found that newer plastic rope and oyster spat collectors leached more phthalates than did older plastic aquaculture gear (Gardon et al. 2020). Given that shellfish farmers report that the gear they use is often decades old (Schoof and DeNike 2017), the amount of leaching over the lifetime of shellfish aquaculture gear may in fact be low compared to other types of plastic products.

3.1.2 Polyvinyl chloride (PVC)

There are two main types of PVC, rigid and flexible. Flexible PVC contains plasticizers, typically phthalate esters (PAEs). Rigid PVC uses metal-based stabilizers and less than 10% plasticizers. Neither type of PVC is known to leach monomer or oligomers but flexible PVC can leach phthalates (Lusher et al. 2017). In PVC used in geoduck aquaculture, metal-based stabilizer concentrations are low and do not appear to leach to the environment, as demonstrated by a study at a Taylor Shellfish farm (ENVIRON 2011). In response to concerns raised during the permit process for a Puget Sound geoduck farm, metals were tested in sediment at an active geoduck aquaculture site and, for comparison, at a control site approximately 600 feet updrift of the culture location. The culture site had an active geoduck aquaculture history of more than 10 years and the area sampled was on its second crop rotation. There were no statistically significant differences identified between metals concentrations in sediment from the control site and the culture site, confirming that PVC pipes were not releasing metals to the environment (ENVIRON 2011).

The findings of the ENVIRON study are consistent with the concentrations of cadmium and other metals that have been measured regularly in Puget Sound fish and shellfish and are higher in urban embayments than in areas where shellfish are grown. In addition, the Washington State Department of Ecology reviewed the potential toxic hazard of PVC in marine environments and determined that this rigid PVC does not pose a significant toxic hazard because its hardened form is stable in the marine environment (Johnson 2010). For these reasons, the SHB has repeatedly rejected the contention that chemicals will leach from geoduck aquaculture gear and adversely affect the environment (SHB 2012, SHB 2013, SHB 2015).

3.1.3 Polyethylene (PE)

Polyethylene can be either high density (HDPE) or low density (LDPE). Shellfish aquaculture gear is typically made from HDPE (Schoof and DeNike 2017). Direct leaching of monomers or oligomers from either type is not a concern for human health (Lusher et al. 2017). A study of leaching from two types of single use polyethylene plastic bags found that they did not affect the fertilization of Venus clams (*Meretrix meretrix*) but both types of bags affected survival, deformity, and shell height (Ke et al. 2019).

3.1.4 Polypropylene (PP)
Direct leaching of monomers or oligomers from polypropylene (PP) is not a concern for human health (Lusher et al. 2017).

3.1.5 Polyethylene terephthalate (PET)
Direct leaching of monomers or oligomers from polyethylene terephthalate (PET) is not a concern for human health (Lusher et al. 2017).

3.1.6 Polystyrene (PS)
Polystyrene (PS), of which Styrofoam is a specific brand, is known to release styrene monomers and oligomers. The FAO document cited papers which found that many products released compounds that could exhibit limited estrogen-like activity, although their potency was not clear (Lusher et al. 2017).

3.2 Sorption and subsequent leaching
Plastics in the marine environment have the potential to sorb chemical contaminants in the water (through adsorption or absorption) and act as sinks for pollution. In addition to the plastics themselves, plastic-associated inorganic and organic matter from aquaculture infrastructure can act as a sink for hazardous environmental contaminants (Bhagwat et al. 2021). Recent studies have found that hydrophobic organic compounds can sorb to many microplastics, with polyethylene the plastic that most strongly sorbed contaminants (Alimi et al. 2018). Polystyrene is also known to sorb contaminants such hexabromocyclododecanes (HBCDs), a type of brominated flame retardants, when those chemicals are commonly found in the marine system (Jang et al. 2016). One study found that mussels inhabiting expanded polystyrene (EPS) buoys did have higher levels of HBCDs than mussels in other habitat matrices in an area where HBCDs were common pollutants (Jang et al. 2016). However, even given the pollution, high-density polyethylene (HDPE), from which nets and flip bags for shellfish are constructed, leached lower levels of HBCDs to resident mussels and were more similar to leaching levels of metal and rock (Jang et al. 2016). A GESAMP (2015) review concluded that microplastics likely only play a small role in transporting hydrophobic organic chemicals (HOCs) to biota, when compared to natural pathways such as sediment.

Bakir et al. (2016) conducted analyses and studies to address concerns that the gut environment might enhance desorption of chemicals from microplastic particles and absorption into the animal. They tested for microplastic concentrations in sediment of 1% and 5% (far higher than the concentrations seen in the Salish Sea), and concluded that "*ingestion of microplastic does not provide a quantitatively important additional pathway for the transfer of adsorbed chemicals from seawater to biota via the gut.*" Beckingham and Ghosh (2017) studied the bioavailability of polychlorinated biphenyls (PCBs) from polypropylene microplastics and concluded that uptake of chemicals from microplastics by sediment-dwelling aquatic organisms is likely to be very small compared with uptake from sediment particles. These studies provide strong evidence to support the GESAMP (2015) conclusions and suggest that there is not significant uncertainty regarding the impacts of chemicals associated with marine microplastics.

4 Summary of studies of microplastics in seafood and their sources

Plastic has been found in seafood of various types in both macro- and microplastic size ranges (Lusher et al. 2017). The type of plastic, the size of the plastic pieces, the source of the plastic, and the potential human health effects vary by region, organism size, feeding strategy of the organism (e.g., filter feeder or selective predator), species, and the part of the organism consumed by humans. Microplastics have the potential to enter a wide range of organisms because of their small size and ubiquity in marine environments. The source of microplastics is often difficult to determine due to both small size and weathering of the material that can change the original chemical signals (Bendell et al. 2020; Martinelli et al. 2020). The amount of microplastics measured in seafood also varies among mollusks, crustaceans, and fish by species and origin (markets vs. environment, wild vs. farmed), and is reported inconsistently between studies (e.g., by weight; by organism; dry vs. wet weight; and tissue-specific, whole organism, or not reported) making comparisons difficult (Danopoulos et al. 2020). This section reviews current knowledge about microplastics in seafood and their sources. It is important to note that data for North America are limited compared to Asia and Europe.

4.1 Microplastics content in seafood

Several review papers have been identified in the literature evaluating microplastics concentrations in seafood. A recent review (Danopoulos et al. 2020) summarized the results of 50 studies published between 2014 and 2020 (46 published in 2017 or later) that reported the amounts and types of microplastic particles measured in seafood for human consumption. Studies evaluated were limited to those that support quantification of microplastics content in seafood. Microplastic content varies both within and between phyla, species, and location; study design also contributed to variability in reported results. Of the 50 studies reviewed, the majority (28) used samples from Asia, while only four used samples from the Americas (others used samples from Europe [13], Africa [2], Australia/Oceania [1], or more than one continent [2]), so it is uncertain how well the available data reflect average microplastic content in Pacific Northwest seafood.

Bom et al. (2021) reviewed 93 studies reporting microplastics concentrations in bivalve mollusks collected from the environment between 2014 and 2021. The studies were conducted mainly in Asia (33) and Europe (31), followed by North America (14). Microplastics concentrations were reported in 70 bivalve species, with mussels and oysters being the major species evaluated.

Wootton et al. (2022) systematically reviewed the global literature investigating microplastics in oysters and identified 29 studies conducted following best practices, i.e., use of chemical digestion, large sample sizes (>10), small sieve sizes, as well as contamination controls and verification of polymer type. The majority of the studies reviewed came from Asia (19), followed by North America (5).

Baechler et al. (2020) identified 24 studies reporting occurrence of microplastics in North American seafood, including 13 studies of shellfish and 11 studies of finfish; however, most of these studies reported microplastics concentrations in the environment (e.g., surface water, sediment), but not in seafood. Baechler et al. (2020) concluded that there is a critical gap in our knowledge of the occurrence of microplastics in North American commercial fishery species.

Average microplastic content reported in mollusks across 27 studies summarized by Danopoulos et al. (2020) ranged from 0 to 10.5 MPs/g, with most of the studies reporting towards the lower end of this range (more than half reported values less than 1 MP/g). Samples were collected from both markets and the environment. The range of microplastic content in market samples was broader compared to environmental samples. The reviewers noted that while there is some evidence that potential contamination in market samples may be mitigated through depuration, this could not be assessed based on a lack of sufficient data. They concluded that *"it is not clear whether MP [microplastic] contamination after the collection of seafood has a significant effect, or if it is mitigated by depuration."* Similarly, there was no apparent pattern based on the source of the sample (farmed or wild). Similarly, Bom et al. (2021) reported that the predominant mean microplastic concentrations were between 0 and 3 MPs/g in mussels, less than 1 MPs/g in oysters, and less than 0.5 MPs/g in other species like clams, cockles, and scallops. Also, Wootton et al. (2022) reported a global average microplastic concentration of 1.41 MPs/g in oysters, with the highest average concentration (2.1 MPs/g) from North America, followed by Asia (1.5 MPs/g), Oceania (0.45 MPs/g), and Europe and the Middle East (both 0.3 MPs/g).

Average concentrations reported in five crustacean studies summarized by Danopoulos et al. (2020) ranged from 0.14 - 8.6 MPs/g. All five studies assessed environmental samples, and four of the five assessed wild organisms. Seven fish studies summarized by Danopoulos et al. (2020) reported mean contents ranging from 0 to 2.9 MPs/g. Five of these seven studies collected organisms directly from their environment. Four of those five sampled wild fish and one sampled farmed fish. The remaining two studies sampled market fish and did not report their origin (wild or farmed). One study (Akhbarizadeh et al. 2020) reported a mean of 1.28 MPs/g in canned tuna and was the only canned or dried fish sampled among the seven fish studies. The authors noted that canned and dried fish may be affected by airborne microplastic contamination during processing; however, the mean concentration reported for canned tuna was within the range reported for unprocessed fish.

Gopal et al. (2022) also reviewed microplastic accumulation in edible marine and freshwater fishes, shrimps, and crabs in South America, Europe, Africa, Asia, Australia, and North America. Although the gastrointestinal tract of some aquatic organisms was reported to contain highly elevated levels of microplastics (up to 7,500 MPs per organism), whether microplastics in these aquatic organisms could progress to human food and really pose a high risk to human consumers was questioned by the authors, given that in most cases these food products are consumed after removal of the entrails and gut area where microplastics predominantly accumulate. The authors also concluded that microplastics in crabs, shrimps, and other aquatic organisms consumed whole or with their gastrointestinal tract still intact have the potential to enter the human body through food consumption, which requires serious scrutiny.

Danopoulos et al. (2020) identified several additional limitations in assessing the available data on microplastics in seafood. One issue is the potential for airborne microplastics to be introduced during seafood processing, making it inappropriate to compare data from canned or dried seafood with that from organisms collected directly from the environment. Similar uncertainty about the potential for contamination to be introduced during processing affects the interpretation of mollusk data. Additionally, inclusion of different tissues or different reporting methods (e.g., particles per individual or by mass) can prevent comparisons or pooling of data.

4.2 Plastics most commonly found in seafood

A recent review (Baechler et al. 2020) found that *"fibers, foams, films, and fragments with recorded chemical signatures of cellophane, high density polyethylene (HDPE), low density polyethylene (LDPE), polyethylene terephthalate (PET, PETE), nylon (PA), polypropylene (PP), polymethylmethacrylate (PMMA), polyurethane (PU, PUR), polystyrene (PS)"* have been identified in the digestive tracts of marine organisms. Recent literature indicates that microfibers are the most abundant type of microplastic found in seafood. Baechler et al. (2020) found that microfibers typically comprised more than 90% of microplastics ingested by marine fishes, crustaceans, and bivalves, while the remainder of ingested materials included microplastic fragments, foams, and films. Overall, PE and PP were the most abundant microplastic polymers reported in recent seafood studies (Jabeen et al. 2017; Karbalaei et al. 2019; Danopoulos et al. 2020).

Potential differences in the materials that are included as microplastics by researchers can influence conclusions about the types of microplastics that are most prevalent in seafood. Danopoulos et al. (2020) found that only about half of the studies they reviewed reported materials derived from cellulose (i.e., cellophane, cellulose, and rayon) and it was not clear whether these materials were not reported in the other studies because they were not present or because they were not included as microplastics. This is important because when these materials were included, cellophane was the most predominant material reported in molluskan studies. PET, rayon, and polyester were the next most abundant. When cellulose-related materials were not reported, PE and PP were most abundant. Such differences in classification can influence conclusions about microplastic composition as well as total content. PE and PA, then PP and PET, were reported as the most abundant polymers in crustaceans (Danopoulos et al. 2020). In bivalves, PE was the primary polymer identified, followed by PP, PET, polyester, cellophane, and PS (Bom et al. 2021). In fish, PE and PP were the most abundant, followed by PET and cellophane (Karbalaei et al. 2019; Danopoulos et al. 2020). PET was the most common polymer type reported in canned tuna and mackerel, followed by PS and PP (Akhbarizadeh et al. 2020).

HDPE and PVC are used for shellfish aquaculture. Nets and oyster flip bags are composed of HDPE, while high-density PVC pipes are used for geoduck aquaculture (Schoof and DeNike 2017). Other polymers commonly reported in seafood are not used for shellfish aquaculture, including cellulose-related materials, PP, PA, PET, and others.

While PE microplastics are prevalent in seafood and marine environments, most studies do not differentiate between HDPE, which is used in shellfish aquaculture in the Pacific Northwest, and LDPE and PE, which are not used in shellfish aquaculture in the Pacific Northwest. Generally, LDPE appears to be noted more frequently than HDPE. For example, Wootton et al. (2022) quantified microplastic presence and polymer type in commercially farmed oysters across eight aquaculture sites in southern Australia and linked 62% of the verified microplastics to vexar plastic netting, a LDPE used in aquaculture production in Australia. However, nets used for oysters in the Pacific Northwest are made of HDPE, not LDPE. Actually, PE plastics are among the most heavily produced primary plastic polymers globally and comprise a large portion of globally generated primary plastic waste (Geyer et al. 2017); these polymers are not unique to aquaculture. While there is some evidence that HDPE forms microplastic fibers and fragments in marine environments with high salinity (Weinstein et al. 2016), it is not clear whether these materials are observed in seafood or how much of the observed PE is HDPE.

Another recent literature review (Coyle et al. 2020) summarized microplastic polymers found in various marine samples from the water column, ocean and beach sediments, and biota. Plastics recovered included HDPE and PVC in the water column and PVC in the sediment. PE (but not HPDE) was found in biota, while HDPE and PVC were not; however, only one biota study (on benthic macroinvertebrates) was included in the summary. PVC microplastics have not been commonly reported in seafood. Where reported, PVC is typically found in lower abundance compared to the more commonly reported polymers (including PE, PP, PET, PA, and PS) (Miller et al. 2020). A recent study found that PVC made up only 0.3% of microplastics found in seabed sediments around Hong Kong (Cheang et al. 2018).

Based on the types of polymers found to be most abundant in seafood, aquaculture does not appear to be a major source, and there is no specific evidence indicating that microplastics derived from aquaculture equipment are present in seafood.

5 Conclusions

In conclusion, the field of marine microplastics is still relatively young. It is clear that microplastics are ubiquitous, but their source is difficult to determine. Plastics that have been degraded are difficult to identify (Bendell et al. 2020; Martinelli et al. 2020), and the methods used to analyze plastic contents in organisms varies widely which strongly alters study outcomes.

Current research suggests that marine shellfish aquaculture does not significantly increase microplastics load in marine water. Given that gear is not allowed to escape and is properly disposed of at the end of its life cycle aquaculture is not expected to increase microplastics load in the future. There is also no current evidence to suggest that marine microplastics found in bivalves originate predominately from aquaculture. In fact, a recent literature review of microplastics in oysters found that, on average, wild caught oysters contained more microplastics than farmed oysters. There is evidence that oysters in Puget Sound and the Salish Sea have very low microplastic concentrations (average of less than 1 particle per oyster; Covernton et al. 2019; Martinelli et al. 2020). Bendell et al. (2020) indicate that clams have slightly higher microplastic concentrations (0 to 3 average particles per clam) because they are less selective about what they ingest; however, Shumway et al. (2023) refute the claim that clam are less selective than oysters.

Of plastics used in marine shellfish aquaculture, the most likely to degrade, leach, and sorb contaminants appears to be EPS which is often used in buoys. Other harder plastics, such as HDPE and PVC that are used for shellfish aquaculture do not contribute significantly to microplastic pollution, microplastic consumption by marine organisms, or leaching of chemical components.

While there is sentiment against shellfish aquaculture from some sectors (Bendell Undated), current research suggests that much of the resistance to shellfish farming from the general public is based on a lack of trust (Ryan et al. 2017). Communication about conservation measures routinely undertaken by shellfish growers should be used to provide the public with a better understanding of their contribution to reducing the plastic loads and potential microplastic sources in the Salish Sea.

As described above, industry practices in Washington and British Columbia to limit loss of aquaculture gear ensure that it will not contribute substantially to marine plastic debris in the future through the use of codes of practice and penalties for noncompliance. Codes of practice for shellfish farmers include standards on the use and maintenance of gear such as routinely inspecting gear, designing and constructing equipment to withstand extreme weather conditions, and repairing and replacing gear as needed. Application of these codes of practice assures that shellfish aquaculture operations as a whole will not have cumulative impacts to increase the load of plastic debris in Washington or British Columbia waters. Over the past decade bi-annual beach cleanups organized by Washington shellfish farmers to remove all forms of marine debris have led to a sharp downward trend in the amount of aquaculture-related and other marine debris. Because most of the debris is from sources other than aquaculture, shellfish aquaculture operations may be responsible for a net reduction of marine debris.

Acronym	Definition	Example Application
POLYMERS		
PS	polystyrene	
EPS	expanded polystyrene	buoys[1]
	Styrofoam	single-use food containers
PP	polypropylene	ropes
PE	polyethylene	ropes
HDPE	high-density polyethylene	buoys, nets and culture bags[1]
LDPE	low-density polyethylene	trash bags, tubing, food packaging[2]
PET, PETE	polyethylene terephthalate	common beverage bottle material and in textiles[3,4]
PMA, PMMA	polymethyl methacrylate	polyacrylate glass substitute (Plexiglas, Lucite, and Perspex)[5]
PPC	polypropylene carbonate	biodegradable thermoplastic used for high-performance polyurethane elastomers operating in harsh environments[6]
PU, PUR	polyurethane	insulation, cushions, soles of shoes, tires, adhesives, sportswear[7]
	rayon	clothing[4]
	cellophane	typically transparent thin film made of regenerated cellulose used as packaging material[8]
PA	polyamide	commonly referred to as nylon; used in clothing[3]
	poly(t-butyl acrylate)	paint, adhesive, fuel, textiles[4]
PC	polycarbonate or poly(bisphenol A carbonate)	wide range of industrial applications[4]
PVC	polyvinyl chloride	
	rigid PVC	geoduck aquaculture[9]
	flexible PVC	
PLASTIC ADDITIVES AND POTENTIAL LEACHED CHEMICALS		
HOCs	hydrophobic organic chemicals	includes polychlorinated biphenyls, organochlorine pesticides, hexachlorocyclohexanes, and hexabromocyclododecanes[10]
	styrene	Styrofoam monomer/oligomer[9]
BPA	bisphenol A	polycarbonate monomer[11]
	phthalates	plastic rope, flexible PVC[12]
PAEs	phthlalate esters	flexible PVC[9]
PBDEs	polybrominated diphenyl ethers	
HBCD	hexabromocyclododecane	

1 Jang et al. 2019
2 https://plasticranger.com/what-is-ldpe/
3 Castelvetro et al. 2021
4 Martinelli et al. 2020
5 https://www.plexi-craft.com/acrylic-plexiglass-lucite-clear-plastic
6 https://polymerdatabase.com/Polymer%20Brands/PPC.html
7 https://www.polyurethanes.org/en/what-is-it/
8 https://www.britannica.com/technology/cellophane
9 Lusher et al. 2017
10 Ogonowski et al. 2017
11 https://www.niehs.nih.gov/health/topics/agents/sya-bpa/index.cfm
12 Gardon et al. 2020

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