A global review on implications of plastic in seafood

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Executive Summary

Microplastics are commonly consumed by seafood species however, there is still limited understanding of the effects and implications that microplastics may have on the fishing and aquaculture industry. This project summarises research on the effects that microplastic may be having on seafood species and the contribution that the seafood industry is having to marine plastic pollution. Global literature on microplastic effects in seafood species revealed 1) that 93% of all species were negatively affected by plastics, although many studies used increased levels of microplastic contamination that are not environmentally relevant (i.e., generally do not reflect environmental conditions); and 2) 23% of plastic pollution in the marine and coastal environment originates from fishing and aquaculture sources. This report provides clear-sighted recommendations on the threats and opportunities that plastics hold for the seafood sector, as well as avenues for potential mitigation and reduction.

Background

Plastics are a crucial material for many fishing and aquaculture practices due to their versatility and water-repelling nature and are widely used across the seafood industry. Yet, plastic pollution is a significant global issue, with an abundance of research finding seafood species ingest plastic and microplastic, which has the potential to cause a number of negative biological and chemical effects. Despite numerous suggestions of the impacts of micro- and nanoplastics, we lack an understanding of their potential effects on seafood species and how they may reverberate through the fishing, aquaculture, and broader seafood industry sectors.

Aims/objectives

This study aimed to (1) undertake a systematic review of the global data on the effects and implications of plastic pollution on seafood species; (2) identify the percentage of plastic in marine environments coming from sources related to the seafood industry; (3) highlight key knowledge gaps, opportunities, and threats of plastic in the seafood sector; and (4) disseminate findings and information on effects and implications of plastic pollution on seafood species to fishers and managers**.**

Methodology

First, we systematically searched and reviewed the literature to collate the current knowledge on the effects of microplastic on seafood. There were 629 studies identified, and data on the experimental conditions, responses measured and effects were synthesised.

We completed a second systematic review of the literature for studies investigating the potential sources of plastic pollution in the marine environment. This review found 188 studies investigating the presence and source of plastic in waterways globally. This information was compiled, and data summarised.

Results/key findings

Microplastics were found to affect 93% of all specimens tested, however the levels of exposure varied. In many cases, effects were not seen until the exposure levels reached concentrations that were not environmentally relevant and are much higher than those currently found in our marine environment. There were several different effects recorded, including changes to behaviour, development and growth, immune function, reproductive, biomarker levels and mortality.

We found that globally 23% (±1.7%) of marine and coastal plastic can be attributed to fishery and aquaculture sources. There was a range of different results reported across studies, varying from 0% to 98%.

Implications for relevant stakeholders

This review provides industry, managers, and policymakers with an updated synthesis on the potential effects that plastic pollution and microplastics may pose to the seafood industry. It provides evidence that microplastics affect seafood species and highlights the importance of ensuring the levels of plastic in our environment do not reach concentrations that elicit and magnify these effects.

Keywords

Plastic pollution, microplastic, effects, fish, bivalves, crustaceans, molluscs, seafood industry

Introduction

As a result of our reliance on plastic materials, humans produce and use over 380 million tonnes of plastic annually (Geyer et al., 2017). An abundance of this plastic eventually ends up in the environment, with estimates of up to 12.7 million tonnes reaching the ocean each year (Jambeck et al., 2015). Plastic is now deemed ubiquitous across our waterways, with an estimate of 82 to 358 trillion pieces of plastic particles floating in the ocean (Eriksen et al., 2023). As plastic waste breaks down into smaller pieces, microplastics are formed (defined as pieces less than 5mm in size). Primary microplastics refer to plastic particles intentionally manufactured for various industrial or commercial purposes, such as microbeads in cosmetics or pellets used in plastic production (Worm et al., 2017). Secondary microplastics are smaller plastic fragments that result from the breakdown of larger plastic items due to weathering, sunlight, and other environmental factors (Worm et al., 2017).

Both primary and secondary microplastics have been documented in a variety of marine species, including those that are caught and sold as seafood in Australia and globally (Ogunola et al., 2022; Rochman et al., 2015; Wootton et al., 2021a; Wootton et al., 2022). This includes important commercial fish (e.g., sardines, mackerel, tuna), crustacean (e.g., crabs, prawns) and bivalve species (e.g., oysters, mussels) from aquaculture and wild-caught sources (Bom and Sá, 2021; D'Costa, 2022; Wootton et al., 2021b). Microplastics can be consumed through primary ingestion, where fish mistakenly eat plastic either by confusing it for food or inhaling it unintentionally. Alternatively, secondary ingestion occurs when predators consume prey that has already ingested plastic (Nelms et al., 2018). This transfer through the food chain can result in the accumulation of microplastics within organisms at higher trophic levels, though recent meta-analyses suggest biomagnification is not supported by current field observations (Miller et al., 2020; Provencher et al., 2019).

Plastic ingestion can potentially cause a range of effects on biota species, with the size, quantity and type of plastic all contributing (Foley et al., 2018). When large quantities of plastic debris and microplastics are ingested, false satiation can occur, where a feeling of fullness prevents the individual from feeding appropriately, eventually causing nutrient deprivation and even starvation (Cole et al., 2011). Furthermore, the nature of micro but also even smaller nano-plastics (<1 µm) means that they are hydrophobic, allowing a suite of contaminants to adsorb to the plastic pieces from the water column, creating a ‘chemical cocktail’ and increasing the potential risks that microplastics pose to seafood (Rochman, 2015). The combination of the adsorbed chemicals, as well as the synthetic materials and chemicals that already exist within the microplastic, have the potential to lead to a plethora of negative effects. This includes toxicity to the digestive and endocrine systems, changes in reproductive function and behaviour, and even mortality (Foley et al., 2018). Additionally, nutrition and growth problems could occur, impacting fish health and potentially stock productivity.

Despite numerous suggestions of the impacts of micro- and nanoplastics we lack an understanding of their potential effects on seafood species and how they may reverberate through the fishing, aquaculture, and broader seafood industry sectors. Knowledge of the consequences of nano- and microplastics is crucial for bridging the gap in assessing the potential harm they pose to seafood species and the subsequent implications for the seafood industry. This report aims to address this question, providing a systematic review of current literature on microplastic effects on seafood species, in the context of potential risks that this may pose to fisheries and aquaculture industries.

Further to this, plastics are a crucial material for a large number of fishing and aquaculture practices due to their versatility and water-repelling nature and are widely used across the seafood industry. Plastic materials are used in nets, ropes, lines and other fishing gear, as well as in the cages and floats in aquaculture infrastructure. The packaging used to transport seafood produce to seafood shops for purchase is also commonly plastic, with styrofoam boxes, plastic crates and plastic liners, wrappers and bags used across the supply chain. While plastic materials are commonly used across the fishing and aquaculture industries, there is limited detail on the sources and quantity of these plastics which may end up in our marine environment. Previous reports in 2015 and 2016 estimated 80% of marine plastic was from land-based sources and 20% from marine based sources (Jambeck et al., 2015; Li et al., 2016). However, this information requires updating, and we require further evidence to correctly calculate the abundance of plastic that may be directly linked to the fishery and aquaculture industries. Therefore, we reviewed global studies that collected plastic in the marine environment to compile information on the amount and percentage of plastic from fishery and aquaculture sources. This review compiles an accurate picture of the industry's contribution to marine plastic pollution and can be harnessed to identify opportunities and threats of plastic contamination to the seafood sector, as well as tailor targeted actions to reduce and mitigate plastic use.

Objectives

1. Undertake a systematic review, collating, synthesising, and analysing global data on the effects and implications of plastic pollution in seafood species and the seafood industry.

2. Identify potential sources of plastic in marine environments, including the percentage coming through seafood sources.

3. Highlight key knowledge gaps, opportunities, and threats of plastic in the seafood sector.

4. Disseminate findings and information on effects and implications of plastic pollution on seafood species to fishers and managers.

Method

Systematic review

For the first two milestones, systematic literature searches were completed. Considering its wide acceptability and preference in the scientific community, we followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Moher et al., 2010) for both literature searches. All statistical analyses and graphs were completed using R (Version 2021.09.1) and Microsoft Excel.

Effects and implications of plastic pollution on seafood species

The literature search used both Scopus and Web of Science scientific citation databases, accessed through the University of Adelaide library. The search was completed on the 2nd of August 2022 and the title, abstract and keywords searched using the following criteria: (*plastic*) AND (fish* OR crustacea* OR bivalv* OR mollusc* OR seafood) AND (effect* OR impact* OR toxicity). The asterisk acts as a wildcard, to allow derivatives of the words to be recognised (e.g., effect* also searches for effects, or effecting). These search terms found 7,307 studies in Web of Science and 12,474 studies in Scopus, totalling 15,245 following the removal of duplicates (Figure 1).

The abstract and title of the 15,245 studies were initially scanned for eligibility, with studies that investigated the effects of plastics or chemicals associated with plastics on seafood species selected (n=897). Due to the large number of studies identified, and the research question being investigated, it was decided that only studies that tested microplastic specifically (rather than chemicals related to microplastic such as Bisphenol A, Benzenol, etc.) would be included, so a further 335 studies were removed. However, studies that tested the effects of microplastics in combination with other chemicals (e.g., polypropylene and benzo(a)pyrene) were still included. These studies were included as microplastics commonly adsorb chemicals in the marine environment, so for a holistic picture of the effects of microplastic it is important chemicals are also considered. Seafood species included fish, crustaceans, molluscs (of any species) and also included commonly used model species, that are commonly used laboratory based studies, such as zebrafish (*Danio rerio*), medaka (*Oryzias latipe*), Daphnia (*Daphnia spp*.) and brine shrimp (*Artemia spp*.).

Information from a suite of variables was collected, including study location, species, age, sample size, polymer type tested, route of exposure and details on the types of effects recorded (see Table 1). Data were taken directly from the text or data tables of individual studies.

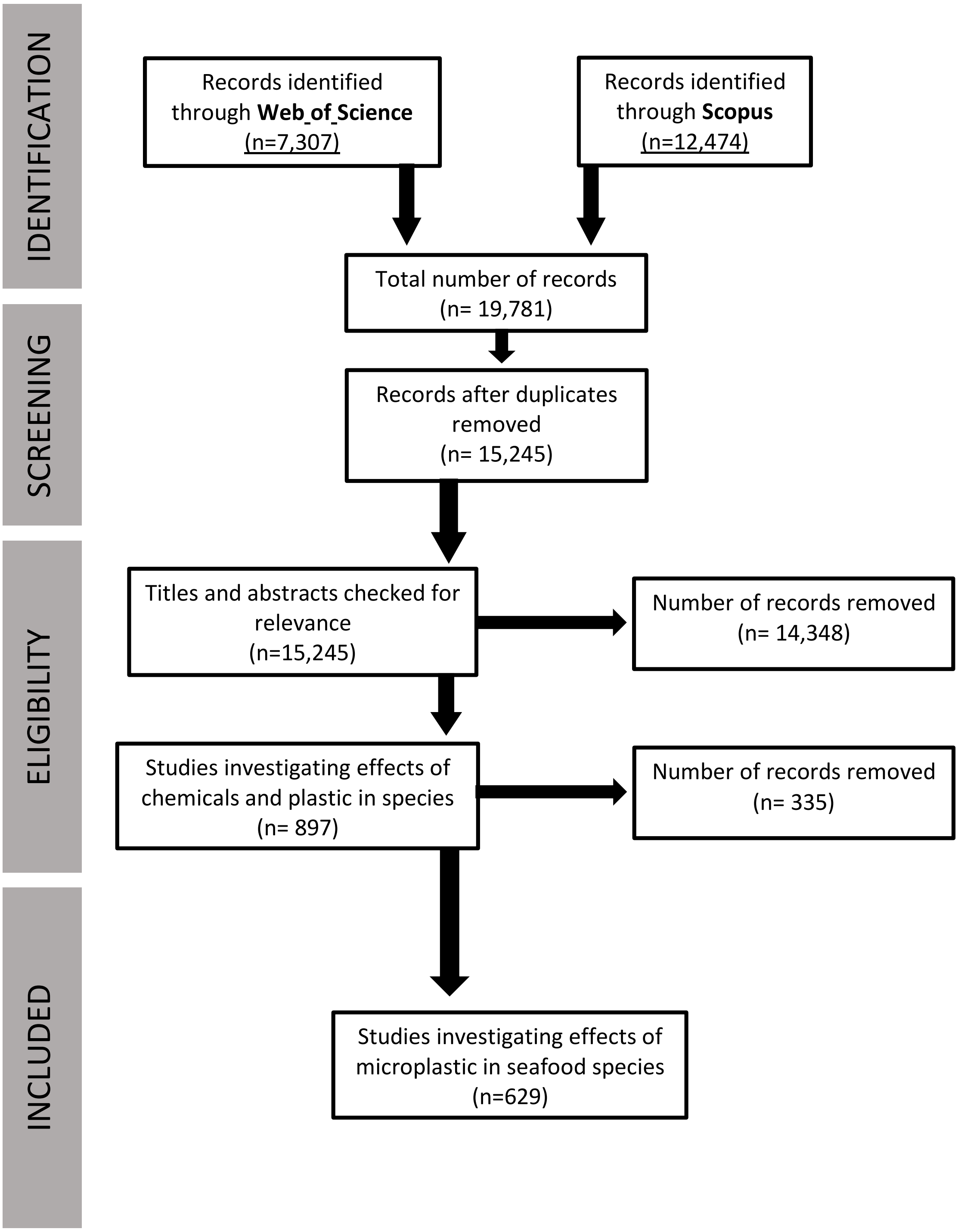


Figure 1: Flow chart outlining the criteria for inclusion of studies in the systematic review for the first milestone search following the PRISMA (Preferred Reporting Items for Systematic Reviews) framework.

Table 1: Summary of information extracted from studies investigating the effects and implications of plastic pollution on seafood species.

	Variable	Description and range
Study information	Authors and title	Author list and title
	Location	Country where the experiment took place
	Experimental set-up	Laboratory, wild
Species information	Species	e.g., *Gadus morhua*
	Species group	Fish, Crustacean, Mollusc
	Age	Embryo, Larvae, Juvenile, Sub-adult, Adult
	Sample size tested	Number of samples per treatment tested
Microplastic	Polymer type	Type of polymer species exposed to (e.g., polyethylene, polypropylene, etc.)
	Size	Size of microplastic used in exposure, reported in μm. In studies where multiple sizes were tested, a list is provided
	Concentration	Concentration of microplastic species were exposed to. In studies where multiple concentrations were tested, a list is provided
Contaminant	Contaminant tested	Yes or No if an additional contaminant was tested with plastic
	Contaminant type	Information on additional contamination (e.g., Cadmium, Ammonia, etc.)
	Concentration	Concentration of contaminant species were exposed to. In studies where multiple concentrations were tested, a list is provided
Exposure	Exposure pathway	Water, ingestion, ingestion via prey, injected
	Exposure time	Time exposure occurred for (seconds, minutes, hours or days). In studies where multiple times were tested, a list is provided
Effects	Effect seen	Yes, No, NA
	Description of effect/s observed	Qualitative summary of effects tested
Effect measured	Mortality	Mortality, Immobility
	Reproductive success	Hatching rate, Heart rate, Neonate production, Age of first brood, Malformation rate, Average hatching time, Fertilisation rate, Number of offspring, Number of eggs, Brood size, Hatching success, Mortality of offspring, Sex hormone count, Frequency of spawning event, Pregnancy condition, Percentage of pregnant individuals, Number of aborted eggs, Deformities in young
	Biomarkers	Oxidative biomarkers (e.g., ROD, SOD, CAT, GSH, MSA, N+/K+-ATPase, ROS, LPO, GPx), Enzymes (e.g., PPS, LPS, AMS, Trypsin, Chymotrypsin), Genetic information (e.g., DNA damage, RNA)
	Development	Growth, Body length, Body weight, Condition factor, Hepatosomatic index, Viserosomatic index, Weight gain rate, Specific growth rate
	Immune function	Phagocytosis assay, % granulocytes, % haemocytes, Proinflammatory cytokine levels, Glutathione metabolism, Lysosomal membrane stability, Haemocyte total count, Phagocytic activity of haemocytes, Hemolymph protein concentration, Cytokine levels, Immunoglobin levels, Red blood cell count, White blood cell count, Packed cell volume estimation, Genetic analysis of genes related to immune function, Phytohemagglutinin level
	Behaviour	Locomotion, Swimming speed, Feeding rate, Environment exploration, Swimming trajectory, Predatory performance, Distance moved, Clearance rate, Territorial contest, Activity level, Resting behaviour, Feeding behaviour, Seizures, Shoaling,
	Histopathology	Gill, Liver, Intestine, Muscle tissue, Larvae, Gastro-intestinal tract, Pancreas, Spleen, Skin, Brain, Testes, Ovaries, Lysosome, Soft tissues, Hemocyte
	Effective and lethal doses	EC50, ED50, LD50, LC50

Potential sources of microplastic in the marine environment

The second literature search also used Scopus and Web of Science scientific citation databases. The search was completed on the 1st of April 2023 and the title, abstract and keyword searched using the following criteria: (*plastic*) AND (source*) AND (seafood* OR fishing OR aquaculture OR fisheries). These search terms found 1,978 studies in Web of Science and 988 studies in Scopus, totalling 2,373 following the removal of 593 duplicates (Figure 2).

Abstracts and titles of 2,373 studies were scanned for eligibility, with studies that sampled plastic or microplastic in coastal environments selected (n=518). These 518 studies were downloaded, and further checked for eligibility and appropriate data. A further 330 studies were removed as they did not provide appropriate information on the sources of plastic pollution (e.g., microplastic studies that at times determine plastic type but not the specific source), were review papers, sampled biota, freshwater environments, or used modelled data.

From the remaining 188 studies, information from a suite of variables was collected, including study location, year, type of sampling, the total number of plastics counted, the plastic load and the measuring unit, and the percentage of plastic that was attributed to having originated from fisheries or aquaculture sources (see Table 2). Data were taken directly from texts, graphs or data tables from studies.

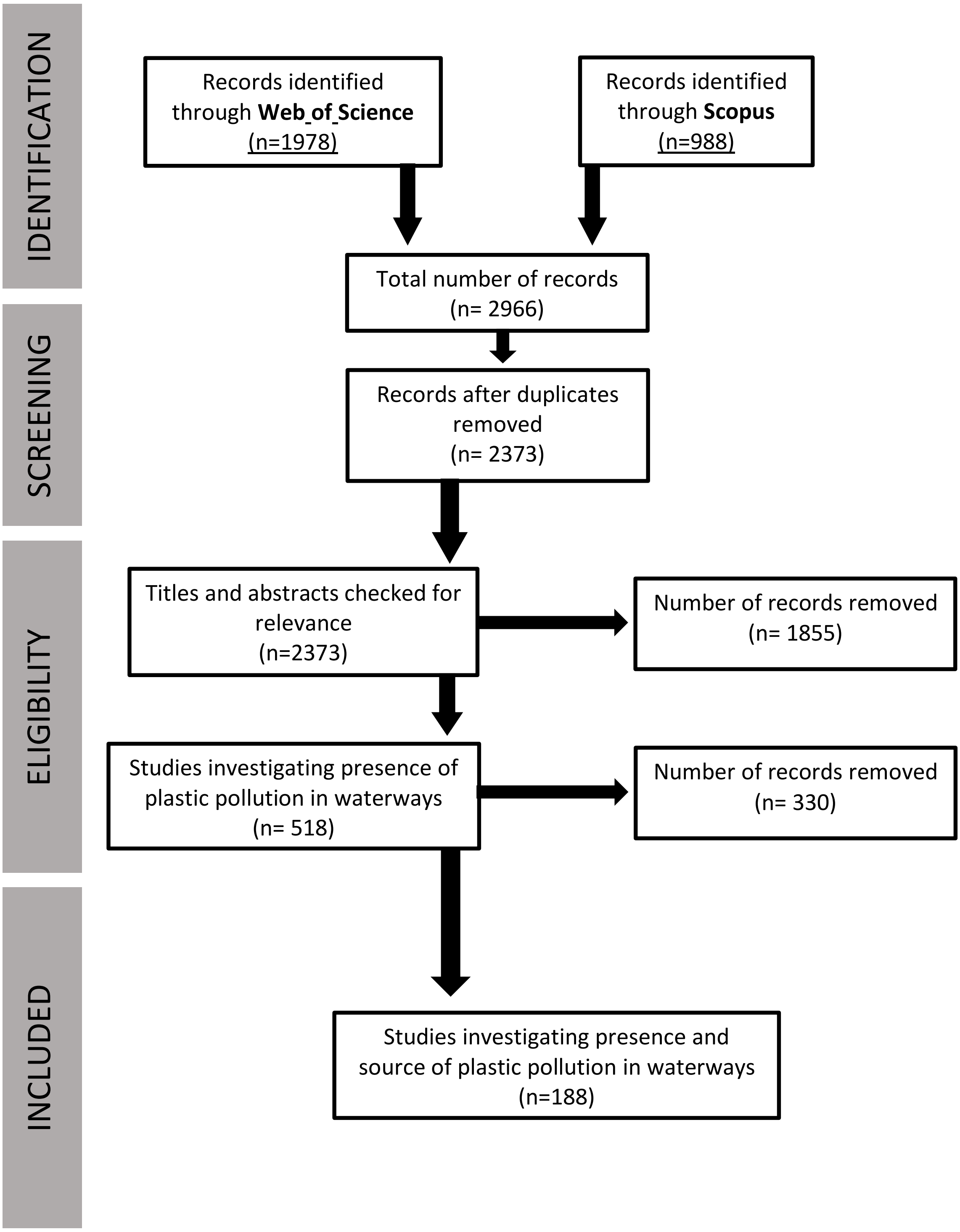


Figure 2: Flow chart outlining the criteria for inclusion of studies in the systematic review for the second milestone search following the PRISMA (Preferred Reporting Items for Systematic Reviews) framework.

Table 2: Summary of information extracted from studies investigating potential sources of microplastic in the marine environment.

	Variable	Description and range
Study information	Authors and article title	Author list and title
	Year(s) the sampling took place	1994 - 2021
	Location, country and latitude, longitude	e.g. Nha Trang, Vietnam (12.2529, 109.1899)
	Region	North America, South America, Europe, Middle-East, Africa, Asia, Oceania, Antarctica
Survey type	Sample collection	Beach survey, Surface water trawl, Scuba survey, Bottom trawl, Visual surface survey, Debris retention boom, Remote operated video
	Matrix	Beach survey, Water, Sediment
	Environment	Coastal, Estuarine, Marine, Freshwater
	Size limit	>0.45µm - >5mm, Not reported
Results	Plastic load	Average amount of plastic per unit of measure
	Plastic load measuring unit	Unit that plastic load is reported in (e.g., pieces/m^2, kg/km^2)
	Total number of plastics collected/counted	Count of the number of plastic items surveyed
	Percentage of plastic from fisheries and/or aquaculture	Average percentage of plastic items that originated from the fishery or aquaculture industry

Results and Discussion

Effects and implications of plastic pollution on seafood species

There were 629 studies which exposed microplastics to fish, crustacean and mollusc species. Most studies came from China, where our search found 205 studies (Figure 3). The countries with the next highest research effort were Italy and Portugal, with 39 and 38 studies testing microplastics in seafood species, respectively. This was followed by Spain (N=36), United States of America (N=33) and Korea and the United Kingdom (both N=23). Australia had a total of nine studies included (Table 3). The nature of this experimental based research means that global research effort is still applicable in the Australian setting, even if not occurring on species commonly found in Australian waters.

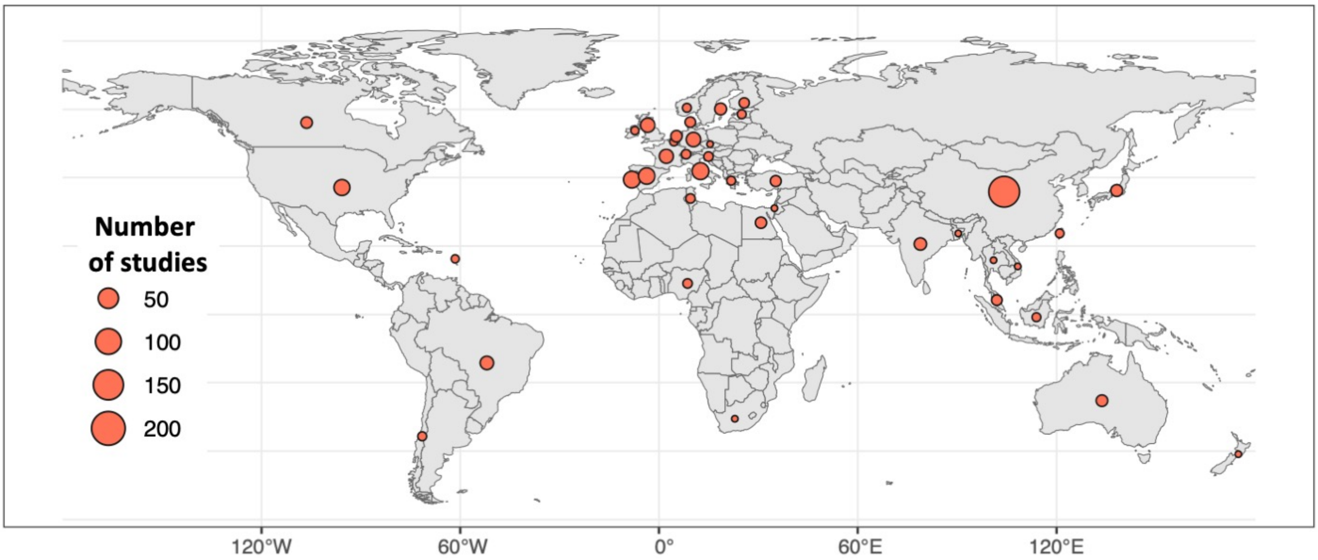


Figure 3: World map with locations of studies that expose microplastics to seafood species. The size of the dot correlates to the number of studies from the country.

The majority of studies (N=312) tested microplastic effects on fish, with almost half (N=152) on model organisms (zebrafish and medaka) (Figure 4). Sixty different species were tested, including popular seafood species *Salmo trutta* (trout), *Oreochromis sp* (tilapias), *Sparus aurata* (gilt-head bream) and *Cyprinus carpio* (carp). There were 148 studies in total testing 46 different species of crustaceans, including major seafood species such as *Litopenaeus vannamei* (whiteleg shrimp), *Penaeus monodon* (tiger prawn) and *Marsupenaeus japonica* (Japanese tiger prawn) but similar to fish, a large portion of studies (N=84) were on model organisms (daphnia and brine shrimp). Additionally, there were 139 studies testing molluscs (including bivalves and gastropods), with 56 experimenting with commercially important mussel species from the *Mytilus* family (*Mytilus edulis, Mytilus coruscus, Mytilus galloprovincialis)* and 13 from the *Crassostrea* oyster family.

The mix of model organisms and seafood species creates a rich dataset that covers species from several trophic levels, habitats and geographic regions. Model organisms like zebrafish and daphnia offer a standardised approach and directly comparable data, with effects related to other seafood species through shared evolutionary pathways and similarity in biological processes. The rapid reproduction and short lifecycles of model organisms enable the study of long-term effects in a compressed timeframe. While smaller in size, these models provide foundational insights that contribute to a broader understanding of microplastic impacts in aquatic ecosystems. In the same sense, the inclusion of species of seafood that are common in fisheries and aquaculture is important, as relying solely on model organisms may overlook specific biological responses unique to seafood, limiting our understanding of the comprehensive ecological and health implications of microplastic contamination.

Across all species groups, there was a large percentage of studies that found microplastic to affect tested specimens (94.2% in all fish, 89.9% in all crustaceans, 93.5% in molluscs). This trend is replicated across model organisms (97.3% of fish and 91.7% of crustaceans) (Figure 4) and likely reflects the tendency to publish significant results over non significant ones. Overall, despite the clear trend in studies describing effects from microplastics, there is a large variation in experimental designs and conditions across studies, with differences in concentrations tested, exposure route (Figure 5), exposure time, polymer type tested (Figure 6), and type of effect and endpoint measured (Figure 7).

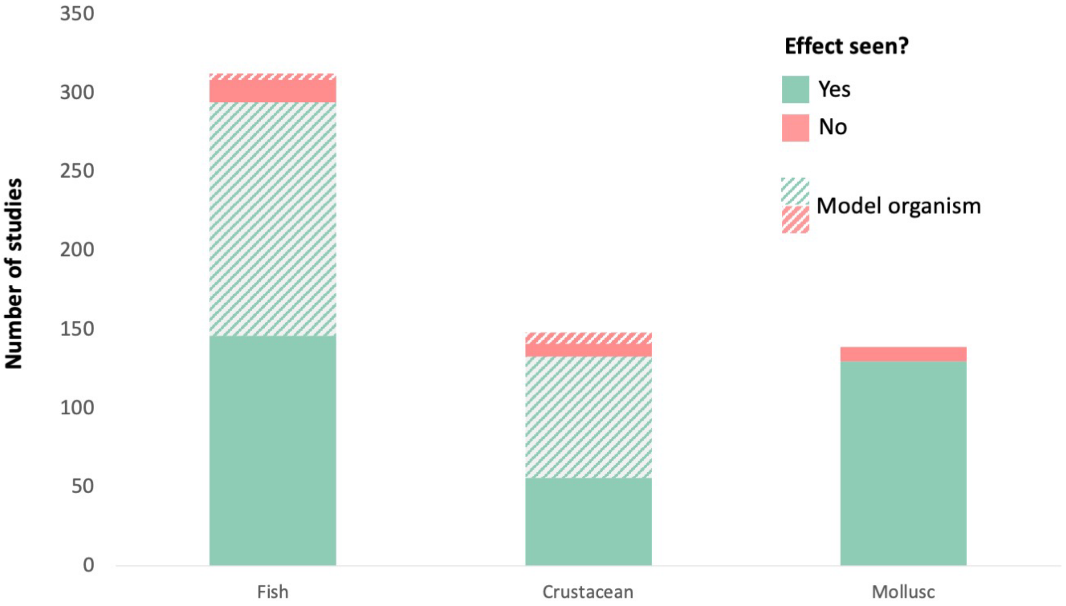


Figure 4: Number of studies per biota group showing effects or not of microplastics. Green shows studies where effects were observed, while pink shows studies where effects were not observed. The hatched line pattern represents number of studies using model experimental organisms (e.g., zebrafish, daphnia, medaka and brine shrimp). Thirty-four studies are not included due to not specifically testing effects (e.g., ingestion, trophic transfer etc.).

Further to this, between the studies there is a large variation in the concentration of microplastics that seafood organisms are exposed to. The vast majority of studies (99.3%) exposed specimens to maximum levels of microplastic higher than what is currently estimated in the marine environment (environmentally relevant levels of 1µg/L as seen in Lenz et al. (2016)). Note this value included only the 389 studies which reported their microplastic exposure concentrations in weight per volume. Some studies exposed specimens to levels as high as six grams per litre (LaPlaca and van den Hurk, 2020), significantly more than what is likely to be found in the environment.

The most common exposure route for the microplastics was via water (66% of studies) (Figure 5). Usually, water exposure involved adding microplastics into the tank or holding container where the specimens were housed (e.g., Romano et al., 2018). Ingestion was the other most commonly used method for exposure, where 28% of studies fed the test specimens microplastics by combining it in differing percentages with feed (e.g., Beiras et al., 2018). A small percentage of studies (2.3%) exposed organisms to microplastic via prey items (e.g., prey items consumed microplastic before being fed to the tested organism). The latter method aimed to test trophic transfer of microplastics. For example, Kim et al. (2022) exposed yellow croaker (*Larimichthys polyactis)* to plastic via brine shrimp. Overall, the large variation in exposure and experimental approaches creates difficulties in comparing the amount of microplastics that are being consumed by the tested organism, and subsequently directly comparing the effects or implications of the microplastics on the organisms.

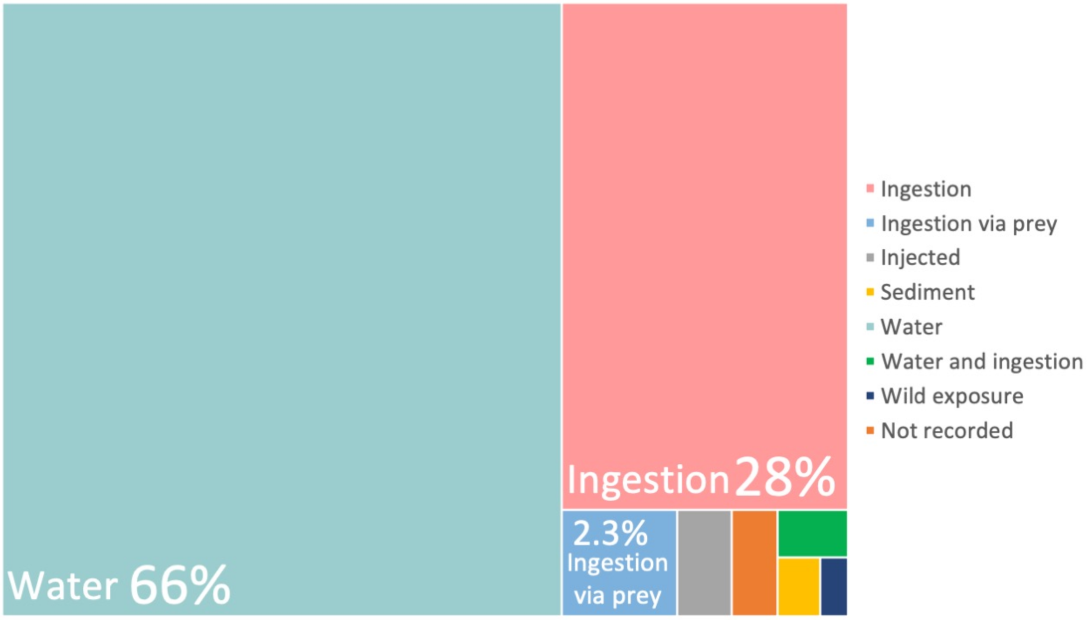


Figure 5: Percentage of studies using different routes of exposure of microplastic (Total N = 629).

When it came to the type of polymer that specimens were exposed to, almost half of the studies (49.6%) used polystyrene (Figure 6). The size of the polystyrene varied from 0.05µm (e.g., Elizalde-Velázquez et al., 2020) to 500µm (e.g., Graham et al., 2019). The next most common polymer type was polyethylene (20.2%), which includes a mixture of high-density polyethylene and low-density polyethylene. Additionally, there were several studies that compared or tested a variety of different polymers (10.8%). Interestingly, only 14 studies (2.2%) used microplastics that were collected from the environment. Using microplastic sourced from the environment likely reflects a more realistic complex composition, sizes and degradation stages of the microplastic pollution specimens face in the environment. The wide array of polymer types used across studies could influence the different effects observed. For instance, more flexible polymers might lead to increased ingestion rates, while brittle ones could result in greater fragmentation within organisms. Additionally, variations in the natural chemical properties among the different polymer types may be responsible for eliciting distinct biological responses.

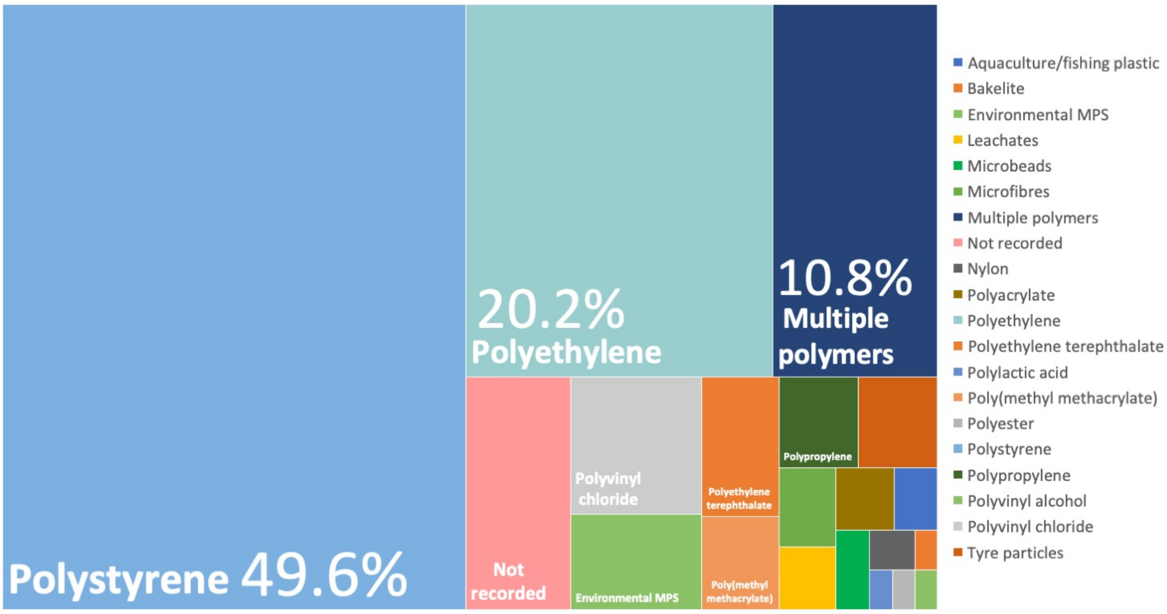


Figure 6: Number of studies that exposed organisms to particular polymer types. Multiple polymers refer to studies that exposed a variety or mix of polymers (Total N = 629).

There were 186 studies (29.6%) that also tested the effects of contaminants, as well as microplastic. Contaminants included a wide array of heavy metals, pesticides, pharmaceuticals, organic pollutants, and plastic residues. The most common contaminant tested was benzo(a)pyrene, a polycyclic aromatic hydrocarbon (PAH) compound that is formed during the incomplete combustion of organic materials such as fossil fuels, tobacco, and certain foods. The addition of contaminants into the studies adds an important layer of information as to how microplastics may be interacting with contaminants in the marine environment (Rochman, 2015). Incorporating both contaminants and microplastics in the analysis of their effects on marine species is crucial due to the intricate interplay of stressors within marine ecosystems. Contaminants like heavy metals and organic pollutants can interact with microplastics, potentially magnifying adverse impacts on organisms' health and ecological interactions. Additionally, there are limited studies investigating compostable/biodegradable polymers (e.g., polylactic acid), which would be interesting to explore further, considering the potential increase of these sorts of polymers in the marine environment (Chen, 2022). Further to this, it would be interesting to compare how the negative effects of microplastic may differ to those caused by natural debris (e.g., sand particles, rocks). One study from Australia comparing the effects of natural particles to polyvinyl chloride (PVC) particles in mussels found that PVC caused slight decrease in body condition compared to natural particles (Yap et al., 2020). However, another study, also from Australia, found that there was no differences in effects between natural particles and PVC/ Polymethyl Methacrylate (relative to controls with no particles) in mussels (Hamm et al., 2022).

There was a large variety in effects tested, endpoints measured, and types of data collected across the 629 studies. Broadly there were eight key groups of effects measured (Figure 7), although within each effect the data collected varied across a diverse suite of endpoints (see Table 1 above for a full description, or Table 3 for examples). By far, the most common experiment, related to changes in biomarker responses (430 studies). These biomarkers included oxidative stress indicators, such as reactive oxygen species (ROS) and different antioxidant enzyme activity (e.g., glutathione peroxidase GSH, superoxide dismutase SOD, catalase CAT) as well as markers of inflammation, genotoxicity, and cellular damage. Mortality of species was also commonly recorded, with 279 studies collecting data on mortality as an endpoint, with data often collected on survival rate, mortality rate, and time to mortality after exposure to microplastics. Information collected on development (N= 243) included parameters such as growth rate, size, weight, and changes in developmental milestones; while behaviour (N=168) included changes in feeding, activity levels, predator-prey interactions, movement patterns, and habitat preference. Histopathology studies (N=149) looked at the histology and pathology of several different organs and reproductive success (N=132), collecting data on changes in reproductive organ development, egg production, sperm quality, fertilisation success, and embryo viability. A total of 71 studies tested for half maximal effective and lethal concentration (e.g., EC50, LC50) (N=71). Finally, tests on immune function (N=56) collected information on immune cell counts, immune enzyme activity, expression of genes related to immune responses and phagocytic activity.

In Australia specifically, there have only been nine studies investigating microplastic exposure in fish, crustacean and mollusc species (Table 3). In these studies, there were a range of different exposure conditions, and endpoints measured (Table 3). Noticeably, there are only three studies that tested species (*Mytilus galloprovincialis, Mytilidae spp.*) which are commonly consumed as seafood (Hamm et al., 2022; Tosetto et al., 2017; Trestrail et al., 2021; Yap et al., 2020). This highlights a clear gap in literature focusing on testing the effects of microplastic on common Australian seafood species, and we recommend more research is completed to help fill this space.

Overall, the literature reported that exposure of seafood species to microplastic, irrespective of the polymer type, size, concentration, or time, caused several negative effects, including reduced consumption, decreased growth, compromised immunity, inflammation and altered gene expression (Figure 8). This aligns with recent meta-analyses on freshwater and marine fish (e.g., Hossain and Olden, 2022) and studies that looked at a small number of specific response categories (e.g., Foley et al., 2018), and which also highlight many studies with no impact. It is important to highlight that whilst effects are reported, the variety in methodology makes it intrinsically difficult to accurately compare studies and the datasets are hampered by the use of unrealistic exposure conditions. A need for more consistent tests, methodological approaches and setups, as well as reporting information is key for broader comparison.

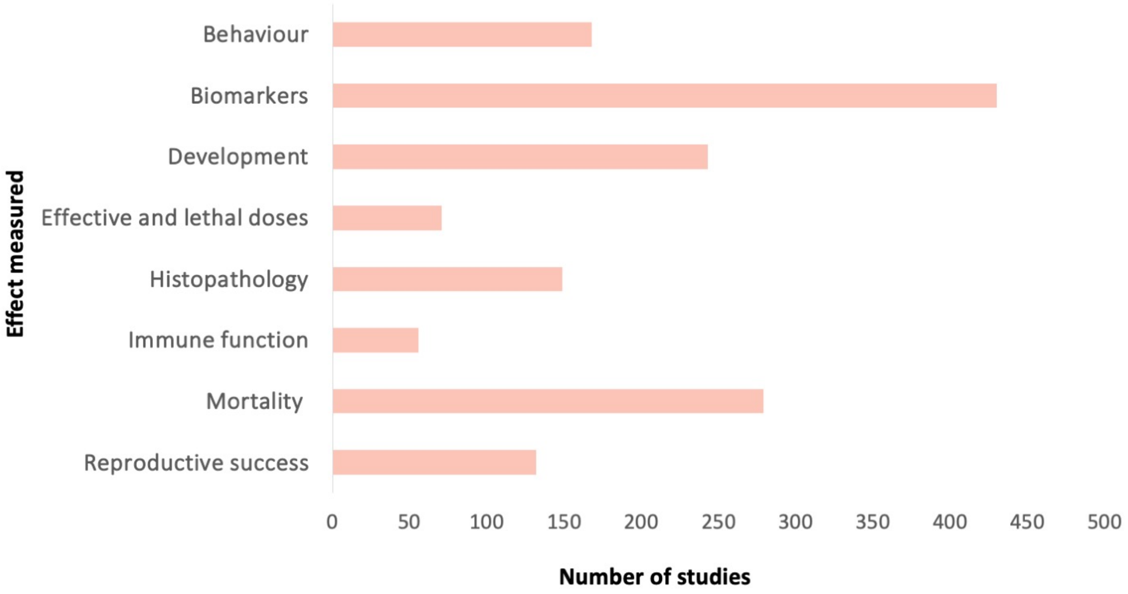


Figure 7: Number of studies which tested different effects. Within each effect group a variety of different metrics were measured (see Table 1 in methods for list of measured effects)

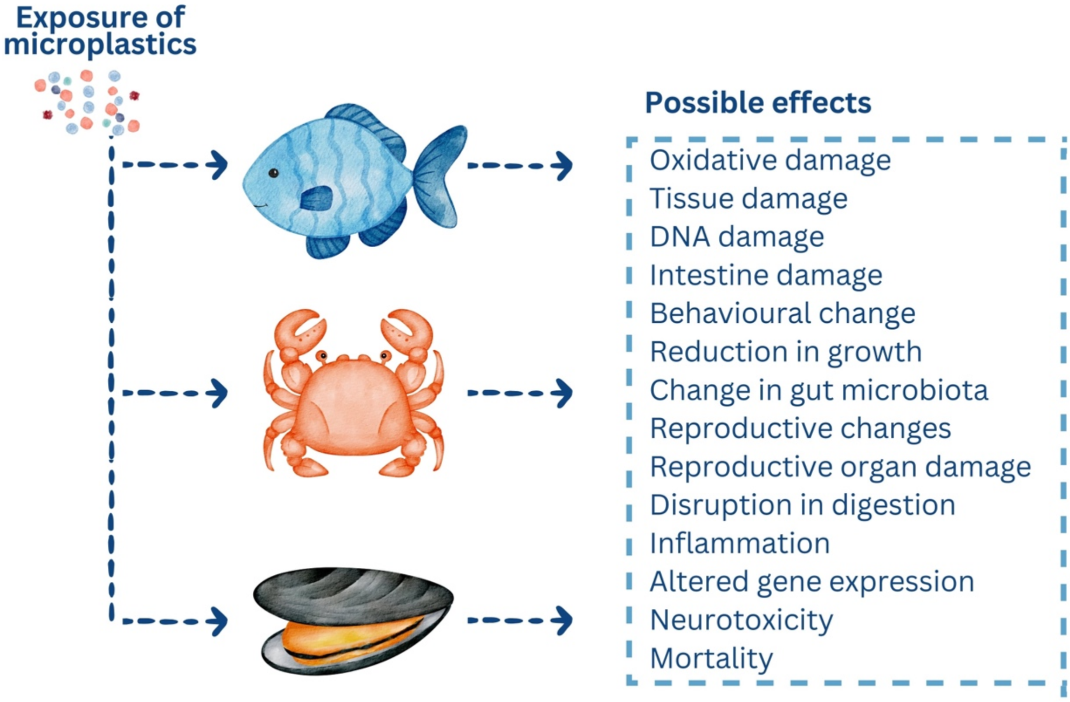


Figure 8: Summary graphic highlighting some of the key effects that were identified in studies exposing microplastic to seafood species.

Table 3: Summary of studies exposing seafood species to microplastic from Australia.

Study title	***Species tested***	**Group of species**	**Age**	**Sample size**	**Polymer type and concentration**	**Exposure time and pathway**	**Time**	**Description of effects seen**	**List of tested effects**	**Reference**
Foaming at the mouth: Ingestion of floral foam microplastics by aquatic animals	*Artemia spp., Daphnia magna, Danio rerio*	Crustacean, fish	Nauplii, neonate, embryo	15 per treatment	Phenol-formaldehyde. 0, 1, 10, 20, 30, 40, 50 mg/mL.	Ingestion	48 hours, 96 hours	Regular foam microplastic leachate and physical presence of MPs exerted separate and cumulative effects of changes in biomarkers	Exposure, biomarker analyses, hatching rate, mortality, phenol compound quantification	(Trestrail et al., 2020)
Trophic transfer of microplastics does not affect fish personality	*Bathygobius krefftii*	Fish	Adult	14 per treatment	Polyethylene	Ingestion via crustacean	Until crustacean was consumed	No effects seen	Personality, behaviour, trophic transfer	(Tosetto et al., 2017)
Microplastic exposure interacts with habitat degradation to affect behaviour and survival of juvenile fish in the field	*Pomacentrus ambionensis*	Fish	Nauplii	10 per treatment	Polystyrene. 167 MPs/L	Ingestion	4 days	Bolder and more active fish that stray further from shelter	Behaviour, survival	(McCormick et al., 2020)
Effects of microplastic exposure on the body condition and behaviour of planktivorous reef fish (*Acanthochromis polyacanthus)*	*Acanthochromis polyacanthus*	Fish	Juvenile	30 per treatment	Polyethylene terephthalate. 0, 0.025, 0.055, 0.083, 0.1 mg/L	Ingestion	6 weeks	Negative effect on growth and body condition	Growth, body condition, behaviour	(Critchell and Hoogenboom, 2018)
Uptake and depuration kinetics influence microplastic bioaccumulation and toxicity in Antarctic krill (*Euphausia superba)*	*Euphausia superba*	Crustacean	Adult	15 per treatment	Polyethylene. 0, 10, 20, 40 or 80% plastic diet	Ingestion	10 days	No effects seen	Mortality, depuration, weight loss	(Dawson et al., 2018)

A comparison with natural particles reveals a small specific effect of PVC microplastics on mussel performance	*Mytilus galloprovincialis*	Mollusc	Adult	10 per treatment	Polyvinylchloride. 1.5, 15, 150 mg/L	Water	35 days	Body mussel condition lowered, but no difference in byssus production, respiration and survival rates	Mortality, respiration rates, byssus production, weight change, body condition index (BCI).	(Yap et al., 2020)
Microplastics alter digestive enzyme activities in the marine bivalve, *Mytilus galloprovincialis*	*Mytilus galloprovincialis*	Mollusc	Adult	6 per treatment	Polyethylene, Polystyrene. 10,000-50,000 MPs/L	Water	7 days	Enzyme activity altered, decreased cellulase and xylanase. No change to laminarinase, lipases, esterase, increased amylase, protease.	Enzyme activity	(Trestrail et al., 2021)
Microplastics on beaches: ingestion and behavioural consequences for beachhoppers	*Platorchestia smithi*	Crustacean	Adult	10 per treatment	Polyethylene. 3.8% dry weight of sediment	Ingestion	72 hours, 120 hours	Reduced jump height, increase in weight.	Behaviour related to survival, weight and length changes.	(Tosetto et al., 2016)
Plastic and natural inorganic microparticles do not differ in their effects on adult mussels (*Mytilidae*) from different geographic regions.	Mytilidae	Bivalve	Adult	Variable	Polymethyl Methacrylate, Polyvinyl Cholride	Water	6 weeks	Significant effects of suspended particles on respiration rate, byssus production and condition index of the animals. There was no significant effect on clearance rate and survival. No differences observed between natural and inorganic particles.	Survival, respiration rates, clearance rates	(Hamm et al., 2022)

Potential sources of microplastic in the marine environment

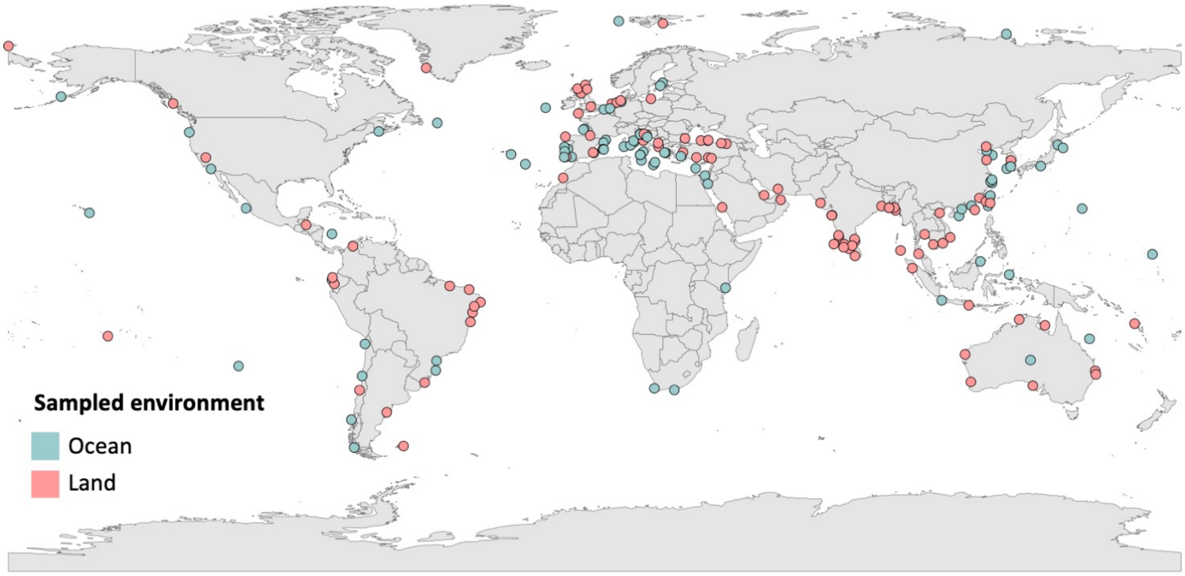


Figure 9: Global map of studies which investigate plastic pollution sources in marine environments. The blue shows studies that sampled in the ocean (e.g., open water trawls, scuba surveys), while the pink shows studies that sampled on the coast (e.g., beach survey).

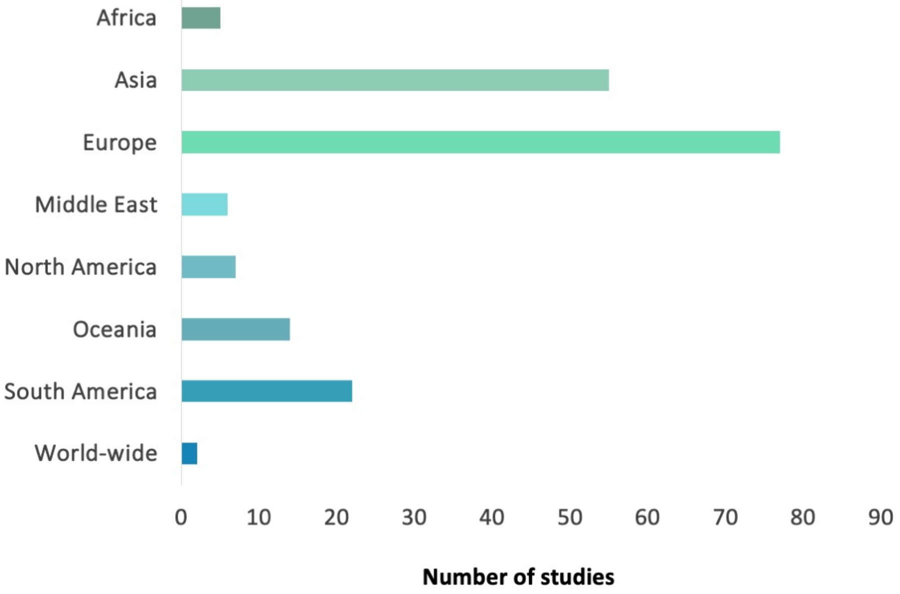


Figure 10: Number of studies investigating the sources of plastic pollution in marine and coastal environments from different regions.

There were 188 studies identified globally that investigated the sources of plastic pollution in marine and coastal waters (Figure 9). Regionally, there was a focus on research across Europe and Asia, with limited studies completed in Africa and the Middle East (Figure 10). This is reflected in the literature globally, where European and Asian countries tend to have a larger number of studies related to plastic pollution compared to other regions (Wootton et al., 2021b). Many additional studies were found that documented microplastic occurrence across coastal and marine environments (e.g., Karthik et al., 2018; Tan et al., 2020; Zhu et al., 2023) but these studies were excluded as whilst they reported polymer types, the exact sources of where those polymers may have originated were not identified and were only inferred, hence they were not included in the review.

Ninety-three studies focused on the ocean (e.g., water trawls or scuba surveys), while the remaining 107 were undertaken on the coast (e.g., beach surveys). The number of studies sampling plastic pollution in coastal and marine environments has grown rapidly over the past two decades (Figure 11). This trend is seen across a plethora of plastic literature (Iroegbu et al., 2021; Ostle et al., 2019; Wootton et al., 2021b), so was no surprise. While a decrease in the number of studies with data collected in the past three years may be expected, due to a natural delay in data being analysed and studies published, interestingly there is a slight dip in the number of studies published in 2021 to 2022 (Figure 11). This could potentially be due to research in the plastic pollution field moving towards a more increased focus on micro- and even nano-plastics. Whilst technological developments are key to increasing our capacity to identify the source of weathered microplastics in aquatic environments, studies, where plastic pollution can easily be identified back to its origins, continue to play an important role in our understanding of the spread of plastic. Without such data, it is difficult to monitor and attribute the sources and pathways of contamination, hence mitigation strategies are near impossible.

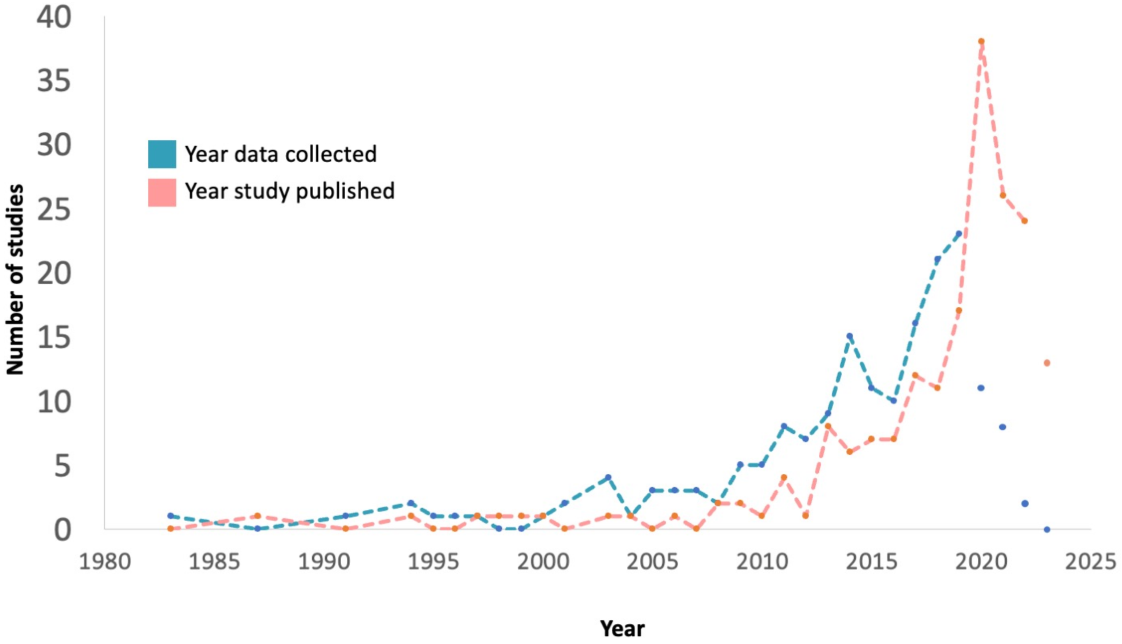


Figure 11: Number of studies investigating the sources of plastic pollution in marine and coastal environments since 1983. The blue line shows the year in which the data were collected, and the pink line shows the year that the study was published.

Globally, when all studies that contain information on the sources of plastic pollution are included, 23% (±1.7%) of plastic identified was attributed to fishery and aquaculture sources (N=162). Twenty-six studies were not included in the average calculations as they did not report data on sources with a category related to fishing/aquaculture. A range of different percentages were reported, varying from as low as 0% (Taryono et al., 2020) to as high as 98% (Consoli et al., 2018). Nonetheless, the finding of 23% is comparable to previous estimates suggesting ~20% of plastic pollution in the ocean originates from marine sources (Jambeck et al., 2015; Li et al., 2016). When comparing regions, Africa has the highest average percentage of plastic from fishing and aquaculture sources (29.25% ±10.8) (Figure 12). Oceania had the second lowest average percentage (18.1%), after the Middle East (13.7%).

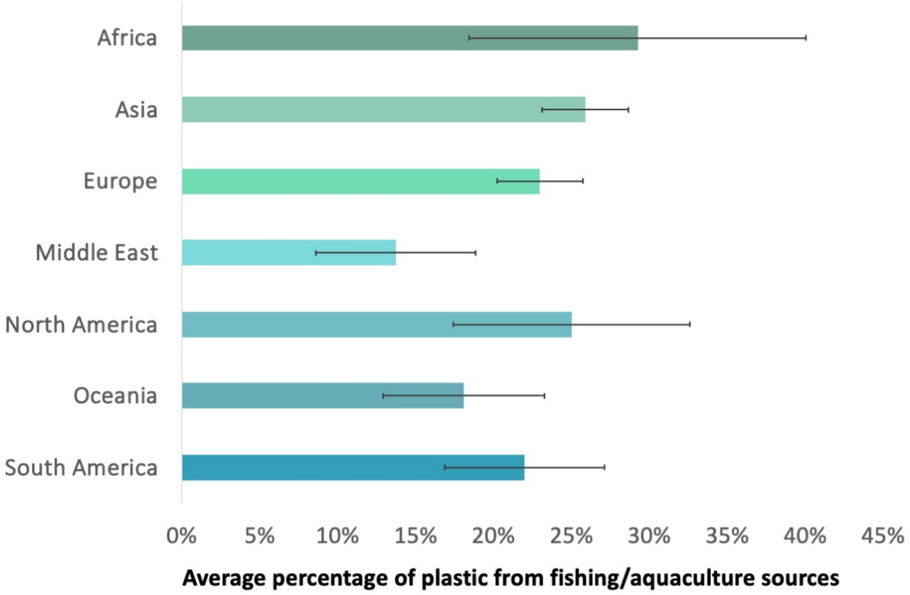


Figure 12: The average percentage of plastic pollution that can be attributed to fishing and aquaculture sources per region globally. The error bars represent the standard error of the data.

The most common sampling method was land-based beach surveys (Figure 13), with 105 studies sampling this way. Surface water and bottom trawls were the next most common, with 27 and 26 studies collecting their data using these methods respectively. Interestingly, the sampling method appears to impact the portion of plastic that can be attributed to fishing or aquaculture sources (Figure 14). Studies that collected their data using beach surveys, had the lowest percentage of plastic from fishing or aquaculture sources (18.1% ±1.5), Remote Underwater Video surveys detect a higher amount of plastic from fishing and aquaculture sources (50.3% ±8.8), likely linked to the spatial scale of the data collected using this method (e.g., it would be easier to detect large items like fishing nets etc., using the video). This discrepancy in methods highlights the importance of considering the research question of interest when collecting data, and ensuring methods are comparable.

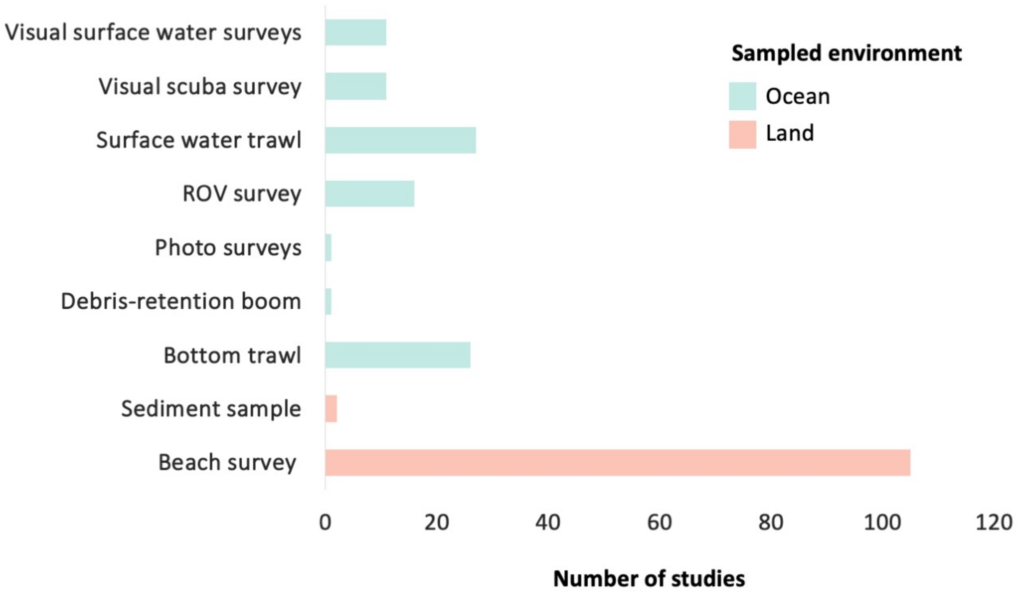


Figure 13: Number of studies investigating the sources of plastic pollution in marine and coastal environments using different sampling methods.

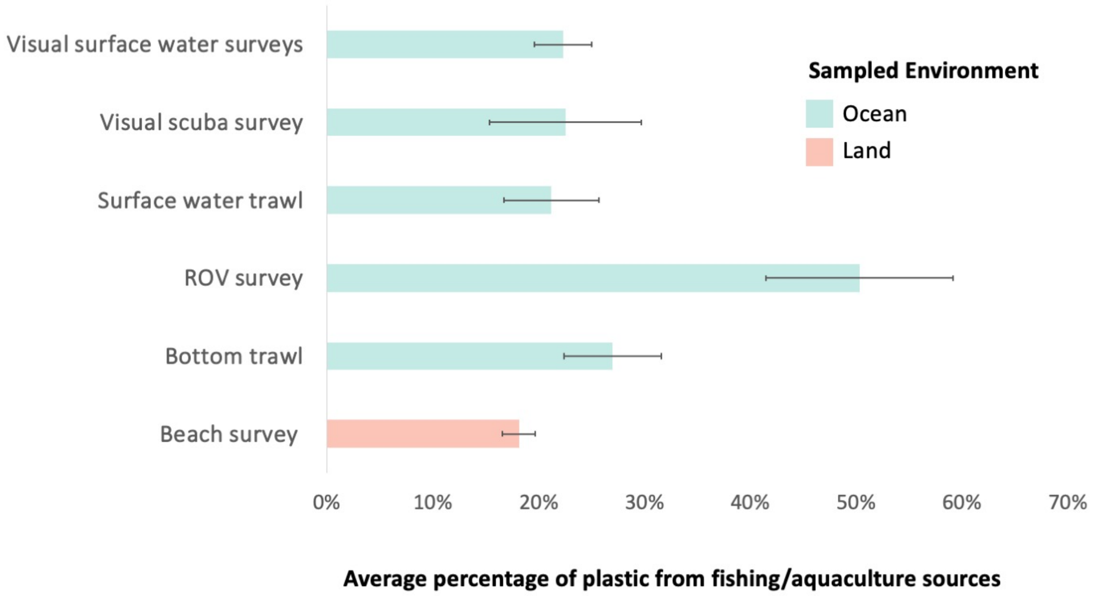


Figure 14: The average percentage of plastic pollution that can be attributed to fishing and aquaculture sources per sampling method. The error bars represent the standard error of the data.

Knowledge gaps, opportunities, and threats of plastic in the seafood sector

Plastic and microplastic pollution present significant knowledge gaps, opportunities, and threats to the fishing and aquaculture industries. The extent of plastic's impact on aquatic ecosystems and seafood safety requires further research, as the accumulation of these materials in water bodies and marine life is still not fully understood. However, this challenge also opens doors for innovation in waste management and sustainable packaging solutions that could reshape industry practices. Opportunities lie in developing advanced filtration and waste collection technologies to mitigate plastic contamination and in creating consumer demand for responsibly sourced seafood. On the other hand, the weight of evidence indicates plastic pollution can pose a direct threat to marine life, as ingestion of microplastics by seafood species could have biological and ecological consequences. Thus, precautionary principles should apply. Meeting consumer demands and addressing their concerns involves devising strategies to predict risks, implement managerial adjustments, and establish supply chains that minimise or eliminate plastic use through alternative eco-friendly packaging (e.g., disposable oyster trays (sugarcane pulp)). This process can serve as a foundation for exploring plastic substitutes for fishing equipment and materials, a task that presents an even greater challenge. Below, in Table 4, we highlight some of the key knowledge gaps, opportunities, and threats that plastic poses to the fishing, aquaculture and seafood sectors.

Table 4: Table highlighting the key knowledge gaps, opportunities and threats of plastic and microplastic in the fishing, aquaculture and seafood sectors.

Knowledge gaps	
Ecotoxicological understanding	A lack of synthesised understanding exists regarding the full range of impacts of micro- and nanoplastics on seafood species, particularly in terms of long-term ecological effects.
Economic impact assessment	Limited studies assessing the economic consequences of plastic contamination on fishing, aquaculture, and the broader seafood industry.
Seafood contamination	Quantification of the extent of plastic contamination in seafood. Understanding effect and thresholds for human impacts of microplastics is critical from food (seafood ingestion). This will help to establish thresholds of contamination, consumption and compare with other ambient contamination.
Ecosystem-level effects	Limited research examines the cumulative effects of plastics on marine ecosystems and the potential cascading impacts on entire food chains.
Adaptation and mitigation strategies	There is a need for research on effective strategies to reduce plastic pollution, including the development and implementation of sustainable packaging alternatives. While there are already some options on the market (e.g., biocane oyster trays, biodegradable plastic packaging for fishmongers, biodegradable liners for crates) focus on making these economically viable or even incentivised for fishers and fish mongers would be pertinent.

Microplastics in the seafood supply chain	Information on where in the seafood supply chain microplastics may be contaminating seafood produce (e.g., during processing or directly from the marine environment).
Threats	
Ecological disruption	Plastics can harm marine ecosystems, affecting species populations, habitat integrity, and biodiversity through ingestion, entanglement, and chemical contamination.
Food safety concerns	Microplastics in seafood raise potential human health risks due to ingestion of contaminated products, with associated toxins possibly entering the food chain.
Market reputation	The seafood industry could face reputational damage due to public backlash and consumer aversion if effective measures to mitigate plastic pollution are not adopted.
Regulatory and legal pressure	Increasing regulations to curb plastic pollution might lead to compliance challenges and financial implications for seafood businesses not adapting to sustainable practices.
Opportunities	
Technological innovation	Advances in waste management and recycling technologies provide opportunities to minimise plastic waste and develop circular economy models within the seafood sector. Further to this, alternatives to plastic use in fishing and aquaculture practices throughout the supply chain require investigation.
Consumer awareness and demand	Growing public concern about plastic pollution creates an incentive for seafood industries to adopt sustainable practices and reduce plastic usage, meeting consumer preferences. Developing biodegradable or recyclable packaging materials can align with environmental goals while catering to market demands for eco-friendly products.
Collaborative research initiatives	Partnerships between research institutions, industries, and regulatory bodies can accelerate understanding and action in addressing plastic-related challenges.

Conclusion

A global systematic review of over 600 studies found that microplastics can have negative effects on a range of seafood species, with changes in hormone levels, reproduction, behaviour, growth, and even mortality all observed. Although more than 90% of studies reported negative effects on the tested species, the concentration of microplastics that the specimens were exposed to were commonly much higher than what we would currently find in our marine environment.

The second literature review combined data from 188 studies to estimate the sources of plastic in the marine environment. This review found that on average 23% of the plastic that is found in our marine environment originated from the fishing and aquaculture industries, although a range of results were reported (0%-93%).

The insights provided throughout this study help recognise both opportunities and challenges posed by plastic contamination in the seafood sector, enabling precise strategies to minimise plastic usage and its impact.

Implications & Recommendations

This project provides the fishing and aquaculture industries, seafood consumers and managers with information on the potential threats and concerns that plastic may pose to seafood species. Although we found that most studies report negative implications of microplastic exposure to seafood species, the concentrations of contaminants the species were exposed to are significantly higher than what is currently found in the marine environment. These unrealistic exposure conditions, and mostly short-term experiments, hamper our understanding of long-term risks of microplastics in seafood. This finding indicates that the current risk of microplastics to the seafood industry is likely low, and the chance of the microplastics in Australian waters having large-scale impacts on the health of our fish stocks is limited. However, we should consider a precautionary approach and strive to lower plastic use within the seafood industry, among consumers and industry, to ensure that the microplastic levels in our environment do not reach higher levels where likelihood of negative effects occurring is increased. The seafood industry's proactive approach to addressing plastic waste serves as a response to growing consumer worries about contamination. Additionally, it helps meet consumers' increasing expectations for ethical practices, sustainability, and environmentally friendly attributes.

As is highlighted in Table 4 of the results and discussion, there are a number of key areas of research that need to be further explored. Whilst there are several limitations regarding data comparability across all information in this review, we suggest further analysis across specific response variables and comparable endpoints through meta-analysis. This could provide key information on potential thresholds and detail the risks of specific endpoints and how these may change depending on the species and concentration of microplastic and polymer type.

Extension and Adoption

Considering the field of microplastics is an emerging field, and the data we were collecting has the potential to be negatively communicated, it was essential that the messages we shared were clear. We worked alongside SafeFish and the communication team at FRDC to ensure that all of the outputs created from this project (multiple graphics and a summary video) were appropriately messaged. The summary video and graphics can be viewed below, in the project materials section.

The graphic used to announce the project has been shared widely across social media, and in a news article written in Fish News which informed those within the seafood industry that the project had commenced, while providing a broad overview of the project. The graphic was also shared at the Australian Society of Fish Biology 2022 conference on the Gold Coast, various community talks, and at the Microplastics and Seafood: Human Health symposium in the United Kingdom. Seafood stakeholders from around the world were present at the symposium, as were microplastic and fishery scientists.

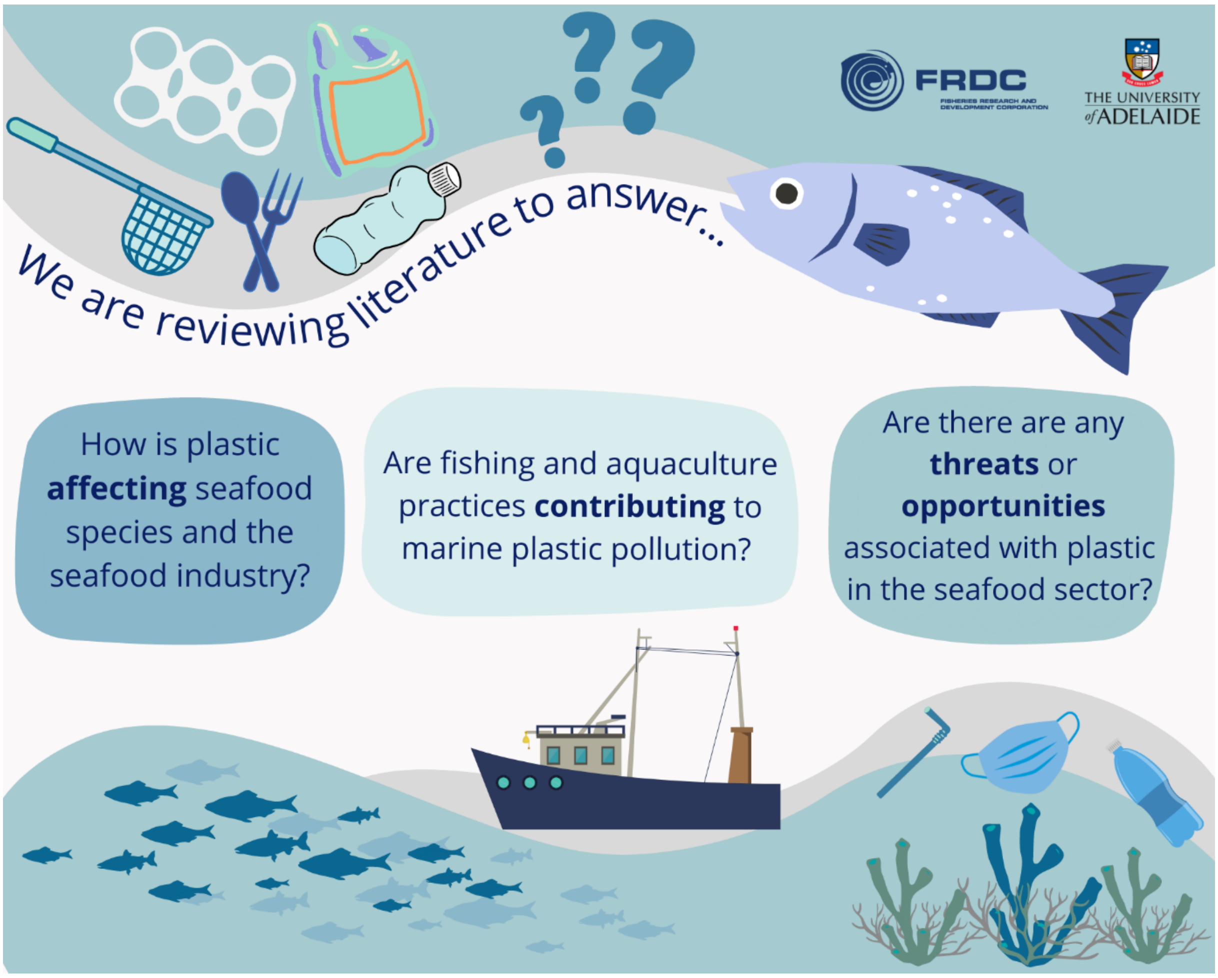
The final graphic and video will be shared across social media channels, and at upcoming conferences and community presentations. Additionally it will be shared with state and commonwealth fisheries agencies. A conference abstract on the implications of plastic pollution in seafood species has been accepted at the joint Indo-Pacific Fish Conference / Australian Society for Fish Biology 2023 conference in Auckland, where findings from both systematic literature searches will be presented. Furthermore, at the World Fisheries Congress in Seattle occurring in early 2024 a similar conference abstract has been accepted and results from this project will be presented.

The project team provided a submission to the Australian Parliament's Inquiry into plastic pollution in Australia's oceans and waterways. As part of the Inquiry a Public Hearing was held in Adelaide on the 26th of June, where a representative from the project team spoke, and shared some of the early findings from this project.

Research publications are also currently under preparation.

Project materials developed

Summary graphic introducing the project



We are reviewing literature to answer...

How is plastic **affecting** seafood species and the seafood industry?

Are fishing and aquaculture practices **contributing** to marine plastic pollution?

Are there are any **threats** or **opportunities** associated with plastic in the seafood sector?

Summary video of the research can be seen at this link:
https://www.youtube.com/watch?v=q7kix9yC-x8

Summary of results from the project

EFFECTS OF MICROPLASTIC ON SEAFOOD

Small pieces of plastic
are commonly consumed
by seafood species

We reviewed
600+ studies
testing the effects of
microplastics

Microplastics had **impacts** on...

Behaviour
Growth
Reproduction

But...
many experiments use
higher concentrations
than in the current environment

We must continue
reducing plastic use,
to help keep seafood safe

THE UNIVERSITY
of ADELAIDE

FRDC
FISHERIES RESEARCH AND
DEVELOPMENT CORPORATION

Appendices

List of researchers and project staff

- Dr Nina Wootton – The University of Adelaide
- Dr Patrick Reis Santos - The University of Adelaide
- Professor Bronwyn Gillanders – The University of Adelaide
- Rhiannon Van Eck – The University of Adelaide

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