water

MDPI

Article

First Evidence of Microplastic Contamination in Antarctic Fish (Actinopterygii, Perciformes)

Min Zhang †, Shigang Liu †, Jun Bo, Ronghui Zheng, Fukun Hong, Fulong Gao, Xing Miao, Hai Li and Chao Fang *

Laboratory of Marine Biodiversity, Third Institute of Oceanography, Ministry of Natural Resources, Xiamen 361102, China
* Correspondence: fangchao@tio.org.cn
† These authors contributed equally to this work.

check for updates

Citation: Zhang, M.; Liu, S.; Bo, J.; Zheng, R.; Hong, F.; Gao, F.; Miao, X.; Li, H.; Fang, C. First Evidence of Microplastic Contamination in Antarctic Fish (Actinopterygii, Perciformes). *Water* **2022**, *14*, 3070. https://doi.org/10.3390/w14193070

Academic Editor: Judith S. Weis

Received: 31 July 2022
Accepted: 27 September 2022
Published: 29 September 2022

Abstract: Microplastic (MP) pollution in Antarctica is a hot topic that has gained increasing attention in recent years. However, information regarding MP pollution in Antarctic fishes is currently very limited. The present study provides the first evidence of the occurrence and characteristics of MPs in species from five families of the order Perciformes, from the Amundsen Sea (AS) and Ross Sea (RS), Antarctica. MP abundances within the order Perciformes were at a medium level on a global scale, but were higher than those reported in other Antarctic organisms. The detection rate and abundance of MPs in the order Perciformes from the RS (50% and 1.286 items individual^{-1}) were both higher than those from the AS (36% and 1.227 items individual^{-1}). Moreover, the major composition and size of MPs were, respectively, polyacrylamide (PAM) and 100–200 µm in the RS, but rayon and 500–1000 µm in the AS. These differences may be attributed to the different onshore scientific research stations, wastewater treatment facilities, marine activities, ocean currents, and local gyres in the two sea areas. Among the five fish families, members of the Artedidraconidae ingested the smallest MPs and the highest proportion of PAM, which is probably associated with their habitat and degradation effect of unique gut microbiome. The higher hazard index of MPs in fish from the RS is due to the presence of PAM and epoxy resin, which may also have far-reaching health implications for other Antarctic organisms and humans through food web transmission. Overall, long-term monitoring of MP pollution in Antarctic fish and their surrounding marine environment is highly desirable.

Keywords: microplastics; Amundsen Sea; Ross Sea; order Perciformes; risk assessment

1. Introduction

The continuous accumulation of plastic waste in marine environments has attracted increasing attention in various fields, and marine plastic pollution has been listed as a major global environmental threat along with climate change, ozone depletion, and ocean acidification [1]. An increasing number of studies have demonstrated the detrimental effects of anthropogenic plastic pollution on marine species and ecosystems [2]. To date, nearly everywhere on Earth has been exposed to plastics, from remote islands to deep seas, and even the polar regions [3–7]. A myriad of microplastics (MPs), generally defined as smaller than 5 mm, are produced directly in the size or as a result of plastic degradation through a series of physicochemical and biological processes [8,9]. Serious concerns have been raised about the spread of MPs within food chains and their potential impacts on the species ingesting them [7,10,11].

The Antarctic continent is considered an almost unpopulated region, where human impact remains probably the lowest on the planet [12,13]. Antarctic waters are isolated from the northern oceans by strong circumpolar frontal systems which provide a relatively substantial barrier to the transfer of MPs [3,14]. However, the Antarctic Polar Front meanders seasonally, and the generation of eddies could provide potential southward paths for some materials [12,15]. Recent evidence has shown the presence of MPs in Antarctic environments and animals, such as surface waters [16,17], deep-sea sediments [18], amphipods [19], sea stars [20], penguins and sea birds [21,22], and mammals [23]. Various types of MPs have been detected in the Antarctic region, including polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinylchloride (PVC), rayon, resin, polyamide (PA), acrylic (AC), polyester (PES), polyethylene terephthalate (PET), and polytetrafluoroethylene (PTFE), indicating their ubiquitous occurrence and multiple sources in Antarctica [7,12,24]. These MPs may be derived from ocean circulation as well as human activities within the Antarctic region, such as scientific research bases and ship activities (scientific research, fishing, and tourism), but their specific sources and distribution remain unclear [3,12,25].

Fish are important consumers in the Antarctic ecosystem because they play an important role in circulating energy in the marine food web [26,27]. A large proportion of the biodiversity and endemic biomass composition of Antarctic fish are predominantly benthic fish, such as most of those belonging to the order Perciformes [26]. Perciform fish families are widely distributed in Antarctic waters. However, to date, most studies have focused on Antarctic animals such as penguins and seals, as well as seabirds, with only rare investigations of fish [7]. Inside organisms, MPs accumulate persistent and toxic organic pollutants, which may eventually reach humans [28–30]. However, no conclusive evidence of the negative effects of plastics on Antarctic fish has been reported. Studying the status of MPs pollution in Antarctic fish (particularly in dominant species) can provide a critical theoretical and practical basis for understanding the potential impacts of MPs in Antarctic ecosystems. Lithner et al. (2011) carried out environmental and health hazard rankings and assessments of plastic polymers based on their monomers [31,32]. This study used polymer monomers of MPs and hazard scores as indices to assess the risk of MPs to Antarctic fish and human health.

The Ross Sea (RS), between Victoria Land and Marie Byrd Land, provides a habitat for a diverse array of benthic and mesopelagic species, and top predators that benefit from its nutrient-rich water [17]. Meanwhile, scientific investigations are frequent in this region owing to the existence of several research bases, such as the Mario Zucchelli Base in Terra Nova Bay, RS [33]. In addition, wastewater treatment plants, ship traffic (research, fishing, and tourism), RS gyres, and other currents could all promote the release of MPs at the local scale [12,33,34]. The Amundsen Sea (AS) lies between Cape Flying Fish (northwestern tip of Thurston Island) to the east and Cape Dart (Siple Island) to the west [35]. The westward-flowing Antarctic Coastal Current and research activities at the Siple Island and Russkaya bases may largely contribute to the occurrence of MPs in this sea area [36]. However, knowledge of the differences in MP contamination between the RS and AS is still scarce, and there is virtually no information about the potential influence of MPs on fish in these two sea areas.

The purposes of this study were to: (i) compare MP pollution in the order Perciformes between the RS and AS; (ii) compare MP pollution among different families of order Perciformes in the two areas; and (iii) assess the risk of MPs in the order Perciformes based on the chemical hazards of plastic polymers.

2. Materials and Methods

2.1. Field Sampling and Data Collection

Samples were collected from six sites in Antarctica using a bottom trawling net (2.2 m wide, 0.65 m high, 6.5 m long, 20 mm mesh diameter). Two sampling sites were in the RS ranging from 170°33′00″ E to 175°23′59″ E, 74°59′52″ S to 74°59′55″ S. Four sampling sites were in the AS ranging from 113°20′45″ W to 117°19′20″ W, 72°15′17″ S to 73°31′09″ S (Figure 1). The specific environment information of six sites was collected (Table 1).

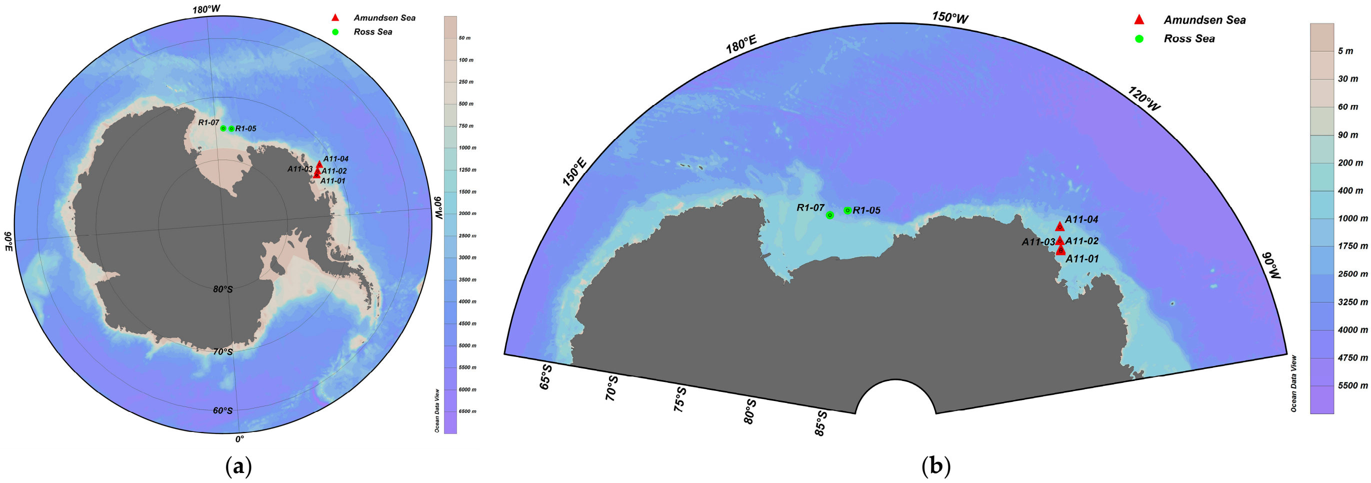


Figure 1. Sampling sites in the AS and RS: (**a**) overall map; (**b**) local map.

Table 1. The environmental information of the six sites.

Site	Depth/m	Salinity	Temperature/°C
A11–01	622	31.71	−1.800
A11−02	659	32.25	−1.800
A11−03	609	31.71	−1.800
A11−04	502	30.62	−1.800
R1−05	332	31.38	−0.203
R1−07	285	31.71	0.204

A total of 36 Antarctic fish samples were collected, all of which belong to the class Actinopterygii, order Perciformes. Among these, 22 fish samples belonging to five families (Nototheniidae, Channichthyidae, Artedidraconidae, Bathydraconidae, and Zoarcidae) were caught in the AS. The remaining 14 fish samples, belonging to four families (Nototheniidae, Channichthyidae, Artedidraconidae, and Zoarcidae), were sampled from the RS. Overall, a total of 10 fish species from five families were sampled from the RS and AS. Representative images of the 10 fish species are shown in Figure 2. All fish were wrapped with aluminium foil and kept in clean sealed bags, which were frozen in a refrigerator at −20 °C until analysis (from March to December 2020). The animal study protocol was approved by the ethics committee of Xiamen University (XMULAC20190066).

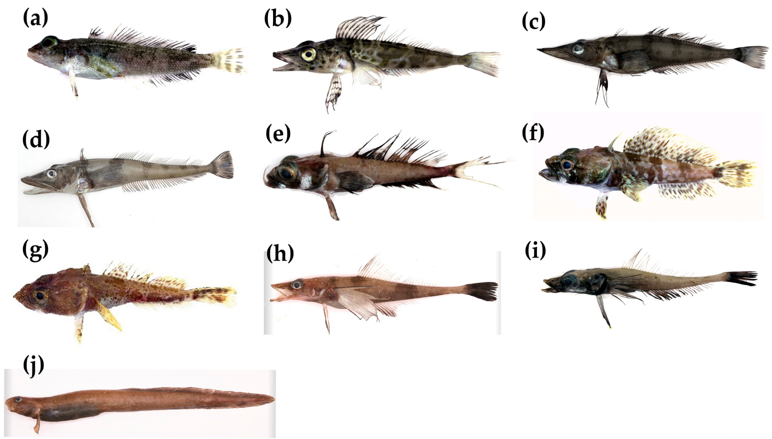


Figure 2. The 10 fish species in five families collected in the AS and RS: (**a**) *Trematomus scotti*; (**b**) *Pagetopsis maculatus*; (**c**) *Dacodraco hunteri*; (**d**) *Chionodraco myersi*; (**e**) *Dolloidraco longedorsalis*; (**f**) *Histiodraco velifer*; (**g**) *Pogonophryne albipinna*; (**h**) *Vomeridens infuscipinnis*; (**i**) *Akarotaxis nudiceps*; (**j**) *Ophthalmolycus amberensis*.

2.2. Digestion of Samples and MP Analysis

After defrosting, physiological information including body length and weight was measured and recorded for each sample. The gastrointestinal tract was dissected for MP extraction as described previously [37,38]. Briefly, each gastrointestinal tract was transferred into a 1 L glass beaker and 10% KOH (*w*/*v*) solution was added to immerse the sample absolutely. Then the digestion process lasted for 18–24 h at 60 °C and 300 rpm in an oscillation incubator until the tissues were digested completely. KOH was used due to it has higher efficiency in digesting biological tissues and had no impact on the integrity and appearance of the plastic polymers compared to other digesting solutions under the same condition [39–41].

Subsequently, the digestion solution was added with the same volume of saturated sodium chloride solution (1.2 g mL^{-1}) and stayed overnight in short-stemmed glass funnels to improve the flotation efficiency of MPs. Afterwards, the overlying solution was filtered through a GF/A cellulose nitrate membrane filter (1.6 µm pore size and 47 mm diameter, Whatman). The filters were stored in covered glass Petri dishes for further analysis.

The filters were observed using a Nikon P-RN2 stereo microscope equipped with a DS-Fi3 charge-coupled device (CCD) camera (Nikon Corporation, Tokyo, Japan). Suspected MPs on the filters were photographed and picked out using a needle and tweezers. The sizes of the suspected MPs were measured using the NIS element imaging software (version 5.20.00, Nikon Corporation, Tokyo, Japan). All suspected MPs were identified using Fourier transform infrared microscopy (µ-FTIR) (Nicolet iN10, Thermo Fisher Scientific Inc., Waltham, MA, USA). The instrument parameters were set as follows: spectral wavenumber range of 675–4000 cm^{-1} with a resolution of 4 cm^{-1} and 32 co-scans. The obtained spectra were compared with the database from Thermo Fisher (Waltham, MA, USA), and a matching degree >70% between the sample and standard spectra was considered acceptable [38,42]. The detection limit for MP size in the present study was 10 µm.

2.3. Quality Assurance/Quality Control (QA/QC)

QA/QC was performed as reported previously [37,42]. In short, all plastic materials were excluded and rinsed with pre-filtered Milli-Q (MQ) water three times before use. All fish were thoroughly washed with pre-filtrated MQ water thrice to avoid contaminating the digestive tracts prior to dissection. Latex gloves and 100% white cotton lab coats were worn throughout the experimental process. All reagents were filtered over a GF/A filter and stored hermetically. The samples were treated inside an ultra-clean work table (Airtech, Suzhou, China) with a vertical wind, which was placed in a specialised laboratory where all plastic materials were strictly prohibited. Three procedural blanks were created by filling the pre-cleaned beakers with filtered MQ water and processed synchronously to monitor background contamination. No MPs were detected in the procedural blanks.

2.4. Risk Assessment of MPs on Human Health and Organisms

The health risk level of Lithner's model refers to the potential hazard to human health and organisms [31]. Five levels (I–V) are defined according to hazard grades ranging from 0 to 10,000. Level V is the most hazardous (the hazard score ranges from 1000 to 10,000) and may cause cancer; Level IV (the hazard score ranges from 100 to 1000) may cause skin sensitisation and is very toxic to aquatic life with long-lasting effects; Level III (the hazard score ranges from 10 to 100) may be toxic if inhaled, swallowed, or in contact with skin and also very acute toxic to aquatic life; Level II (the hazard score ranges from 1 to 10) may cause skin, eye, and respiratory irritation and is harmful if inhaled or swallowed; Level I (the hazard score ranges from 0 to 1) is the least toxic option and may only be classified as highly flammable and liquid substances. The formula used to calculate the polymer hazard risk index (H) in this study was based on previous study [32]. The H values in this study were calculated by multiplying the percentage of MP polymer types in each fish by the hazard score of the MP polymers, which could be obtained from the datasheet of Lithner's model [31,38].

2.5. Statistical Analysis

The abundance and size of MPs in Antarctic fish were expressed as the average ± standard error (S.E.). SPSS 26.0 for Windows software (SPSS Inc., Chicago, IL, USA) was used for statistical analyses. The Shapiro–Wilk test was used to analyse the normality of all data. If the data were abnormally distributed, the Kruskal–Wallis test was used to identify significant differences. If the data were normally distributed, then a homogeneity test of variances was conducted using Levene's test. One-way analysis of variance (ANOVA) followed by Tukey's honest significant difference (HSD) test (homogeneity of variance). If the data showed an abnormal distribution or heterogeneity of variance, a nonparametric test followed by the Mann–Whitney U test was performed. Differences were considered statistically significant at $p < 0.05$.

The comparison of MP contamination and health hazard levels in the order Perciformes was performed between RS and AS. However, the comparison of MP contamination and health hazard levels among five fish families of order Perciformes was carried out only in the AS due to the sample quantity of most families in the RS did not meet the statistical requirements ($n \geq 3$).

3. Results

3.1. Biological Characteristics of Collected Fish Samples

All five families represented in the collected samples comprise demersal fish. The preferred water depths of Nototheniidae, Channichthyidae, Artedidraconidae, Bathydraconidae, and Zoarcidae range from 20–793, 200–800, 203–1674, 371–915, and 140–826 m, respectively (Table 2). The distribution ranges and body lengths of the fish species are presented in Table 2.

Table 2. The biological characteristics of the collected 10 species of fish in 5 families.

Family	Genus, Species	Distribution [a]	Depth Range [a] /m	Number of Samples/ Individue	Life Stage	Feeding Methods	Average Length/cm (Average ± SD)
Nototheniidae	*Trematomus, Trematomus scotti*	Southern Ocean: South Shetland, South Orkney islands, RS, Breid Bay, Weddell Sea, and Antarctic Peninsula	20–793	22	8 Juveniles, 14 Adults	Carnivore [a]	12.22 ± 1.50
Channichthyidae	*Pagetopsis, Pagetopsis maculatus*	Southern Ocean: circum-Antarctic on the continental shelf	200–800	1	Adult	Carnivore [43]	15.80 [b]
	Dacodraco, Dacodraco hunteri	Southern Ocean: probably circum-Antarctic on the continental shelf	300–800	1	Adult	Carnivore [43]	22.50 [b]
	Chionodraco, Chionodraco myersi	Southern Ocean: circum-Antarctic on the continental shelf	200–800	2	Adults	Carnivore [a]	24.05 ± 3.61
Artedidraconidae	*Dolloidraco, Dolloidraco longedorsalis*	Southern Ocean: Weddell Sea, Graham Land, Queen Mary Land, South Victoria Land	203–1145	3	Adults	Carnivore [a]	10.93 ± 0.90
	Histiodraco, Histiodraco velifer	Southern Ocean: East Antarctica (South Victoria Land, MacRobertson Land, RS, Weddell Sea)	210–667	1	Adult	Carnivore [44]	16.50 [b]
	Pogonophryne, Pogonophryne albipinna	Southern Ocean: RS	1565–1674	1	Adult	Carnivore [45]	8.50 [b]

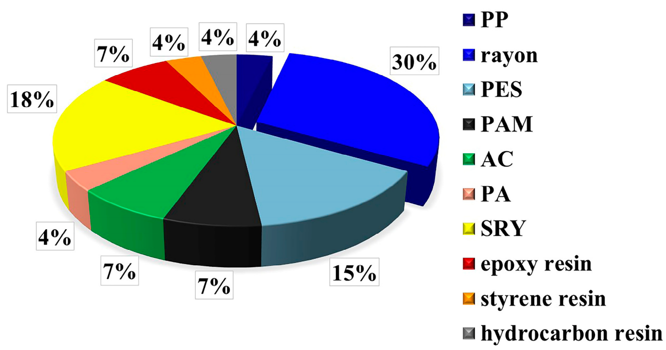
Table 2. *Cont.*

Family	Genus, Species	Distribution [a]	Depth Range [a] /m	Number of Samples/ Individue	Life Stage	Feeding Methods	Average Length/cm (Average ± SD)
Bathydraconidae	*Vomeridens, Vomeridens infuscipinnis*	Southern Ocean: Weddell and RSs, South Orkney Islands and Antarctic Peninsula	500–813	1	Adult	Carnivore [46]	21.50 [b]
	Akarotaxis, Akarotaxis nudiceps	Southern Ocean: Antarctic continental shelf and west of Adelaide Island at the Antarctic Peninsula	371–915	2	Adults	Carnivore [46]	12.75 ± 0.21
Zoarcidae	*Ophthalmolycus, Ophthalmolycus amberensis*	Southern Ocean: circum-Antarctic	140–826	2	1 Juvenile, 1 Adult	Omnivore [47]	25.35 ± 5.16

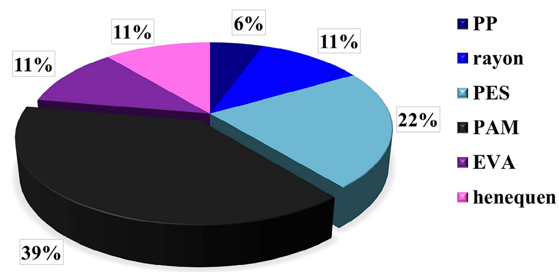
[a] Information came from FishBase: https://fishbase.org (accessed on 6 May 2022). [b] Only one sample was collected. The feeding methods of all species were based on the food items they ingested.

3.2. Comparison of MP Contamination in Order Perciformes between Two Sea Areas

A total of 27 MPs were detected in the gastrointestinal tracts of 22 perciform fish specimens caught in the AS, with a detection rate of 36.36%. The detection rate means the proportion of fish in which MPs were detected in their gastrointestinal tracts. The average abundance of MPs was 1.227 items individual^{-1} (1.914 items g^{-1}). The composition of the MPs in the AS could be classified into ten types: PP, rayon, PES, polyacrylamide (PAM), epoxy resin, hydrocarbon resin, styrene resin, Saran ribbon yarn (SRY), AC, and PA (Figure 3a). Among them, rayon was the dominant polymer type. The size of MPs ranged from 57.98 to 6124.40 μm (average 862.82 μm). The predominant size range of MPs was 500–1000 μm (Figure 4). The colours of MPs were classified into seven categories: black, transparent, yellow, green, blue, white, and gold (Figure 5a). Black, clear, and yellow were the three most common colours, accounting for 26% each. Fibre was the most prevalent MP in AS (66.70%), followed by fragments (29.60%) and particles (3.70%).



(**a**)



(**b**)

Figure 3. The percentages of different compositions of MPs in order Perciformes: (**a**) in the AS; (**b**) in the RS, Antarctica.

A total of 18 MPs were detected in the gastrointestinal tract of 14 Perciformes individuals caught in the RS, with a detection rate of 50%. The average abundance of MPs was 1.286 items individual^{-1} (1.951 items g^{-1}). The MP abundance in the RS was higher than that in the AS, but no statistical difference was observed. The polymer types of MPs in the RS could be classified into six categories: PP, rayon, PES, PAM, ethylene vinyl acetate (EVA), and henequen (Figure 3b). Among these, the dominant polymer type was PAM. The size of MPs ranged from 13.13 to 3090.41 μm (average 669.57 μm). Shorter MPs, ranging from

100 to 200 μm, accounted for the dominant proportion of all MPs (Figure 4). The colours of the MPs were classified into six categories: black, transparent, yellow, green, grey, and pink (Figure 5b). The major colours were the same as those of AS, with black, transparent, and yellow accounting for 39%, 28%, and 11%, respectively. Fibre was the predominant polymer (50%), followed by particles (33%), and fragments (17%).

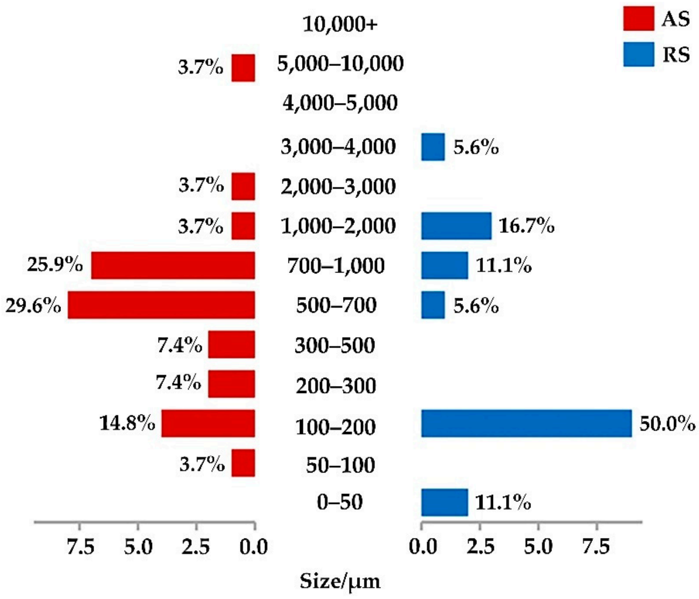


Figure 4. The quantities and percentages of different size ranges of MPs in order Perciformes of the AS and the RS, Antarctica.

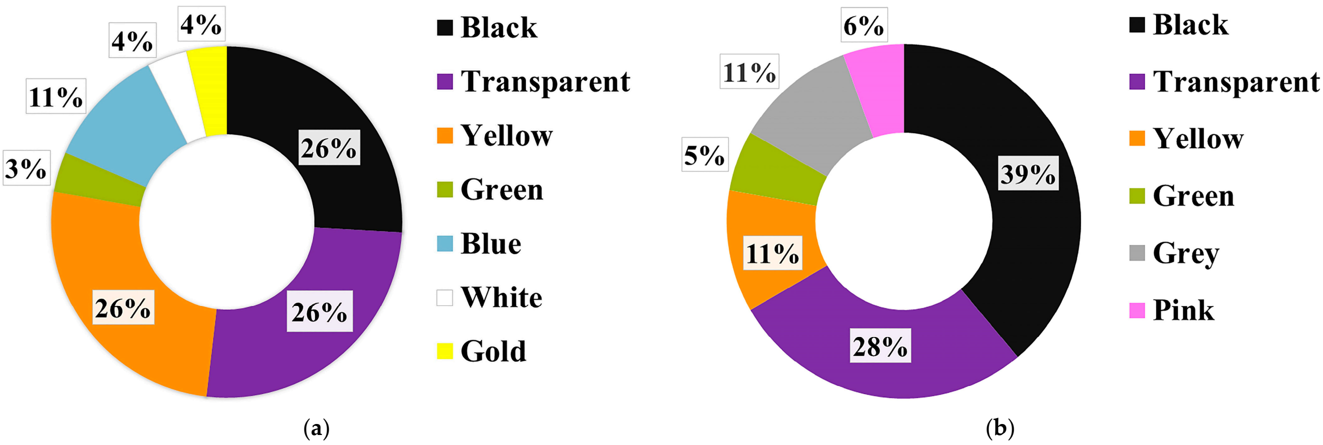


Figure 5. The percentages of different colours of MPs in order Perciformes: (**a**) in the AS; (**b**) in the RS, Antarctica.

3.3. Comparison of MP Contamination among Different Fish Families of Order Perciformes in the AS

A total of 22 fish (Perciformes) collected from the AS can be divided into five families: Nototheniidae, Channichthyidae, Artedidraconidae, Bathydraconidae, and Zoarcidae. Zoarcidae was excluded from the comparison because of the limited sample quantity. No MP was detected in Bathydraconidae. The detection rate of MPs in Nototheniidae was 33.33%, with an average abundance of 0.833 items individual^{-1} (0.726 items g^{-1}). The detection rate of MPs in Channichthyidae was 66.67%, with an average abundance of 2.667 items individual^{-1} (1.41 items g^{-1}). The detection rate of MPs in Artedidraconidae was 33.33%, with an average abundance of 1.000 items individual^{-1} (8.333 items g^{-1}). There was no significant difference in MP abundance among families. There were a total of six MP polymer types in Nototheniidae: PP, rayon, PES, hydrocarbon resin, epoxy resin, and PA. PES was predominant (30%), followed by rayon (20%), and epoxy resin (20%) (Figure 6). The major type of MP in Channichthyidae was Saran ribbon yarn (63%), whereas PAM accounted for the highest percentage (67%) in Artedidraconidae (Figure 6). Black, transparent, and blue were the most common colours among all MPs in the three families (Figure 7). The MP colours that accounted for the largest proportion in Nototheniidae, Channichthyidae, and Artedidraconidae were black (50%), transparent (63%), and black (67%), respectively (Figure 7).

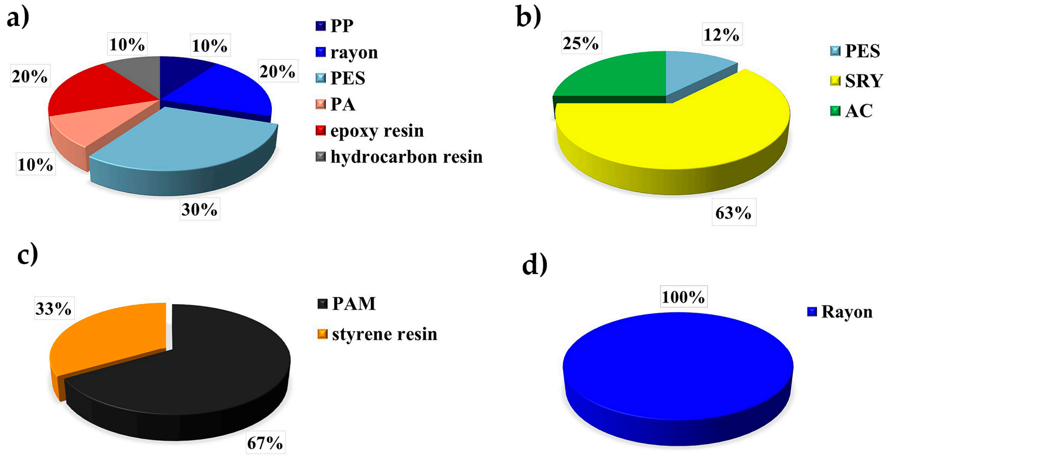


Figure 6. The percentages of different compositions of MPs in the AS, Antarctica: (**a**) family Nototheniidae; (**b**) family Channichthyidae; (**c**) family Artedidraconidae; (**d**) family Zoarcidae.

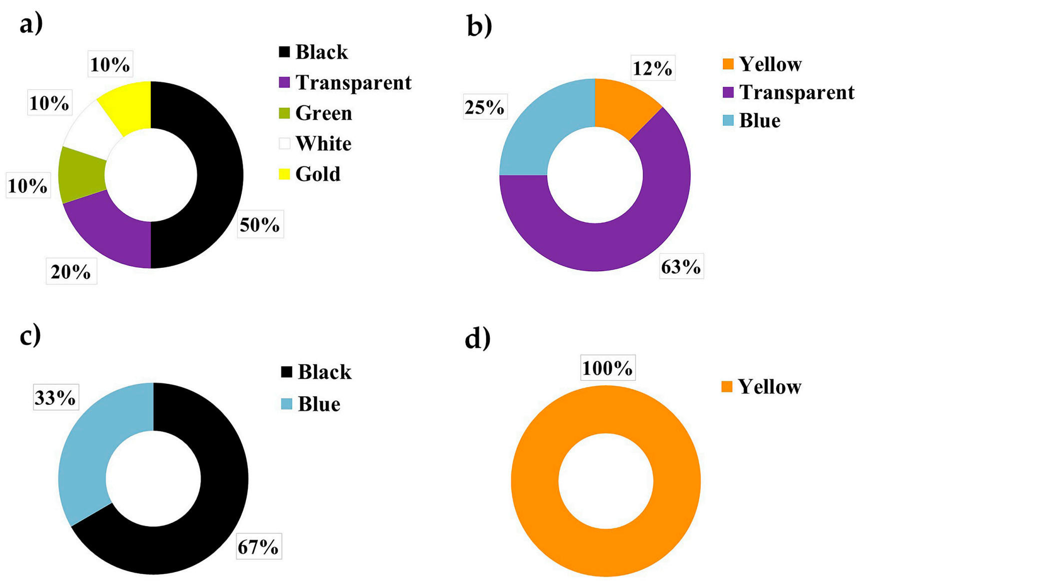


Figure 7. The percentages of different colours of MPs in the AS, Antarctica: (**a**) family Nototheniidae; (**b**) family Channichthyidae; (**c**) family Artedidraconidae; (**d**) family Zoarcidae.

The size of MPs found in different families increased following the sequence Artedidraconidae (57.98 to 144.94 μm, average = 107.07 μm) < Nototheniidae (234.47 to 1029.30 μm, average = 530.84 μm) < Channichthyidae (524.33 to 6124.40 μm, average = 1745.90 μm). Fragments were the most prevalent type in Nototheniidae (50%), followed by fibres (40%), and particles (10%). The MPs found in Channichthyidae and Artedidraconidae were wholly fibres and fragments.

3.4. Environmental and Health Hazard Risk Assessment of MPs

Overall, sampled perciform fish in the RS possessed a higher average hazard grade (1622.68 ± 1106.44) than those in the AS (483.99 ± 382.70). The H levels of MPs of Artedidraconidae in the AS (level V) and RS (level V) were both higher than that of other families (Figure 8). The H level of MPs from Nototheniidae in AS (level IV) was lower than that in RS (level V). In contrast, the hazard level of Channichthyidae in the AS (level III, hazard grade: 78) was higher than that in the RS (level I).

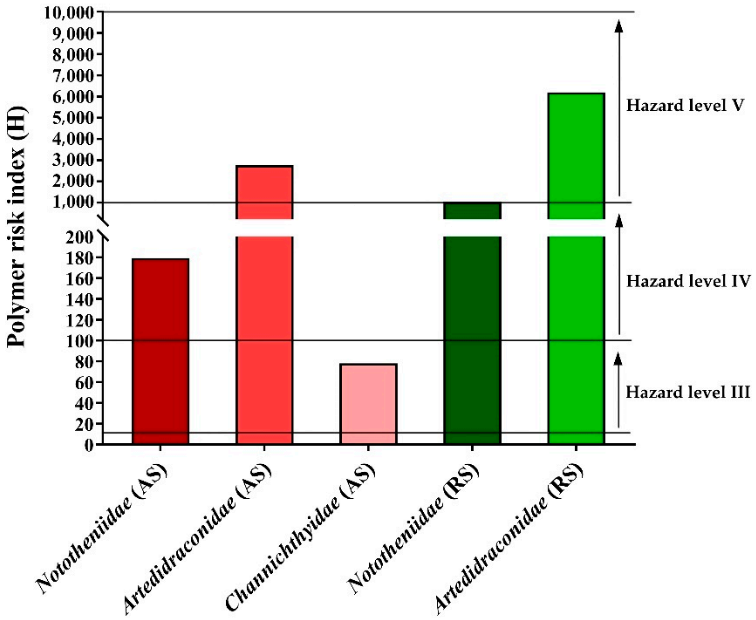


Figure 8. The polymer risk index (H) and hazard level of MP contamination in three fish families in the AS and two fish families in the RS. Family Bathydraconidae in the AS, family Channichthyidae in the RS, and family Zoarcidae in the RS were not shown in figure because there were no MPs detected in them. Family Zoarcidae in the AS was not shown in figure because there was no available hazard score of the MPs rayon detected in this fish family.

4. Discussion

4.1. Comparison of MP Contamination in Fish between Antarctica and Other Regions Worldwide

There has been an increasing number of studies on fish contaminated by MPs globally, but reports on polar regions are scarce. Increasing attention has been paid to MP pollution in Antarctica because scientific research activities have increased dramatically in recent decades. Therefore, it is of great significance to compare MP pollution in fish between Antarctica and other regions (Table 3).

Table 3. Studies on MP abundances in fish species from different waters around the world.

Location	Fish	Sampling Organs	MP Abundance	Main Compositions of MPs	Reference
Amundsen Sea	demersal fish	gastrointestinal tract	1.227 items individual^{-1}, 1.914 items g^{-1}	Rayon, SRY, PES, PAM, AC, epoxy resin	this study
Ross Sea	demersal fish	gastrointestinal tract	1.286 items individual^{-1}, 1.951 items g^{-1}	PAM, PES, rayon, EVA, henequen	this study
Arctic	demersal fish	digestive tract	1.1 ± 0.3 items individual^{-1}	PES, acrylic, PA, PE, EVA	[48]
North Atlantic	mesopelagic fish	digestive tract	0.13 items individual^{-1}	-	[49]
the Gulf of California	benthic fish	gastrointestinal tract	2.72 items individual^{-1}	PAM, PA, PET, PE, PP, polyacrylic	[50]
Turkish territorial waters of the Mediterranean Sea	pelagic fish, demersal fish	gastrointestinal tract	1.36 items individual^{-1}	PS, PA, polyamide resin	[51]
Fortaleza coastal zone, Brazil	pelagic fish	stomach	1.53 items individual^{-1}	PES	[52]

Table 3. *Cont.*

Location	Fish	Sampling Organs	MP Abundance	Main Compositions of MPs	Reference
South China Sea	deep-sea fish	intestine	1.77 ± 0.73 items individual^{-1}	cellophane, PA, PET, PARA, PAE	[53]
Australia and Fiji	reef-associated, demersal and benthopelagic	gastrointestinal tract	1.58 ± 0.23 items individual^{-1}, 0.86 ± 0.14 items individual^{-1}	polyolefin	[54]
Seri Kembangan, Malaysia	reef-associated, pelagic-neritic, benthopelagic and demersal fish	viscera and gills	0.39 items individual^{-1}	PE, PP, PET	[55]
Kerala, India	pelagic fish	muscle and skin; gill and viscera	0.53 ± 0.77 items individual^{-1}; 0.07 ± 0.26 items individual^{-1}	PE, PP, PS, polyurethane	[56]
Goa, west coast of India	benthic fish	gastrointestinal tract	1.4 ± 0.3–7.8 ± 4.4 items individual^{-1}	PAM, polyacetylene, EVOH, PA, PVC	[57]
South China Sea; Indian Ocean	pelagic and benthic nektons	digestive tract	0.39 ± 0.12 items individual^{-1}; 1.00 ± 0.16 items individual^{-1}	PES, PA	[38]

AC: acrylic; EVA: ethylene vinyl acetate; EVOH: ethylene vinyl alcohol; PA: polyamide; PAE: poly(arylether); PAM: polyacrylamide; PARA: polyarylamide; PE: polyethylene; PES: polyester; PET: polyethylene terephthalate; PP: polypropylene; PVC: polyvinyl chloride; PS: polystyrene; SRY: Saran ribbon yarn.

MP abundance in Antarctic fish (order Perciformes) was at a medium level on a global scale (Table 3). There are three possible explanations for the observed spatial variation. First, it is due to differences in species and habitat depths of the fish in different waters. Second, it may be related to different pollution levels of MPs in different water areas. Finally, differences in previous treatments and analysis methods may also affect the level of MPs. The major components of MPs in fish species around the world are derived from clothing weaving, packaging, and fishing gear manufacturing, indicating that these human-related products contribute greatly to the ubiquity of MPs in marine fish.

4.2. Comparison of MP Contamination in Order Perciformes and Other Antarctic Species

This study is the first to document MP contamination in the order Perciformes collected from Antarctica. Comparisons indicated that MP abundances in the order Perciformes were higher than those in other Antarctic species, except for sea stars (Table 4).

Table 4. Studies on MP abundances in different species.

Location	Species	Sampling	MP Abundance	Main Types of MPs	Reference
Admiralty Bay, Antarctica	zooplankton	-	2.40 ± 4.57 items 100 m^{-3}	polyethyleneglycols, PU, PET, PA	[58]
Terra Nova Bay (Ross Sea, Antarctica)	invertebrate species	-	0.7 items mg^{-1}	PA, PE	[59]
Namuncurá at Burdwood Bank, Southwest Atlantic Ocean	sea stars	soft tissue	2.84 ± 3.56 items g^{-1} wet weight	semi-synthetic cellulose	[20]
South Shetland Islands	fish	gastrointestinal tract	0.36 ± 0.51 items individual^{-1}	PET, PP, PA, PAN	[60]
Banzare Banks of Southern Ocean	fish	gastrointestinal tract	0.04 items individual^{-1}	acrylic resin	[10]
Antarctic Peninsula and Scotia Sea region	penguins	scat	0.1 items scat^{-1}	PE, PES	[21]
South Georgia	penguins	scat	0.13 items scat^{-1}	semi-synthetic (viscose, rayon), PET, acrylic, PP	[61]

Table 4. *Cont.*

Location	Species	Sampling	MP Abundance	Main Types of MPs	Reference
Bird Island, South Georgia and Signy Station, South Orkney Islands	penguins	scat	0.23 ± 0.53 items scat^{-1}	PES, rayon	[62]
sub-Antarctic Heard Island	sea birds	digestive systems	0.11 items individual^{-1}	-	[22]
Ardery Island, near the Australian station Casey	sea birds	stomach	1.12 items individual^{-1}	-	[63]
North Head Peninsula, Macquarie Island	fur seals	scat	1.13 items scat^{-1}	PE, PP	[23]
Deception Island, South Shetland Islands	fur seals	scat	0 items scat^{-1}	-	[15]

PA: polyamides; PAN: polyacrylonitrile; PE: polyethylene; PET: polyethylene terephthalates; PP: polypropylene; PU: polyurethanes.

The high MP abundance in order Perciformes may be due to their wide scope of activities, which may provide greater exposure to MPs in the surrounding environment than that of other species. The studied sea areas of AS and RS have a relatively high degree of plastic pollution compared with other Antarctic areas, which could result from frequent scientific research activities and maritime shipping [64,65]. Different feeding habits among species can also affect the bioavailability of MPs [44].

In addition, Antarctic organisms share common polymers such as PA, PE, PES, and PP. These kinds of MPs have been widely detected in marine organisms from the Arctic and other regions, indicating possible global diffusion within marine ecosystems [37,59].

4.3. Comparison of MP Contamination in Fish between AS and RS

The Council of Managers of National Antarctic Programs (COMNAP) documented that there were four scientific research stations around the RS coast, but only one in the AS [66]. It was noted that there were more research states, scientific expeditions, and ship transportation in the RS than in the AS [32,67]. Therefore, one possible reason for the fish that ingested higher levels of MPs from the RS may be related to more MPs being discharged from onshore scientific research stations and marine activities in this sea area [51,67]. Moreover, the different environmental conditions between these two sea areas may also affect MP accumulation by fish. For example, gyres could increase MP pollution in the sea area, especially towards the centre of ocean circulation [68,69]. Therefore, the clockwise-circulating RS gyre may give rise to a higher accumulation of MP locally in the RS, resulting in more MPs being ingested by fish.

Moreover, previous studies have reported that more than half of the stations in Antarctica have no disposal treatments for sewage and wastewater, and the facilities in the stations are not sufficiently advanced [70–72]. The most common type of microfibre in the AS, rayon, may be derived from laundry released in wastewater or transported from the northern Antarctic Peninsula by the westward-flowing Antarctic Coastal Current [12]. As PAM is widely used in water treatment, sewage treatment plants built around the RS may be the main driver of PAM as a predominant polymer in fish [66].

Jiang et al. (2020) reported higher percentages of small MPs (100–500 μm) in the surface waters of Greenland Sea Gyre compared to those in the East Greenland Current [69]. Therefore, the smaller MPs in perciform fish from the RS may result in the accelerated degradation of larger MPs in the clockwise-circulating RS gyre.

4.4. Comparison of MP Contamination among Different Families of Fish

In this study, we aimed to provide a snapshot of different MP accumulation by the Antarctic fish from the level of family, as it was difficult to collect a sufficient number of the same fish species by random sampling. In the long run, the interspecific differences in the MP contamination among Antarctic fish could be clarified with the accumulation of field survey data.

The MP abundances did not vary significantly among different families of fish, which may be related to the species having similar activity scopes and feeding habits. The 100–200 µm MPs in the RS were detected from Nototheniidae, and 500–1000 µm MPs in the AS were detected from Nototheniidae and Channichthyidae. Nototheniidae have a greater potential for interaction with smaller MPs because they can access shallower waters [73]. Meanwhile, the smallest MPs were ingested by Artedidraconidae, both from AS and RS. Therefore, we wondered whether Artedidraconidae has a special gut microbiota capable of metabolizing MPs. This hypothesis was supported by a previous study showing that the enzymes produced by the gut microbiome of superworms (*Zophobas morio*) degrade PS and styrene, leading to MP size reduction [74].

However, PAM was only found in Nototheniidae and Artedidraconidae from the RS. Likewise, it was detected only in Artedidraconidae from the AS. This is probably related to the deep-water habitat of Artedidraconidae which, compared with shallower habitats, may provide greater exposure to PAM that is denser than seawater and therefore sinks readily to deep water [75,76].

4.5. Hazard Risk Assessment of MPs in the Fish Species

We observed the highest hazard indices of MPs in Nototheniidae and Artedidraconidae, which resulted from the presence of epoxy resin and PAM. Among all the polymers detected in the order Perciformes, PAM and epoxy resin are at the highest hazard level (V) because they both comprise monomers with high hazard scores [40]. PAM and epoxy resin can cause serious toxicity to humans, such as skin sensitisation, eye damage, fertility damage, and carcinogenicity [34]. Although no commercial value was reported for the fish species in this study, the fish from the RS may pose potential health risks to other Antarctic organisms and humans through food web transmission. Therefore, long-term monitoring programs are required to better understand the long-term impact of MPs on Antarctic fish and other organisms.

5. Conclusions

In the present study, we investigated MP pollution in the order Perciformes in the AS and RS in Antarctica and assessed the hazard risk of the MPs detected. MP abundances in Antarctic fish were higher than those in other species locally and were at a medium level on a global scale. Moreover, the detection rate and abundance of MPs in fish from the AS were relatively lower than those in fish from the RS. The most common type of MPs in both sea areas was fibre, and the major MP compositions in the AS and RS were rayon and PAM. The hazard risk index of MPs in the RS was higher than that in the AS. The fish family with the highest toxicity risk was Artedidraconidae. Overall, the extensive occurrence of MPs in Antarctic fish has raised a warning alarm. Further investigations are required to assess the MP pollution risk of other organisms across the food chain in the AS and RS. Future studies should explore the potential for use of Artedidraconidae as an indicator taxon for monitoring MP pollution and risk assessment in Antarctica. In addition, we still need to investigate the levels and characteristics of MP pollution in water, sea ice, glaciers, and sediments (including coastal land) in the two sea areas, assessing the causes or the relationships regarding MP contamination between species and the surrounding environment. With increasing public attention on MPs in the Antarctic environment, the development of tools and technologies to reduce and tackle MP emissions from existing and future local scientific research should also be considered.

Author Contributions: Conceptualization, M.Z. and C.F.; methodology, J.B., R.Z. and C.F.; software, M.Z.; validation, S.L.; investigation, S.L., X.M. and H.L.; resources, F.H.; data curation, M.Z. and F.G.; writing—original draft preparation, M.Z.; writing—review and editing, C.F.; visualization, M.Z.; supervision, C.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by "Impact and Response of Antarctic Seas to Climate Change, grant number IRASCC2020-2022-NO.01-02-02B & 02-03", "First batch of the Youth Innovation Fund Project of Xiamen in 2020 (grant number 3502Z20206099)", "Natural Science Foundation of Fujian Province (grant number 2021J01506)", "National Key Research and Development Program of China (grant number 2019YFD0901101)", and "National Natural Science Foundation of China (grant number 41977211)".

Institutional Review Board Statement: The animal study protocol was approved by the ethics committee of Xiamen University (XMULAC20190066).

Data Availability Statement: Not applicable.

Acknowledgments: The authors thank Ran Zhang, Rui Wang, Yuan Li, and Longshan Lin from the Third Institute of Oceanography (TIO), MNR, for technical assistance.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the study design; collection, analyses, or interpretation of data; writing of the manuscript; or decision to publish the results.

References

1. Ding, J.; Li, J.; Sun, C.; Jiang, F.; Ju, P.; Qu, L.; Zheng, Y.; He, C. Detection of microplastics in local marine organisms using a multi-technology system. *Anal. Methods.* **2019**, *11*, 78–87. [CrossRef]
2. Ford, H.V.; Jones, N.H.; Davies, A.J.; Godley, B.J.; Jambeck, J.R.; Napper, I.E.; Suckling, C.C.; Williams, G.J.; Woodall, L.C.; Koldewey, H.J. The fundamental links between climate change and marine plastic pollution. *Sci. Total Environ.* **2022**, *806*, 150392. [CrossRef] [PubMed]
3. Suaria, G.; Perold, V.; Lee, J.R.; Lebouard, F.; Aliani, S.; Ryan, P.G. Floating macro- and microplastics around the Southern Ocean: Results from the Antarctic Circumnavigation Expedition. *Environ. Int.* **2020**, *136*, 105494. [CrossRef]
4. Barnes, D.K.A.; Morley, S.A.; Bell, J.; Brewin, P.; Brigden, K.; Collins, M.; Glass, T.; Goodall-Copestake, W.P.; Henry, L.; Laptikhovsky, V.; et al. Marine plastics threaten giant Atlantic Marine Protected Areas. *Curr. Biol.* **2018**, *28*, R1137–R1138. [CrossRef]
5. Pereira, J.M.; Rodríguez, Y.; Blasco-Monleon, S.; Porter, A.; Lewis, C.; Pham, C.K. Microplastic in the stomachs of open-ocean and deep-sea fishes of the North-East Atlantic. *Environ. Pollut.* **2020**, *265*, 115060. [CrossRef]
6. Collard, F.; Ask, A. Plastic ingestion by Arctic fauna: A review. *Sci. Total Environ.* **2021**, *786*, 147462. [CrossRef]
7. Caruso, G.; Bergami, E.; Singh, N.; Corsi, I. Plastic occurrence, sources, and impacts in Antarctic environment and biota. *Water Biol. Secur.* **2022**, *1*, 100034. [CrossRef]
8. Kershaw, P.J. *Marine Plastic Debris and Microplastics Global Lessons and Research to Inspire Action and Guide Policy Change*, 1st ed.; United Nations Environment Programme: Nairobi, Kenya, 2016; pp. 26–34.
9. Andrady, A.L. Microplastics in the marine environment. *Mar. Pollut. Bull.* **2011**, *62*, 1596–1605. [CrossRef]
10. Cannon, S.M.E.; Lavers, J.L.; Figueiredo, B. Plastic ingestion by fish in the Southern Hemisphere: A baseline study and review of methods. *Mar. Pollut. Bull.* **2016**, *107*, 286–291. [CrossRef]
11. Law, K.L.; Thompson, R.C. Microplastics in the seas. *Science* **2014**, *345*, 144–145. [CrossRef]
12. Waller, C.L.; Griffiths, H.J.; Waluda, C.M.; Thorpe, S.E.; Loaiza, I.; Moreno, B.; Pacherres, C.O.; Hughes, K.A. Microplastics in the Antarctic marine system: An emerging area of research. *Sci. Total Environ.* **2017**, *598*, 220–227. [CrossRef] [PubMed]
13. Kuklinski, P.; Wicikowski, L.; Koper, M.; Grala, T.; Leniec-Koper, H.; Barasiński, M.; Talar, M.; Kamiński, I.; Kibart, R.; Małecki, W. Offshore surface waters of Antarctica are free of microplastics, as revealed by a circum-Antarctic study. *Mar. Pollut. Bull.* **2019**, *149*, 110573. [CrossRef] [PubMed]
14. González-Pleiter, M.; Edo, C.; Velázquez, D.; Casero-Chamorro, M.C.; Leganés, F.; Quesada, A.; Fernández-Piñas, F.; Rosal, R. First detection of microplastics in the freshwater of an Antarctic Specially Protected Area. *Mar. Pollut. Bull.* **2020**, *161*, 111811. [CrossRef] [PubMed]
15. Garcia-Garin, O.; García-Cuevas, I.; Drago, M.; Rita, D.; Parga, M.; Gazo, M.; Cardona, L. No evidence of microplastics in Antarctic fur seal scats from a hotspot of human activity in Western Antarctica. *Sci. Total Environ.* **2020**, *737*, 140210. [CrossRef] [PubMed]
16. Pakhomova, S.; Berezina, A.; Lusher, A.L.; Zhdanov, I.; Silvestrova, K.; Zavialov, P.; van Bavel, B.; Yakushev, E. Microplastic variability in subsurface water from the Arctic to Antarctica. *Environ. Pollut.* **2022**, *298*, 118808. [CrossRef]
17. Cincinelli, A.; Scopetani, C.; Chelazzi, D.; Lombardini, E.; Martellini, T.; Katsoyiannis, A.; Fossi, M.C.; Corsolini, S. Microplastic in the surface waters of the Ross Sea (Antarctica): Occurrence, distribution and characterization by FTIR. *Chemosphere* **2017**, *175*, 391–400. [CrossRef]

18. Cunningham, E.M.; Ehlers, S.M.; Dick, J.T.A.; Sigwart, J.D.; Linse, K.; Dick, J.J.; Kiriakoulakis, K. High Abundances of Microplastic Pollution in Deep-Sea Sediments: Evidence from Antarctica and the Southern Ocean. *Environ. Sci. Technol.* **2020**, *54*, 13661–13671. [CrossRef]
19. Jones-williams, K.; Galloway, T.; Cole, M.; Stowasser, G.; Waluda, C.; Manno, C. Close encounters-microplastic availability to pelagic amphipods in sub- antarctic and antarctic surface waters. *Environ. Int. J.* **2020**, *140*, 105792. [CrossRef]
20. Cossi, P.F.; Ojeda, M.; Chiesa, I.L.; Rimondino, G.N.; Fraysse, C.; Calcagno, J.; Pérez, A.F. First evidence of microplastics in the Marine Protected Area Namuncurá at Burdwood Bank, Argentina: A study on *Henricia obesa* and *Odontaster penicillatus* (*Echinodermata: Asteroidea*). *Polar Biol.* **2021**, *44*, 2277–2287. [CrossRef]
21. Fragão, J.; Bessa, F.; Otero, V.; Barbosa, A.; Sobral, P.; Waluda, C.M.; Guímaro, H.R.; Xavier, J.C. Microplastics and other anthropogenic particles in Antarctica: Using penguins as biological samplers. *Sci. Total Environ.* **2021**, *788*, 147698. [CrossRef]
22. Auman, H.J.; Woehler, E.J.; Riddle, M.J.; Burton, H. First evidence of ingestion of plastic debris by seabirds at sub-Antarctic Heard Island. *Mar. Ornithol.* **2004**, *32*, 105–106.
23. Eriksson, C.; Burton, H. Origins and biological accumulation of small plastic particles in fur seals from Macquarie Island. *Ambio* **2003**, *32*, 380–384. [CrossRef] [PubMed]
24. Mishra, A.K.; Singh, J.; Mishra, P.P. Microplastics in polar regions: An early warning to the world's pristine ecosystem. *Sci. Total Environ.* **2021**, *784*, 147149. [CrossRef] [PubMed]
25. Fraser, C.I.; Morrison, A.K.; Hogg, A.M.C.; Macaya, E.C.; van Sebille, E.; Ryan, P.G.; Padovan, A.; Jack, C.; Valdivia, N.; Waters, J.M. Antarctica's ecological isolation will be broken by storm-driven dispersal and warming. *Nat. Clim. Change* **2018**, *8*, 704–708. [CrossRef]
26. Barrera-Oro, E. The role of fish in the Antarctic marine food web: Differences between inshore and offshore waters in the southern Scotia Arc and west Antarctic Peninsula. *Antarct. Sci.* **2002**, *14*, 293–309. [CrossRef]
27. Rossi, L.; Caputi, S.S.; Calizza, E.; Careddu, G.; Oliverio, M.; Schiaparelli, S.; Costantini, M.L. Antarctic food web architecture under varying dynamics of sea ice cover. *Sci. Rep.* **2019**, *9*, 12454. [CrossRef]
28. Liu, G.; Zhu, Z.; Yang, Y.; Sun, Y.; Yu, F.; Ma, J. Sorption behavior and mechanism of hydrophilic organic chemicals to virgin and aged microplastics in freshwater and seawater. *Environ. Pollut.* **2019**, *246*, 26–33. [CrossRef]
29. Massos, A.; Turner, A. Cadmium, lead and bromine in beached microplastics. *Environ. Pollut.* **2017**, *227*, 139–145. [CrossRef]
30. Teuten, E.L.; Saquing, J.M.; Knappe, D.R.U.; Barlaz, M.A.; Jonsson, S.; Björn, A.; Rowland, S.J.; Thompson, R.C.; Galloway, T.S.; Yamashita, R.; et al. Transport and release of chemicals from plastics to the environment and to wildlife. *Phil. Trans. R. Soc. B* **2009**, *364*, 2027–2045. [CrossRef]
31. Lithner, D.; Larsson, Å.; Dave, G. Environmental and health hazard ranking and assessment of plastic polymers based on chemical composition. *Sci. Total Environ.* **2011**, *409*, 3309–3324. [CrossRef]
32. Xu, P.; Peng, G.; Su, L.; Gao, Y.; Gao, L.; Li, D. Microplastic risk assessment in surface waters: A case study in the Changjiang Estuary, China. *Mar. Pollut. Bull.* **2018**, *133*, 647–654. [CrossRef] [PubMed]
33. Munari, C.; Infantini, V.; Scoponi, M.; Rastelli, E.; Corinaldesi, C.; Mistri, M. Microplastics in the sediments of Terra Nova Bay (Ross Sea, Antarctica). *Mar. Pollut. Bull.* **2017**, *122*, 161–165. [CrossRef]
34. Grover-Johnson, O. Findings from the Continuous Plankton Recorder in the Ross Sea and the East Antarctic Regions. Supervised Project Report ANTA604, New Zealand, 2017/2018. Findings from the Continuous Plankton Recorder in the Ross Sea and the East Antarctic Regions. Available online: https://ir.canterbury.ac.nz/bitstream/handle/10092/15837/Microplastics%20in%20the%20Southern%20Ocean.pdf?sequence=1&isAllowed=y (accessed on 30 April 2022).
35. Feng, J.; Li, D.; Zhang, J.; Zhao, L. Variations in and environmental controls of primary productivity in the Amundsen Sea. *Biogeosciences* **2021**, *296*, 1–44. [CrossRef]
36. Barnes, D.K.A.; Walters, A.; Gonçalves, L. Macroplastics at sea around Antarctica. *Mar. Environ. Res.* **2010**, *70*, 250–252. [CrossRef] [PubMed]
37. Fang, C.; Zheng, R.; Zhang, Y.; Hong, F.; Mu, J.; Chen, M.; Song, P.; Lin, L.; Lin, H.; Le, F.; et al. Microplastic contamination in benthic organisms from the Arctic and sub-Arctic regions. *Chemosphere* **2018**, *209*, 298–306. [CrossRef] [PubMed]
38. Chen, J.C.; Fang, C.; Zheng, R.; Hong, F.; Jiang, Y.; Zhang, M.; Li, Y.; Hamid, F.S.; Bo, J.; Lin, L.S. Microplastic pollution in wild commercial nekton from the South China Sea and Indian Ocean, and its implication to human health. *Mar. Environ. Res.* **2021**, *167*, 105295. [CrossRef] [PubMed]
39. Dehaut, A.; Cassone, A.L.; Frère, L.; Hermabessiere, L.; Himber, C.; Rinnert, E.; Rivière, G.; Lambert, C.; Soudant, P.; Huvet, A.; et al. Microplastics in seafood: Benchmark protocol for their extraction and characterization. *Environ. Pollut.* **2016**, *215*, 223–233. [CrossRef]
40. Karami, A.; Golieskardi, A.; Choo, C.K.; Romano, N.; Ho, Y.B.; Salamatinia, B. A high-performance protocol for extraction of microplastics in fish. *Sci. Total Environ.* **2017**, *578*, 485–494. [CrossRef]
41. Zhang, X.; Yan, B.; Wang, X. Selection and optimization of a protocol for extraction of microplastics from *Mactra veneriformis*. *Sci. Total Environ.* **2020**, *746*, 141250. [CrossRef]
42. Fang, C.; Zhang, Y.; Zheng, R.; Hong, F.; Zhang, M.; Zhang, R.; Mou, J.; Mu, J.; Lin, L.; Bo, J. Spatio-temporal variation of microplastic pollution in the sediment from the Chukchi Sea over five years. *Sci. Total Environ.* **2021**, *806*, 150530. [CrossRef]
43. Hubold, G.; Ekau, W. Feeding Patterns of Post-Larval and Juvenile Notothenioids in the Southern Weddell Sea (Antarctica). *Polar Biol.* **1990**, *10*, 255–260. [CrossRef]

44. Iwami, T.; Numanami, H.; Naito, Y. Behavior of three species of the family Artedidraconidae (Pisces, Notothenioidei), with ref-erence to feeding. *Polar Biol.* **1996**, *9*, 225–230.
45. Lombarte, A.; Olaso, I.; Bozzano, A. Ecomorphological trends in the Artedidraconidae (Pisces: Perciformes: Notothenioidei) of the Weddell Sea. *Antarct. Sci.* **2003**, *15*, 211–218. [CrossRef]
46. Mesa, M.L.; Eastman, J.T.; Licandro, P. Feeding habits of *Bathydraco marri* (Pisces, Notothenioidei, Bathydraconidae) from the Ross Sea, Antarctica. *Polar Biol.* **2007**, *30*, 541–547. [CrossRef]
47. Fanta, E.; Rios, F.S.A.; Meyer, A.A.; Grötzner, S.R.; Zaleski, T. Chemical and visual sensory systems in feeding behaviour of the Antarctic fish *Ophthalmolycus amberensis* (*Zoarcidae*). *Antarct. Rec.* **2001**, *45*, 27–42.
48. Morgana, S.; Ghigliotti, L.; Estévez-Calvar, N.; Stifanese, R.; Wieckzorek, A.; Doyle, T.; Christiansen, J.S.; Faimali, M.; Garaventa, F. Microplastics in the Arctic: A case study with sub-surface water and fish samples off Northeast Greenland. *Environ. Pollut.* **2018**, *242*, 1078–1086. [CrossRef] [PubMed]
49. Lusher, A.L.; O'Donnell, C.; Officer, R.; O'Connor, I. Microplastic interactions with North Atlantic mesopelagic fish. *ICES J. Mar. Sci. Marine Sci.* **2016**, *73*, 1214–1225. [CrossRef]
50. Pinho, I.; Amezcua, F.; Rivera, J.M.; Green-Ruiz, C.; de Jesus Piñón-Colin, T.; Wakida, F. First report of plastic contamination in batoids: Plastic ingestion by Haller's Round Ray (*Urobatis halleri*) in the Gulf of California. *Environ. Res.* **2022**, *211*, 113077. [CrossRef]
51. Güven, O.; Gökdağ, K.; Jovanović, B.; Kıdeyş, A.E. Microplastic litter composition of the Turkish territorial waters of the Mediterranean Sea, and its occurrence in the gastrointestinal tract of fish. *Environ. Pollut.* **2017**, *223*, 286–294. [CrossRef]
52. Dantas, N.C.F.M.; Duarte, O.S.; Ferreira, W.C.; Ayala, A.P.; Rezende, C.F.; Feitosa, C.V. Plastic intake does not depend on fish eating habits: Identification of microplastics in the stomach contents of fish on an urban beach in Brazil. *Mar. Pollut. Bull.* **2020**, *153*, 110959. [CrossRef]
53. Zhu, L.; Wang, H.; Chen, B.; Sun, X.; Qu, K.; Xia, B. Microplastic ingestion in deep-sea fish from the South China Sea. *Sci. Total Environ.* **2019**, *677*, 493–501. [CrossRef] [PubMed]
54. Wootton, N.; Ferreira, M.; Reis-Santos, P.; Gillanders, B.M. A comparison of microplastic in fish from Australia and Fiji. *Front. Mar. Sci.* **2021**, *8*, 690991. [CrossRef]
55. Karbalaei, S.; Golieskardi, A.; Hamzah, H.B.; Abdulwahid, S.; Hanachi, P.; Walker, T.R.; Karami, A. Abundance and characteristics of microplastics in commercial marine fish from Malaysia. *Mar. Pollut. Bull.* **2019**, *148*, 5–15. [CrossRef] [PubMed]
56. Daniel, D.B.; Ashraf, P.M.; Thomas, S.N. Microplastics in the edible and inedible tissues of pelagic fishes sold for human consumption in Kerala, India. *Environ. Pollut.* **2020**, *266*, 115365. [CrossRef] [PubMed]
57. Saha, M.; Naik, A.; Desai, A.; Nanajkar, M.; Rathore, C.; Kumar, M.; Gupta, P. Microplastics in seafood as an emerging threat to marine environment: A case study in Goa, west coast of India. *Chemosphere* **2021**, *270*, 129359. [CrossRef]
58. Absher, T.M.; Ferreira, S.L.; Kern, Y.; Ferreira, A.L.; Christo, S.W.; Ando, R.A. Incidence and identification of microfibers in ocean waters in Admiralty Bay, Antarctica. *Environ. Sci. Pollut. Res.* **2019**, *26*, 292–298. [CrossRef]
59. Sfriso, A.A.; Tomio, Y.; Rosso, B.; Gambaro, A.; Sfriso, A.; Corami, F.; Rastelli, E.; Corinaldesi, C.; Mistri, M.; Munari, C. Microplastic accumulation in benthic invertebrates in Terra Nova Bay (Ross Sea, Antarctica). *Environ. Int.* **2020**, *137*, 105587. [CrossRef]
60. Gao, C.; Cao, Z.; Yan, C.; Zhu, G. Traits and distribution of microplastics in stomach and intestinal tract of *Pleuragramma antarcticum* around the South Shetland Islands. *J. Fish.* **2021**. (In Chinese) [CrossRef]
61. Le Guen, C.; Suaria, G.; Sherley, R.B.; Ryan, P.G.; Aliani, S.; Boehme, L.; Brierley, A.S. Microplastic study reveals the presence of natural and synthetic fibres in the diet of King Penguins (*Aptenodytes patagonicus*) foraging from South Georgia. *Environ. Int.* **2020**, *134*, 105303. [CrossRef]
62. Bessa, F.; Ratcliffe, N.; Otero, V.; Sobral, P.; Marques, J.C.; Waluda, C.M.; Trathan, P.N.; Xavier, J.C. Microplastics in gentoo penguins from the Antarctic region. *Sci. Rep.* **2019**, *9*, 14191. [CrossRef]
63. van Franeker, J.A.; Bell, P.J. Plastic ingestion by petrels breeding in Antarctica. *Mar. Pollut. Bull.* **1988**, *19*, 672–674. [CrossRef]
64. Aronson, R.B.; Thatje, S.; Mcclintock, J.B.; Hughes, K.A. Anthropogenic impacts on marine ecosystems in Antarctica. *Ann. N. Y. Acad. Sci.* **2011**, *1223*, 82–107. [CrossRef] [PubMed]
65. Tin, T.; Fleming, Z.L.; Hughes, K.A.; Ainley, D.G.; Convey, P.; Moreno, C.A.; Pfeiffer, S.; Scott, J.; Snape, I. Impacts of local human activities on the Antarctic environment. *Antarct. Sci.* **2009**, *21*, 3–33. [CrossRef]
66. Council of Managers of National Antarctic Programs. *Antarctic Station Catalogue*; COMNAP: Christchurch, New Zealand, 2017; pp. 86–146.
67. Wright, S.L.; Thompson, R.C.; Galloway, T.S. The physical impacts of microplastics on marine organisms: A review. *Environ. Pollut.* **2013**, *178*, 483–492. [CrossRef] [PubMed]
68. Maximenko, N.; Hafner, J.; Niiler, P. Pathways of marine debris derived from trajectories of Lagrangian drifters. *Mar. Pollut. Bull.* **2012**, *65*, 51–62. [CrossRef]
69. Jiang, Y.; Yang, F.; Zhao, Y.; Wang, J. Greenland Sea Gyre increases microplastic pollution in the surface waters of the Nordic Seas. *Sci. Total Environ.* **2020**, *712*, 136484. [CrossRef]
70. Stark, J.S.; Corbett, P.A.; Dunshea, G.; Johnstone, G.; King, C.; Mondon, J.A.; Power, M.L.; Samuel, A.; Snape, I.; Riddle, M. The environmental impact of sewage and wastewater outfalls in Antarctica: An example from Davis station, East Antarctica. *Water Res.* **2016**, *105*, 602–614. [CrossRef]

71. Gröndahl, F.; Sidenmark, J.; Thomsen, A. Survey of waste water disposal practices at Antarctic research stations. *Polar Res.* **2009**, *28*, 298–306. [CrossRef]
72. Szopińska, M.; Luczkiewicz, A.; Jankowska, K.; Fudala-Ksiazek, S.; Potapowicz, J.; Kalinowska, A.; Bialik, R.J.; Chmiel, S.; Polkowska, Ż. First evaluation of wastewater discharge influence on marine water contamination in the vicinity of Arctowski Station (Maritime Antarctica). *Sci. Total Environ.* **2021**, *789*, 147912. [CrossRef]
73. Lusher, A.L.; Burke, A.; O'Connor, I.; Officer, R. Microplastic pollution in the Northeast Atlantic Ocean: Validated and opportunistic sampling. *Mar. Pollut. Bull.* **2014**, *88*, 325–333. [CrossRef]
74. Sun, J.; Prabhu, A.; Aroney, S.; Rinke, C. Insights into plastic biodegradation: Community composition and functional capabilities of the superworm (*Zophobas morio*) microbiome in styrofoam feeding trials. *Microb Genom.* **2022**, *8*, 000842. [CrossRef] [PubMed]
75. Yezek, L.P.; Duval, J.F.L.; Van Leeuwen, H.P. Electrokinetics of diffuse soft interfaces. III. Interpretation of data on the polyacrylamide/water interface. *Langmuir* **2005**, *21*, 6220–6227. [CrossRef] [PubMed]
76. Alomar, C.; Sureda, A.; Capó, X.; Guijarro, B.; Tejada, S.; Deudero, S. Microplastic ingestion by *Mullus surmuletus* Linnaeus, 1758 fish and its potential for causing oxidative stress. *Environ. Res.* **2017**, *159*, 135–142. [CrossRef] [PubMed]