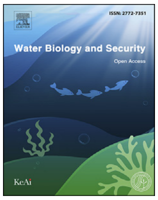
Water Biology and Security 1 (2022) 100034

Contents lists available at ScienceDirect

Water Biology and Security

journal homepage: www.keaipublishing.com/en/journals/water-biology-and-security



Plastic occurrence, sources, and impacts in Antarctic environment and biota

Gabriella Caruso[a,1,*], Elisa Bergami[b,c,1], Neelu Singh[d], Ilaria Corsi[e]

[a] Institute of Polar Sciences, National Research Council, Messina, Italy
[b] British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge, CB3 0ET, UK
[c] Department of Life Sciences, University of Modena and Reggio Emilia, Modena, Italy
[d] Norwegian Polar Institute, Longyearbyen, Norway
[e] Department of Physical Earth and Environmental Sciences, University of Siena, 53100, Siena, Italy

ARTICLE INFO

Keywords:
Anthropogenic impact
Contamination
Microplastics
Southern ocean
Antarctica
Occurrence
Sources
Ecotoxicity
Colonization
Biosecurity

ABSTRACT

Several studies have documented that plastic pollution is affecting one of the most remote and pristine regions of our planet, Antarctica. Plastics of different size and polymeric composition have been retrieved in Antarctic sea ice, surface waters and sediments, with microplastics (mostly fibers) found both in terrestrial and marine organisms. Such evidence raises concerns about potential detrimental effects on biodiversity and ecosystem functions. The present review aims to report the most up-to-date knowledge on occurrence and distribution of plastic pollution in the Antarctic environment and biota including interaction with microorganisms, potential sources, and its impact on Antarctic biota. Our understanding of plastic pollution in this polar region will help us define the human footprint in Antarctica and predict future ecological risks.

1. Introduction

The modern world is severely threatened by the negative consequences of anthropogenic pressures that affect every environmental domain (atmosphere, hydrosphere, pedosphere, biosphere). Anthropogenic activities are causing detrimental effects on both terrestrial and marine environments, however, their full impact is still unpredictable especially in remote regions such as polar environments (Corsi et al., 2021a). Antarctica and the Southern Ocean are subject to increasing levels and diversity of human activities that may severely affect environmental, scientific and historic values within its marine and terrestrial ecosystems and cryosphere (Aronson et al., 2011; Hughes et al., 2018). Plastic pollution in Antarctica and the Southern Ocean is an emerging threat to which the scientific community is spending considerable research effort. Considering the role this polar region plays in global climate equilibrium, maintaining a good environmental status of Antarctic marine ecosystems and preserving their environmental sustainability are both primary objectives contributing to sustainable development of our planet.

The plethora of studies over the last decade indicate that research on plastic occurrence and impact in the Antarctic environment is increasing exponentially. Antarctica and the Southern Ocean are considered to be pristine environments because of their geographic isolation and harsh climate and they are experiencing plastic pollution because of scientific activities, tourism, and fisheries (Corsi et al., 2021a). Plastics can lead to detrimental impacts and affect the ability of polar species to cope with other sources of anthropogenic disturbances they are already experiencing (e.g., climate change, fisheries, tourism) (Stark et al., 2019). First evidence of colonization by microorganisms of plastic debris retrieved in Antarctic territories regardless of size and polymer composition confirmed how plastics can represent a carrier for pathogenic bacteria, as well as for the spread of antibiotic resistance genes/bacteria into Antarctic ecosystems (Cappello et al., 2021; Laganà et al., 2019). Furthermore, the biological fragmentation of polystyrene (PS) microspheres to nanoplastics (<1 μm) (Gigault et al., 2018) by Antarctic krill (Dawson et al., 2018a) and the ingestion of micro-sized PS fragments by an Antarctic collembolan feeding on dumped PS foam from a coastal marine area, raise concerns about the spreading of micro- and nanoplastics in marine and terrestrial ecosystems and the potential repercussion on Antarctic food chains (Bergami et al., 2020a).

---

[*] Corresponding author.

E-mail addresses: gabriella.caruso@cnr.it (G. Caruso), elisa.bergami@unimore.it (E. Bergami), neelu.singh0387@gmail.com (N. Singh), ilaria.corsi@unisi.it (I. Corsi).

[1] These Authors contributed equally to this study.

https://doi.org/10.1016/j.watbs.2022.100034
Received 5 December 2021; Received in revised form 28 January 2022; Accepted 17 March 2022

Since the pivotal study by Waller et al. (2017), an increasing number of studies have documented at various Antarctic regional scales the occurrence of plastic items, including evidence of their interaction with organisms from different trophic levels. This review covers approximately 60 years of research on plastic pollution in Antarctica, including studies with disparate classifications of plastic debris based on their size, shape, and polymer composition. The definition of microplastic within the literature often varies between micrometric plastic pieces up to 5 or 10 mm. Following the size classification proposed by Hartmann et al. (2019), macroplastics (>10 mm), mesoplastics (1–10 mm), microplastics (1–1,000 μm), and nanoplastics (<1 μm) in the Southern Ocean have been retrieved in surface waters (Jones-Williams et al., 2020; Lacerda et al., 2019; Suaria et al., 2020a,b) and sediments (Cunningham et al., 2020; Munari et al., 2017; Reed et al., 2018). Furthermore, microplastics have been found in both marine (Absher et al., 2019; Bessa et al., 2019; Le Guen et al., 2020; Phillips and Waluda, 2020; Sfriso et al., 2020) and terrestrial species (Bergami et al., 2020a) raising concerns over the potential impact on delicate ecosystems and their functionality. For meso- and microplastics, current analytical methods allow us to detect and quantify their occurrence in environmental matrices including biota. Nanoplastics, on the other hand, have rarely been recovered because of the paucity of sampling and analytical equipment for detecting plastics below 10 μm. Only recently, nanoplastics have been traced below the North Atlantic Subtropical Gyre (Ter Halle et al., 2017) and in the Northern and Southern polar ice (Materić et al., 2022) using chromatographic methods (Schirinzi et al., 2019).

Plastic debris can not only have direct impacts (related to their size and shape), but indirectly, they can act as potential vectors of bacteria, contaminants such as metals and organic pollutants, leachates, and plastic additives. Therefore, this review summarises the various aspects of the problem related to plastic debris present in Antarctica, with specific reference to the following: (1) global and local sources, (2) occurrence and distribution in the Antarctic environment and biota, (3) biological impacts and pathways through food webs, (4) plastic-associated microbial communities and contaminants, and (5) legislation and measures in place to mitigate plastic pollution in this remote region.

2. Sources of plastic pollution

2.1. Primary and secondary sources of microplastics

Microplastic pollution can have a primary or secondary origin. Primary pollution is related to microplastic particles intentionally included in commercial products such as cosmetics (e.g., microbeads in scrub products), drug delivery applications (e.g., nanoplastics), detergents, and vectors of pharmaceutical ingredients (Al-Thawadi, 2020). Secondary pollution refers to those microplastics originating from the degradation of larger plastic debris by chemical, physical, or biological processes (Andrady, 2017; Hernandez et al., 2019; Lambert and Wagner, 2016).

2.2. Anthropogenic pressures

Due to its remoteness and the distance of the Southern Ocean from large, populated centers, the amount of plastic debris in the Southern Ocean is estimated to be lower than the concentrations found at other latitudes, such as in the North Pacific subtropical gyre (Suaria et al., 2020a). However, amounts of 10–10,000 particles per square kilometer were estimated in the Southern Ocean by computer simulation (van Sebille et al., 2015). Microplastic fibers found in the Antarctic marine surface waters, sea-ice, sediments and biota likely originate from local sources, such as sewage (treated or untreated), from tourism, fishing and research vessels and from shoreline and scientific research stations (Cincinelli et al., 2017; Eriksson et al., 2013; Fragao et al., 2021; Materić et al., 2022; Munari et al., 2017; Sfriso et al., 2021; Suaria et al., 2020a,b; Waller et al., 2017; Waluda et al., 2020). Currently 76 scientific research stations are located below 60° S belonging to 30 nations where the use of plastics is associated with logistics and field-based activities. Microplastics were found in wastewaters released from Antarctic research stations (Gheorghe et al., 2013). Conversely, offshore Antarctic waters were found to be free of floating microplastics (Kuklinski et al., 2019).

2.3. Atmospheric and oceanic currents

Plastics of various sizes, including nanoplastics, could be delivered to Antarctica through long-range transport by atmospheric and oceanic currents. The role of long-range transport in affecting the distribution patterns of plastics has already been demonstrated in the Arctic (Bergmann et al., 2019; Cózar et al., 2017; Marsh and van Sebille, 2021). A recent review by van Sebille et al. (2020) showed that physical processes are involved in the oceanic transport and distribution of microplastics to polar regions at a global scale. The authors highlighted how plastic particles under the Stokes drift may cross the strong Antarctic Circumpolar Current (ACC) and enter the Southern Ocean, as shown by recent model simulations in the South Atlantic sector (Fraser et al., 2018; Lacerda et al., 2019). Physical forcing can result in increased transport of plastics especially where storm-generated waves are more frequent or strong (Onink et al., 2019).

Circumpolar baselines of floating macro-, meso- and microplastics south of the Subtropical Front have been recently provided (Kuklinski et al., 2019; Suaria et al., 2020a,b). The very low amount of retrieved plastic debris confirms the barrier role played by the ACC in preventing the southward transport of drifting litter in the Southern Ocean (Clarke et al., 2005). However, if nothing is done to globally reduce marine plastic pollution in the future, the spread of buoyant plastics by oceanic currents, probably enhanced by global warming, will no longer be ruled out for remote polar regions (Fraser et al., 2018; Lacerda et al., 2019; Lau et al., 2020). The range of microplastic concentrations reported in surface waters and sediments of the Southern Ocean below the ACC can be attributed to the different locations of the sampling sites and related anthropogenic inputs (e.g., open ocean verses coastal areas, density and magnitude of scientific research stations, etc.).

2.4. Sea ice

In polar regions, micro- and nanoplastics can be trapped in sea ice during its formation, undergo further transformations and become newly bioavailable for sea ice grazing species during the seasonal sea ice melt. These processes have been widely described for Arctic sea ice (Geilfus et al., 2019; Mountford and Morales Maqueda, 2021), in which microplastics can reach concentrations that are several orders of magnitude higher than in the surrounding waters (Peeken et al., 2018). The single case study available in East Antarctic (Kelly et al., 2020) confirms this trend, with microplastics in sea ice (11.71 particles L^{-1} as polyethylene, polypropylene and polyamide) being higher than in seawater, although the concentrations reported are much lower than in Arctic sea ice. These findings suggest that Antarctic sea ice could serve as both a reservoir and source for microplastics in the Southern Ocean for short periods (about 1 year) since the majority of ice is first-year ice and about 80% of it melts each year (Overeem, 2003). Very recently, the Northern and Southern polar ice has been reported to contain nanoplastics (Materić et al., 2022).

It is clear then that global and local sources of plastic pollution from oceanic and land-based inputs deliver a variety of plastic items of different sizes (Aronson et al., 2011; Waller et al., 2017) and shape (fibers, fragments, films) into Antarctic marine waters.

3. Plastic in Antarctic environment and biota

3.1. Occurrence and distribution in the environment

3.1.1. Reports on micro-, meso- and macroplastics

Since the first reports of plastic debris in the surface waters of the New Zealand sector of the Southern Ocean and on Ross Dependency shores

(Carpenter, 1972; Gregory et al., 1984), observations of plastic pollution have dramatically increased. During the first joint marine debris survey covering the most remote areas of the Southern Ocean, floating macroplastics such as a cup and two fishing buoys were found in the Dumont D'Urville and Davis Seas, as well as two pieces of plastic packaging and a fishing buoy retrieved from the Amundsen Sea (Barnes et al., 2010; Convey et al., 2002). The occurrence of macroplastics in remote islands of the Southern Hemisphere was recorded by Barnes (2005), who observed a decreasing trend from equator to pole, although plastics were still found on Antarctic coasts. do Sul et al. (2011) referred to these fragmented observations as the “tip of an iceberg”, revealing just a small part of the problem. Since then, the monitoring of marine debris in the Southern Ocean has increased (Isobe et al., 2017).

Although extensive monitoring surveys are still lacking, large plastic debris and mesoplastics have recently been documented along the shores of sub-Antarctic (Waluda et al., 2020) and Antarctic islands, especially in the maritime Antarctic e.g., King George Island (Cappello et al., 2021; Laganà et al., 2019) and Livingston Island (Almela and Gonzalez, 2021), which is possibly the most altered region of Antarctica (Padeiro et al., 2016; Pertierra et al., 2017). Macro- and mesoplastics (>5 mm) (97.5% by number) along beaches at Bird and Signy islands in the Scotia Sea have recently been reported by Waluda et al. (2020) from a long-term survey conducted over three decades (1989–2019), showing an increasing trend in number of items (about 5.7 per year) but a decrease in their total mass.

Meso- and microplastic monitoring is currently prevalent in the Antarctic Peninsula region. These plastics have largely been documented both in marine surface waters (Jones-Williams et al., 2020; Lacerda et al., 2019; Leistenschneider et al., 2021) and sediments in close proximity to scientific research stations (Absher et al., 2019; Reed et al., 2018) and developed areas, such as the South Shetland Islands and the West Antarctic Peninsula (Fig. 1). But few studies have been conducted in more pristine and remote areas of Antarctica (Fig. 1), such as deep sea sediments (Cunningham et al., 2020), the East Antarctic region surface waters (Isobe et al., 2017), and the Ross Sea surface waters and sediments (Cincinelli et al., 2017; Munari et al., 2017), respectively.

Meso- and microplastics, mostly <300 μm, have been found in surface waters from the Scotia Sea, in the Atlantic sector of the Southern Ocean, down to Adelaide Island, near the Antarctic Peninsula (Jones-Williams et al. (2020). Estimated overall mean concentration was 0.009 ±0.004 fibres m^{-3} with a maximum of 0.019 fibers m^{-3} in the most developed areas (Fig. 1). An average of 34% of the microfibers were identified as cellulose and 57% as synthetic, with polyethylene terephthalate as the most prevalent polymer (53%). Such findings are similar to those reported one year earlier by Lacerda et al. (2019) (0.008 fibres m^{-3}, ranging from 755 to 3,524 items km^{-2}) in the same region. In this last study, the most common plastic polymers found were polypropylene, polyethylene, polyvinylchloride, PS, and polytetrafluoroethylene. Near King George Island, microplastics were recovered in surface water samples collected in Admiralty Bay in 2010–2011 with an average concentration of 2.40 ±4.57 fibers m^{-3} (Absher et al., 2019).

Cincinelli et al. (2017) reported the occurrence of microplastics in the Ross Sea as 0.17–0.34 particles m^{-3} (range 0.0032–1.18), including fragments (mean 71.9, 21.6%), fibers (mean 12.7, 14.3%), and others (15.4, 12.8%) with main polymeric composition being polyester, polyethylene, and polypropylene. Waters collected near the sewage treatment plant outfall of the Italian scientific research station, Mario Zucchelli (MZS), were predominantly fibers likely associated with the washing of textiles inside the station. A similar investigation conducted by Munari et al. (2017) close to the MZS in the Ross Sea showed microplastics in sediments (0.3–22 mm length) although the dominant type was the styrene-butadiene styrene copolymer (94.13% by weight), widely used in pneumatic tires, gaskets, shoes, and waterproofing and probably originating from anthropic activities carried out in the MZS area. These results agree with Reed et al. (2018) who measured fibers in sediments near the Rothera scientific research station (Adelaide Island, Western Peninsula), in which microfibers were prevalent compared to microplastic fragments (2–5 mm length, <0.1 mm diameter, with concentrations of 0–5 pieces per 10 mL).

One study conducted in the deep sea (Scotia Sea and Antarctic Peninsula) by Cunningham et al. (2020) showed microplastic contamination in 93% of sediment cores ($n = 30$) retrieved from different depths (range 136–3342 m). Fragments (56%) and fibers (39%) were the most abundant types of microplastics found, identified mainly as polyester, polypropylene, PS, polyurethane, and polyvinyl chloride. Interestingly,

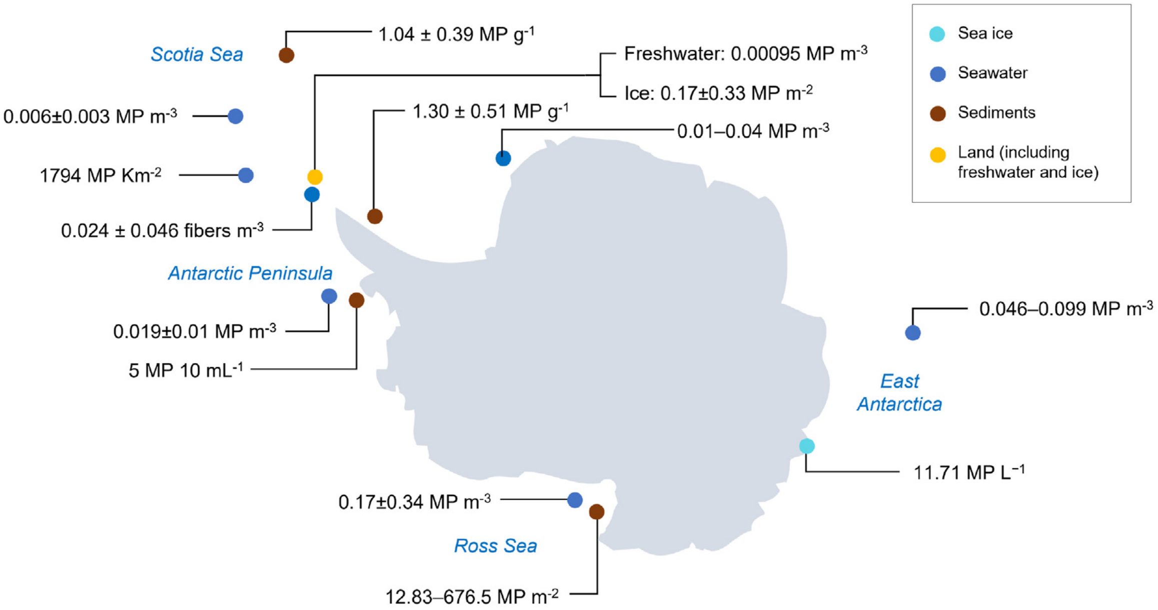


Fig. 1. Distribution of field studies on meso- and microplastics (MP) occurrence in Antarctica and the Southern Ocean (circumpolar studies are not shown). Top right: legend showing sample type analyzed (sea ice, surface waters, (deep sea) sediments; freshwater and ice). For each sample type/location, MP concentrations (average or range) are reported. Data shown are from the following references: sea ice (Kelly et al., 2020), seawater (Absher et al., 2019; Cincinelli et al., 2017; Isobe et al., 2017; Jones-Williams et al., 2020; Lacerda et al., 2019), sediments (Cunningham et al., 2020; Munari et al., 2017; Reed et al., 2018), land, including freshwaters and glaciers (González-Pleiter et al., 2020, 2021).

microplastic loads were 0–9.52 MP/g of sediment, close to the high abundances reported in Arctic deep-sea sediments (Tekman et al., 2020).

3.1.2. Potential sources of variability in plastic pollution research

Quantitative estimates of plastic pollution vary with the different methods used for sampling and analysis. Differences in the quantitative assessment of plastic pollution can result from the methods used for microplastic collection (e.g., neuston plankton net with mesh 330 or 220 μm), sample storage (freezing verses in ethanol or formaldehyde), or processing (e.g., enzymatic, oxidative or alkaline treatments, density separation) and detection and identification of plastic polymers (e.g., visual sorting, optical microscopy, Raman or FTIR spectroscopy). The Antarctic and Southern Ocean Coalition has recently suggested using a Continuous Plankton Recorder (CPR) to monitor *in situ* microplastic distribution in the Southern Ocean, even if this instrument has shown some limitations as a tool to assess the abundance and distribution of microplastics in the Antarctic marine ecosystem (Grover-Johnson, 2018). A standardization of sampling procedures and shared protocols for extraction and detection of microplastics are strongly recommended to achieve a better comparison of field-based data.

3.2. Occurrence and distribution in the biota

3.2.1. Microplastic in terrestrial organisms

Micro-sized PS traces have recently been found in the gut of the Antarctic collembolan *Cryptopygus antarticus* collected in King George Island (South Shetland Islands) (Bergami et al., 2020a) (Fig. 2). Micro-PS fragments matched the composition of a large item of PS foam stranded on the shores of the island. This study is the first and only evidence on ingestion of microplastic by microarthropods like *C. antarcticus* as the pathway of exposure for plastics into Antarctic soil food webs.

3.2.2. Microplastics in marine organisms

Microplastics are found in marine macrobenthos from both human-impacted and pristine Antarctic territories (Fig. 2). Microplastics in coastal marine ecosystems (Fig. 3) were reported in 83% of 12 macrobenthic species (0.01–3.29 items/mg d.w., 1 item per individual, size of 33–1000 μm, mostly round shape) collected in Terra Nova Bay in the Ross Sea close to the sewage treatment plant outfall of MZS, at Camp Icarus and at Adelie Cove (Sfriso et al., 2020). Filter-feeders (bivalves, 1.9 per individual) and benthic grazers (1.2 per individual) showed higher content of microplastics (from 3 to 5 times higher) than omnivores and predators, suggesting that trophic transfer along benthic food chains is unlikely. Specimens collected in the proximity of MZS showed the highest per capita level of microplastics, with lower amounts found in those collected from Camp Icarus and Adelie Cove. Based on μ-FTIR analysis, fibers were mostly composed of nylon (86%), followed by polyethylene (5%), polytetrafluoroethylene, polyoxymethylene, phenolic resin, polypropylene, PS, resin and XT polymer. The similarity with microplastics found in sediments of Road Bay (Munari et al., 2017) provides further evidence that the MZS is the main source of microplastic contamination for the local macrobenthic communities. It has been estimated that local sources account for about 50% based on polymers retrieved in macrobenthos of the MZS site while the rest (e.g., nylon and polyethylene) could originate from global sources as reported by Fang et al. (2018) in Arctic and sub-Arctic benthic species.

There is a paucity of data about microplastic ingestion by Antarctic fish. The only record on microplastics in Antarctic fish was documented in the Antarctic toothfish (*Dissostichus mawsoni*) collected north of the ACC in the Indian Ocean sector and in Southern Ocean (Cannon et al., 2016). Two microplastic items (with a size of 583 and 846 μm) made of acrylic resin were recovered from the gastrointestinal tract of a single specimen out of 342 fish examined, suggesting fish were not ingesting substantial quantities of microplastics (0.3%) in the study area.

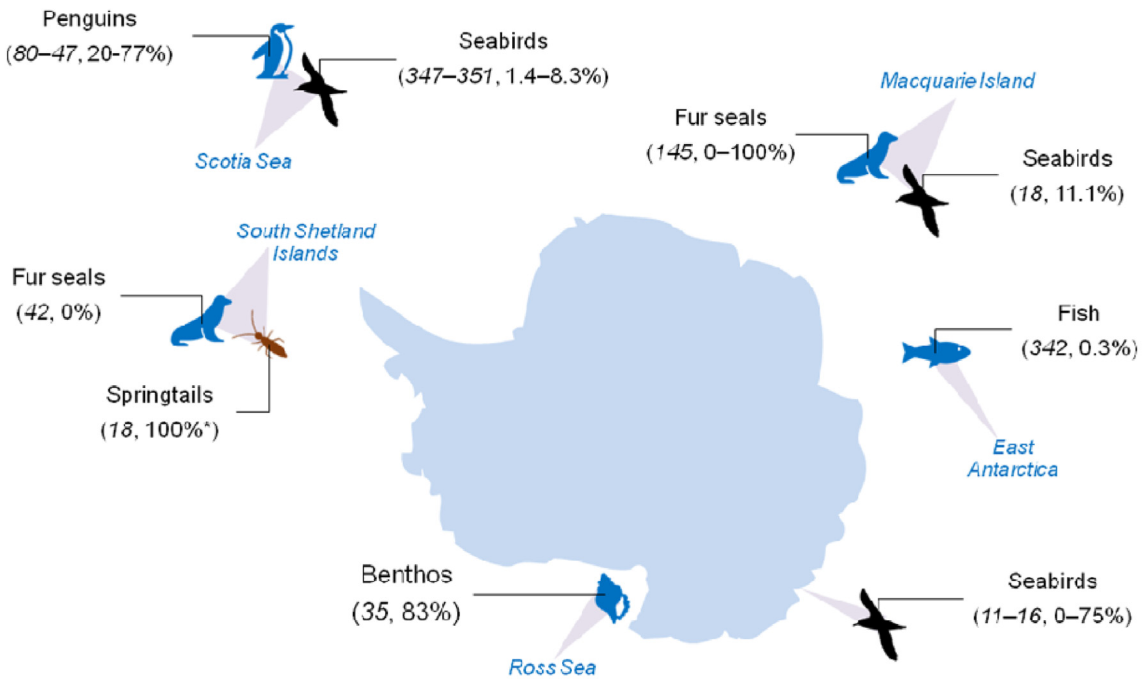


Fig. 2. Distribution of field observations of plastic litter intake (from macro-to microplastics) in Antarctic biota from marine (blue) and terrestrial (brown) ecosystems in Sub-Antarctic (i.e., Bird Island, South Georgia and Signy Island, South Orkney Islands in the Scotia Sea, Macquarie Island, Indian Ocean sector) and Antarctic regions (i.e., South Shetland Islands, Ross Sea, East Antarctica). For each organism, number of biological samples (*n*) and frequency of occurrence (*%*) of plastic intake are shown. * report of colonization on a plastic substrate). Data shown are from the following references: penguin scats (Bessa et al., 2019; Le Guen et al., 2020), fur seal scats (Eriksson and Burton, 2003; Garcia-Garin et al., 2020), seabird carcasses/stomachs (Auman et al., 2004; Phillips and Waluda, 2020; van Franeker and Bell, 1988), fish digestive tracts (Cannon et al., 2016), macrobenthos (Sfriso et al., 2020), Antarctic springtails (Bergami et al., 2020).

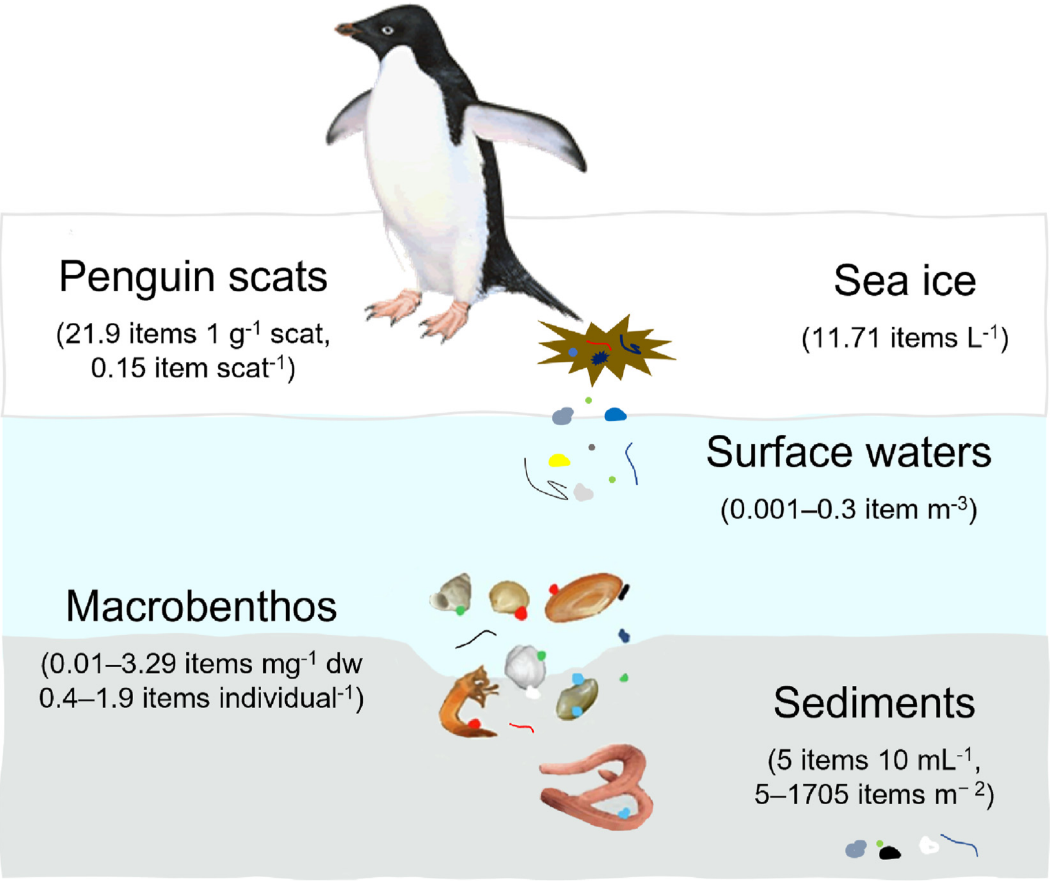


Fig. 3. Average amount of microplastics found in Antarctic marine sediments, surface waters, sea ice and marine biota from macrobenthos to higher predators, from either the most anthropized area, the Antarctic Peninsula and the pristine one, the Ross Sea. Values are from the following studies: penguin scats (Bessa et al., 2019; Fragão et al., 2021; Le Guen et al., 2020), sea ice (Kelly et al., 2020); marine surface waters (Absher et al., 2019; Cincinelli et al., 2017; Jones-Williams et al., 2020; Kuklinski et al., 2019; Lacerda et al., 2019; Leistenschneider et al., 2021; Suaria et al., 2020a, b; Waller et al., 2017); macrobenthos (Sfriso et al., 2020); sediments (Cunningham et al., 2020; Munari et al., 2017; Reed et al., 2018).

3.2.3. Key factors affecting plastic exposure in marine higher predators

Diet, foraging behavior, trophic transfer and distance from developed areas can affect the level of exposure to microplastics of Antarctic marine higher predators. Microplastics have been found in scats of Adélie (*Pygoscelis adeliae*) (15%), chinstrap (*Pygoscelis antarcticus*) (28%) and gentoo (*Pygoscelis papua*) (29%) penguins in breeding colonies over seven seasons (2006–2016) across the Antarctic Peninsula and the Scotia Sea (Fragão et al., 2021) (Fig. 3). From a total of 317 scats analyzed, 35% incorporated meso- and microplastics ($n = 92$; size from 0.63 μm to 5 mm) as fiber (74%) and fragments (26%) with 55% made of cellulose, and 35% of made of polyethylene (80%) and polyester (10%). No quantitative differences were observed in the abundance of microplastics among the three penguin colonies nor in temporal variation over the 10-year survey, suggesting there were no local sources in the Scotia Sea and no increasing exposure over that time. Previously, Bessa et al. (2019) found microplastics in scats of the gentoo penguin from colonies located on Bird Island (South Georgia) and Signy Island (South Orkney Islands). Only 20% of penguin scats from both islands contained microplastics (0.23 ±0.53 items per scat), mainly consisting of fibers and fragments of various size and polymer composition. Microfibers were made of polyester (60%) and of cellulose-rayon (15%), while polyacrylonitrile, polypropylene, polyethylene and polyacrylate were the main component polymers of fragments and films.

Microfiber ingestion by the King penguin *Aptenodytes patagonicus* was also reported by Le Guen et al. (2020) in specimens foraging at South Georgia Island. 77% of King penguin scats contained microfibers of which 88% were of natural cellulose and only 12% of polyester, nylon or rayon). An average of 21.9 ±5.8 microfibers per 1 g of scats d.w. was found, with higher amounts in penguins incubating eggs compared to those raising chicks. Such findings suggest that the different diet and the foraging trips north of the ACC could expose penguins to higher amounts of fibers compared to those not crossing the ACC. For instance, King penguins largely feed on mesopelagic fish, whereas Antarctic krill is the primary component of the diets of gentoo, chinstrap and Adélie penguins. Meso- and microplastics can be mistaken for food and directly ingested by penguins or indirectly by feeding on contaminated prey (Bessa et al., 2019).

The first record of plastic ingestion in Antarctic seabirds was documented in the 1960s by Harper and Fowler (1987) in New Zealand prions (*Pachyptila* spp.) and later by Ryan (1987), and van Franeker and Bell (1988) who showed the incidence of plastic intake in Antarctic petrels. More recent findings were reported by Auman et al. (2004) at Sub-Antarctic Heard Island (53°S, 73°E) in the Southern Indian Ocean during the Australian National Antarctic Research Expeditions carried out in 2000/01. Of 18 seabird carcasses examined [10 South Georgian diving petrels (*Pelecanoides georgicus*), 4 Sub-Antarctic skuas (*Catharacta antarctica*), 1 Southern giant petrel (*Macronectes giganteus*), 2 Antarctic prions (*Pachyptila desolata*) and one unidentified diving petrel (*Pelecanoides* sp.)], only two birds — both Antarctic Prions — had mesoplastics in their digestive tracts. One piece was an orange-pink plastic piece in the proventiculus, sized 8.1 × 5.4 × 0.4 mm, weighing 9.8 mg and one was a light blue plastic piece in the gizzard, sized 6.0 × 4.4 × 0.6 mm, weighing 9.0 mg. In addition, regurgitated Subantarctic skua pellets from Atlas Cove showed the presence of mesoplastics (16.7 × 3.8 × 1.0 mm, 178.83 mg; 5.7 × 4.1 × 2.7 mm, 104.38 mg), detected in a small percentage (0.5%) on the total of dissected casts (396). In spite of the low incidence of plastic particles, this first study underlined the emerging threat related to the persistence of marine debris at relatively remote localities. Golubev (2020) also reported ingestion of a plastic braided rope in an adult Emperor penguin and plastic in two South polar skuas at Mirny and Haswell Islands (East Antactica).

Ryan et al. (2016) reported that in a large survey on microplastics in the fur seal *Arctocephalus gazella* and Sub-Antarctic fur seal *Arctocephalus tropicalis* breeding at Macquarie Island in 1990, scats contained mesoplastic fragments (average 2–5 mm) probably transferred from contaminated prey (e.g., myctophid fish). Previous records back in 2003 by Eriksson and Burton documented 164 mesoplastics (99% < 10 mm long) in the scats of both seal species breeding on Macquarie Island, where myctophid fish is their main prey (Eriksson and Burton, 2003). More recently, Garcia-Garin et al. (2020) found that both fragments and fibers retrieved from 42 scats of male Antarctic fur seals (*A. gazella*) from Deception Island (South Shetland Islands) were not synthetic but made of silicate minerals and chitin. The authors stated that microplastic contamination in fur seals in the Bransfield Strait (Western Antarctica) is still very low or undetectable.

Overall, fibers and fragments from marine invertebrates and scats of higher trophic level predators such as seabirds or mammals are clearly not only of synthetic origin, since cotton-based (cellulose) fibers were also present in samples in which microplastics were found.

4. Eco-/Bio-interactions

4.1. Environmental fate of plastic items in Antarctic waters

4.1.1. Effects of climate conditions on plastic fate

In Antarctica, the extreme climate conditions can affect the plastic fate. Micro- and nanoplastics can originate from the continuous weathering by chemical, physical, and biological degradation processes of plastics in the marine environment (Andrady, 2017). The unique environmental conditions in polar environments (e.g., seasonal sea ice coverage and UV radiation, strong winds, low temperatures) could significantly influence rates of plastic fragmentation processes and its fate in Antarctica (Corsi et al., 2021b; Tocháček et al., 2019).

4.1.2. Interactions with cryopelagic communities

Micro- and nanoplastics entrapped in sea ice can interact with cryopelagic communities. Geilfus et al. (2019) studied the distribution of secondary meso- and microplastics (polypropylene, polyvinyl chloride, polyethylene terephthalate, and 5 size classes from 63 μm to >1,400 μm) in sea ice in a mesocosm experiment. They showed that microplastics were incorporated into the top layer of forming sea ice, with enrichment in plastic particles and ion salts associated with the growth of ice crystals. During sea ice melt, plastics would quickly become bioavailable for cryopelagic communities, including primary producers and zooplankton that are strictly associated with sea ice. Sea ice food web species exposed to higher concentrations of micro- and nanoplastics released from the sea ice are more susceptible to the potential ecotoxicological consequences of exposure to meso- and microplastics. A recent laboratory study by Hoffman et al. (2020) showed that the Arctic ice algae *Fragillariopsis cylindrus* was able to interact with PS microbeads (0.5 μm, at a concentration of 90,000 beads mL^{-1}) during the process of sea ice growth, affecting microplastic surface binding and behavior. They suggested that the exopolymeric substances (EPS) produced by the ice algae played a role in eco-corona formation, which matches previous results on the effects of nanoplastics on marine diatoms from other latitudes (Grassi et al., 2020). "Eco-corona" is an umbrella term used to identify the biomolecules naturally present in seawater that are adsorbed onto nanomaterials (and nanoplastics), driving their interaction with biological systems and ultimately their fate and toxicity (Corsi et al., 2020). The concept has been recently extended to include microplastics, although these display a different physical behaviour compared to nanoplastics. Based on recent agreements, nanoplastics are defined as any synthetic polymeric material exhibiting colloidal behavior in the environment, within the size range between 1 and 1000 nm (Gigault et al., 2018). In aqueous media, they are prone to agglomeration with other colloids including natural organic matter (NOM), showing high surface specificity and biological reactivity (Corsi et al., 2021b).

Pradel et al. (2021) recently demonstrated the different behaviors of micro- and nanoplastics in simulated sea ice under laboratory conditions. The authors showed that while microplastics were trapped in sea ice, nanoplastics were distributed at the seawater/ice interface due to their colloidal properties, being associated with NOM. A first characterization of nanoplastic behaviour in Antarctic-like conditions was carried out by Bergami et al. (2019), using PS nanoparticles (PS NPs) as a proxy. Incubation in filtered Antarctic seawater at low temperatures (i.e., <0 °C) was found to alter the agglomeration properties of PS NPs regardless of their surface charges after 24 h, suggesting potential consequences on their bioavailability to Antarctic organisms.

4.2. Interaction with chemicals in polar waters and additives leaching

The primary risk related to plastic items results from their high chemical stability and persistence in the environment. Once discharged in the environment, plastics are often recalcitrant to degrade *in situ* and provide a suitable substrate for the adsorption of both legacy and emerging pollutants (Caruso, 2019; Lo Giudice et al., 2018). Adsorbed contaminants can be transported after plastic ingestion by aquatic organisms, with possible bioaccumulation through the food web (Hasan Anik et al., 2021; Lo Giudice et al., 2019; Sharma and Chatterjee, 2017; Wu et al., 2019). The eco-corona present on the surface of micro- and nanoplastics also contributes to the increased bioavailability of pollutants, with the so-called "Trojan horse" mechanism that relies on their internalization by cells and release of any toxic molecules that are adhering onto their surfaces.

Many categories of contaminants have been shown to adsorb onto the surface of micro- and nanoplastics, including polycyclic aromatics hydrocarbons, polychlorinated biphenyls (PCBs), dioxins, phthalates, perfluoroalkyls, metals, flame retardants, pesticides and all chemical compounds characterized by high hydrophobicity. For some of these compounds, endocrine interference has been observed. A recently published study has provided evidence of the ability of PS nano- and microplastics to carry benzo(a)pyrene to mussel hemocytes and to cause toxicity *in vitro* (Katsumiti et al., 2021).

Hexabromocyclododecanes, which are non-aromatic brominated flame retardants used as additives to PS, have been found in Antarctic seawater and sediments (Chen et al., 2015; De-la-Torre et al., 2020), stressing the need to perform further ecotoxicological studies to evaluate suitable biomarkers of exposure and effects of such contaminants and their ability to be transferred along the Antarctic food chains. Gao et al. (2018) studied the sources and transport mechanisms of flame retardants and plasticizers in lake and marine waters of Fildes Peninsula and identified multiple local sources such as wastewater, air traffic, research stations, and feces.

Yu et al. (2021) reviewed the adsorption behavior and interaction of organic micropollutants with micro- and nanoplastics. Besides acting as vectors for organic micropollutants into aquatic organisms, micro- and nanoplastics are also a direct source of toxic compounds through leaching of plastic additives and through the interactions of micro- and nanoplastics with micropollutants that may have severe ecotoxicological impacts once they enter food webs. Emphasis is given to the adsorption/desorption mechanisms as well as to the environmental factors affecting this process. The main factors influencing the adsorption of organic micropollutants onto nano- and microplastics can be classified into: intrinsic properties of micro- and nanoplastics (i.e., polymer type, size, surface area, weathering, plastic additives and functional groups); environmental factors (i.e., salinity, pH, dissolved organic matter, ionic strength) and factors related to the characteristics of the organic micropollutants (i.e., hydrophobicity, concentration, functional groups, surface adsorption via van der Waals forces or hydrogen bonds, and pore filling). Gouin et al. (2011) and Koelmans et al. (2014) have developed two different biodynamic models to evaluate the relevancy of MPs as a vector for the pollutant, but the overall scenario remains unclear.

Current knowledge about microplastic-contaminant interactions and the potential health risks is, however, in its infancy, and requires further investigation. Since the Southern Ocean and Antarctica are particularly vulnerable to climate warming and invasive species, it is important to monitor all environmental and anthropogenic stressors potentially causing changes in biodiversity. This issue is of most concern when considering ingestion by suspension-feeders of small plastic fragments that can carry toxins (Graham and Thompson, 2009). Waste dumps and soil that can leach into the marine environment contaminants that are adsorbed on their surface should be taken into consideration when related to ice-melt processes, because warming temperatures can mobilize pollutants entrapped into ice structures (Lo Giudice et al., 2019).

5. Impact on Antarctic organisms

5.1. Microbial communities: Colonization and effects

5.1.1. Plastic is a suitable substrate for colonization by microbial communities

The terms “plastisphere” (Zettler et al., 2013) and “eco-corona” (Corsi et al., 2020) have been created to identify those specific and well-adapted microorganisms and biomolecules naturally present in seawater that are associated with the surface of plastic debris. Within the members of the plastisphere, three distinct communities have been distinguished: (i) a component represented by generalist colonising microbes; (ii) a transient component, including microorganisms that are transiently associated with plastic items; (iii) a core of specifically plastic-associated members, although there is still debate whether the plastisphere represents an obligate assemblage specifically associated with plastics, compared with other microorganisms that are present in the surrounding waters (Amaral-Zettler et al., 2020; Nguyen et al., 2021; Oberbeckmann et al., 2016, 2018; Oberbeckmann and Labrenz, 2020).

5.1.2. Consequences of microorganism-plastic interactions

The colonization by marine microorganisms of plastic debris entering the ocean may alter the density and therefore the sinking rates of neutrally and positively buoyant fragments (Chen et al., 2019; Rummel et al., 2017). However, their repercussions at the ecosystem-level remain largely unexplored (Amaral-Zettler et al., 2020; Caruso, 2015, 2020; Harrison et al., 2011). Conversely, increasing evidence has shown that, as an attachment substrate, plastic debris can serve as a carrier for the spread of various species of microorganisms, including potential pathogens and antibiotic-resistant bacteria (Cappello et al., 2021; Caruso, 2015, 2020; Laganà et al., 2019). Current knowledge about microbial colonization of extreme environments such as the Antarctic region is limited (Caruso, 2020; Lee et al., 2016; Webster and Negri, 2006). This issue requires further understanding since it is particularly relevant for the protection of marine biodiversity, especially considering the role of plastics as substrates for the settlement of “biofouling” communities (i.e., benthic suspension-feeding invertebrates) in the water column and on the sea floor. Therefore plastics may provide new habitat for harmful and/or invasive species, with the potential for biosecurity implications and other ecological impacts, as reviewed in Audrézet et al. (2021). In the marine environment the colonization of plastics by microorganisms may have significant ecological impacts, however, data on epiplastic organisms are still lacking for many oceanic regions. Lacerda et al. (2020) have characterized for the first time the fungi belonging to the plastisphere within the Southern Hemisphere, stressing the need to further investigate the potential impacts of plastic-associated eukaryotes in these ecosystems.

5.2. Effects at different trophic levels of Antarctic marine food webs

The effects caused by plastics have been studied from single marine organisms up to the level of population and ecosystem services (e.g., carbon cycle). The current state of knowledge on microplastics in polar regions has recently been reviewed by Mishra et al. (2021) and Singh et al. (2021), and previously by Tirelli et al. (2020), who tried to provide a baseline for the availability of microplastics to consumers at different trophic levels including benthic organisms, birds and fishes. The ingestion of microplastics may cause a physical threat through internal abrasion while, at the same time, toxic chemicals may also cause adverse health outcomes. Due to their high surface area to volume ratio, multiple organic and inorganic pollutants can adsorb to the surface of microplastics causing indirect toxicity (Eerkes-Medrano et al., 2015; Rochman et al., 2013). Moreover, the effects due to chronic exposure to chemicals may be more severe than physical damage (Rochman et al., 2013) and impact assessments for ecotoxicological implications are needed (Vázquez and Rahman, 2021).

Large plastic items have been ingested and entangled by Antarctic marine wildlife, as shown by the entanglement of a female fur seal and a chinstrap penguin with a half-ingested fishing rope at Livingston Island, Southern Shetland Islands (Bravo Rebolledo and van Franeker, 2015). Waluda and Stanilad (2013) reported 1,033 Antarctic fur seals *A. gazella* were entangled in packaging and synthetic/fishing nets at Bird Island, South Georgia over a 23 year-observation period (Waluda and Staniland, 2013). Golubev (2020) further reported an entangled Adélie penguin in a fishing line at Mirny and Haswell Islands (East Antactica). While entanglement can lead to suffocation and drowning, ingestion of large plastic debris has been associated with lesions, inflammation, blockage of the digestive tract and starvation (Gregory, 2009). Therefore, inclusion of observations relating to plastic ingestion and entanglement in long-term monitoring programs should be included in monitoring the health of Antarctic seabirds and sea mammals.

A bench-scale study by Dawson et al. (2018b) on Antarctic krill *E. superba* explored the toxicokinetics and negative effects of polyethylene microspheres (~30 μm, 0–116 beads mL^{-1}) after a 10-day exposure period followed by 15 days post exposure recovery. The authors reported no acute toxicity and no bioaccumulation in the exposed krill but measured high uptake and depuration rates. Further studies are needed to elucidate potential bioaccumulation and effects of microplastics on physiology and survival of Antarctic krill following long-term exposure. Antarctic krill plays a central role in Antarctic marine food webs (Atkinson et al., 2012; Trathan and Hill, 2016), therefore it is crucial to understand if microplastics may affect krill biomass in the Southern Ocean. Some authors have hypothesised that small microplastics may be transferred from the lowest trophic levels (i.e., phyto- and zooplankton) to higher predators (Nelms et al., 2018; Puasa et al., 2021). However, Fragão et al. (2021) determined the content of microplastics and ingested prey (mainly krill) in scats from Adélie, gentoo and chinstrap penguins, but found no significant correlation between the number of microplastics and krill. Future studies should focus on the effects of plastic litter and microplastics at the different trophic levels of Antarctic marine food webs, ranging from benthic to pelagic communities up to top predators.

5.3. Effects of nanoplastics

Antarctic marine biota may suffer from exposure to nanoplastics alone and/or in combination with other stressors. Although nanoplastic abundances are not yet available in the Southern Ocean, some pioneering bench-scale ecotoxicology studies have been conducted to investigate the negative effects of model nanoplastics in key Antarctic marine species. The first study was performed on the Antarctic sea urchin *Sterechinus neumayeri* exposed to PS NPs as a proxy for nanoplastics (Bergami et al., 2019). Sea urchin immune cells (i.e., the coelomocytes) were experimentally exposed to PS NPs in *in vitro* short-term cultures (6 and 24 h) under controlled laboratory conditions. PS NPs were found internalised in sea urchin phagocytes and associated with a decrease in phagocytic capacity. Negatively charged PS NPs (PS–COOH, 1 and 5 μg mL^{-1} after 24 h) were associated with increases in inflammatory response and oxidative stress in exposed coelomocytes. These findings showed for the first time the sensitivity of immune cells of *S. neumayeri* to nanoplastics, showing the need for further investigation under real-time exposure scenarios to assess the potential for adverse effects of nanoplastics as emerging stressors.

Further studies were conducted on Antarctic zooplankton that were exposed to either single (nanoplastics), or combined stressors (nanoplastics and ocean acidification). Adverse effects of PS NPs on juvenile Antarctic krill (*E. superba*) following acute exposure (48 h) have recently been reported (Bergami et al., 2020b). Although no mortality after 48 h was found, an increase in exuviae production (12.6 <1.3%) and impaired swimming activity were reported in juveniles exposed to positively charged PS NPs (i.e., PS-NH_2). The authors also documented the presence of aggregates of PS NPs in Antarctic krill fecal pellets (FPs), which confirmed the waterborne ingestion and egestion following short-term exposure. The presence of nanoplastics in krill FPs was found to significantly affect krill FP structure and sinking velocities. Changes in the composition of the biogenic material (e.g., FPs) sinking to the Southern Ocean floor could have serious ecological consequences enhancing remineralisation and altering Carbon export and sequestration into the deep sea (Lespes et al., 2020).

Rowlands et al. (2021) investigated the impact of single and combined exposures to PS NPs and low seawater pH (pCO_2 ~900 ppm, pH 7.7) on the embryonic development of Antarctic krill. Following exposure to negatively charged PS NPs, a reduction in the proportion of embryos reaching the limb bud stage (13.17%) compared to controls (21.84%) was observed, suggesting that reduced seawater pH might affect bioavailability and toxicity of nanoplastics, as already demonstrated for PS microplastics (Wang et al., 2020). Manno et al. (2021) addressed the single and combined effects of nanoplastics (PS NPs, 1 μg mL^{-1}) and ocean acidification (pCO_2 of 750 ppm, pH 7.8) on the sub-Antarctic pteropod *Limacina retroversa* following short-term exposure (48 h). They showed how PS NPs were able to disrupt the ability of pteropods to counteract increasing ocean acidification, resulting in higher mortality (PS–COOH: 11.1 ±4.8%, PS-NH_2: 36.1 ±4.8%, low pH and PS-COOH: 22.2 ±4.8%, low pH and PS-NH_2: 47.2 ±4.8%). These findings underline the need to understand the impact of plastic in combination with other stressors, reflecting future climate change scenarios.

6. Current policies for control and mitigation

Despite reports on macroplastics in the Antarctic region, the problem was under evaluated until the first recovery of microplastics from the Southern Ocean surface waters (Isobe et al., 2017). Since then, microplastics have been identified as a serious emerging threat by international Antarctic scientific organizations (i.e. Antarctic and Southern Ocean Coalition, ASOC, 2017). Actions aimed at monitoring the sources, distribution pathways, and effects of marine litter on biota as well as mitigating and reducing those impacts have become increasingly urgent. In 1989, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) launched an international monitoring program to track plastic debris along the Antarctic shore, in seabird colonies, and at sea (CCAMLR Secretariat, 2019). Over the years, these initiatives have contributed to the generation of field-based data sets for long-term marine debris assessments.

Based on recent evidence of plastic litter and microplastic occurrence in Antarctica, including Antarctic Specially Protected Areas (Almela and Gonzalez, 2020; González-Pleiter et al., 2020) and biota, a general agreement among countries operating in Antarctica was developed to support scientific research on this issue (Secretariat of the Antarctic Treaty, 2019). Launched in 2018 by the Scientific Committee on Antarctic Research (SCAR), the Plastic in Polar Environment Action Group (Plastic-AG) aims to assess: (i) the occurrence and distribution of plastics in polar environments; (ii) the sources and fate in the polar regions; (iii) the impacts on polar ecosystems and biodiversity; (iv) the potential remediation and mitigation solutions both at local and global scales (SCAR Plastic-AG, 2018). Similarly, the Protocol on Environmental Protection of the Antarctic Treaty (including Annex I: Environmental Impact Assessment, Annex III: Waste Disposal and Waste Management and Annex IV: Prevention of Marine Pollution) is addressing this issue within the Antarctic Treaty area (Zhang et al., 2020). Annex IV states that plastic disposal into the sea is banned (e.g. fishing lines, nets and plastic garbage bags), thereby limiting any potential adverse impact on Antarctic marine wildlife from that debris. Additional measures to reduce plastic input into the Antarctic environment have been promoted by decision-making institutions such as CCAMLR and the Council of Managers of National Antarctic Programs (COMNAP). The management of wastes from research stations is strictly regulated in accordance with the Environmental Protocol and enforced at a national level, for example, with the Government of South Georgia and the South Sandwich Islands (GSGSSI) legislation in the Scotia Sea region. CCAMLR adopted specific measures for fisheries (i.e., Conservation Measure 26–01) as for instance the restriction on the use of plastic packaging bands (used to secure bait boxes), responsible for marine mammal entanglements, and track of gear loss from longline vessels on a haul-by-haul basis to the CCAMLR Secretariat. A recent shared agreement on data collection and marine debris retrieval has been established among several stakeholders, including CCAMLR, the International Association of Antarctica Tour Operators (IAATO), SCAR, the Global Partnership on Marine Litter (GPML), and Oceanites (Antarctic Treaty Secretariat, 2019; CCAMLR Secretariat, 2019; COMNAP; Phillips and Waluda, 2020; Waluda et al., 2020). The Environmental Protection Group of the COMNAP has identified four key recommendations for National Antarctic programs (listed at: COMNAP 2022): promoting education, research, clean-up activities and knowledge sharing to tackle plastic pollution in Antarctica.

Regarding the removal of microplastics, different physical, chemical, and biological methods have been proposed. Their mode of action, efficiency of removal, advantages and disadvantages have been reviewed by Bhatt et al. (2021) and Hasan Anik et al. (2021). Mitigation actions for the prevention of release of microplastic in the Antarctic marine environment were presented in 2019 at the XLII Antarctic Treaty consultative meeting. Recommendations included a ban on products containing microbeads and the use of effective filtration technologies to reduce the amount of microplastics being released from sewage treatment plants and from vessels within the common Antarctic Treaty area. These measures promoted by the United Nations Ocean Decade initiative (United Nations Environment Programme, 2021) are the result of a combined effort of the major Antarctic institutions, the researchers involved in the SCAR Plastic-AG and other stakeholders and they represent the first step towards an ambitious target for the Southern Ocean to become “a clean ocean, where sources of pollution are identified, reduced or removed”. Like the Association of Arctic Expedition Cruise Operators (AECO) in the Arctic, the primary mission of the International Association of Antarctica Tour Operators (IAATO) is to conduct environmentally responsible, private-sector travel to Antarctica, educating visitors and raising awareness about environmental protection and adherence to Antarctic Treaty regulations and conventions (IAATO, 2020).

The recent establishment of the marine protected area (MPA) in the Ross Sea region in 2017, the second MPA created in Antarctica, is an example of a large-scale conservation measure aimed to protect Antarctic biodiversity and large-scale ecosystem processes from environmental and anthropogenic threats (CCAMLR, 2016), including plastic pollution.

7. Knowledge gaps and final remarks

7.1. Gaps in the knowledge of pathways, distribution, and transport of plastics in Antarctica

Although the ubiquity of plastic pollution is well recognized, major knowledge gaps regarding the pathways, distribution, and transport of plastics in Antarctica still exist. Comparison of studies on microplastic abundances in the Southern Ocean is hindered by the lack of standardized and shared methods for sampling, isolation and identification of micro- and nanoplastics (SCAR Plastic-AG, 2019). This analytical issue is crucial for remote polar regions where low plastic levels are expected compared to other latitudes, since the use of non-effective methods may increase sample cross-contamination and lead to overestimation of microplastic quantification. Standardization of microplastic analysis is therefore required to allow the overall assessment of microplastic pollution in surface waters and sediments of the Southern Ocean and particularly in the most remote territories where a lower abundance of plastic is expected (e.g., Eastern Antarctica).

7.2. Gaps in the knowledge of the effects of plastic pollution on the Antarctic biota

The effects of plastic pollution on Antarctic biota as well as on the physiological responses in key polar species are far from being fully known. Antarctic organisms, from plankton to higher trophic levels, including fish, sea birds and mammals can ingest plastic debris carrying adsorbed contaminants which may undergo bioaccumulation and/or biomagnification within the food chain. Future advances in this research field should include the following aspects (i) adhesion properties of chemical contaminants (e.g., PCBs): associated with plastic pollution; (ii) ecotoxicological effects on the biota, including biotransportation, bioaccumulation and biomagnification; (iii) physico-chemical characterization and biodegradation pathways (via chemical or heat stress) of contaminants and their ecotoxicological impacts.

Plastic waste, together with other contaminants reaching Antarctica, could represent a further threat to such a delicate ecosystem and its biodiversity. Besides large plastic items, which are now regarded as contaminants, the potential uptake and effects of micro- and nanoplastics together with the related adsorbed/leached chemicals (e.g., organic pollutants and plastic additives respectively) at both the cellular and whole organism levels need to be further investigated. Key bioindicator species representative of Antarctic environments should be the focus of future studies to unravel impacts at ecosystem level and their services.

7.3. Suggested measures to mitigate and/or reduce plastic pollution in Antarctica

Detailed identification of the sources of plastic pollution is needed to implement the monitoring and mitigation strategies to tackle plastic pollution in Antarctica and the Southern Ocean (Eriksen et al., 2020). The patterns of distribution of plastic debris in different environmental matrices and habitats must be considered, including surface and deep waters, sediments, and biological communities. To fully understand the direct and indirect consequences of plastics on this remote polar region, extensive monitoring and international cooperation is required.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Author contributions

Gabriella Caruso: Conceptualization; Data curation; Formal analysis; Supervision; Validation; Writing - original draft; Writing - review & editing. Elisa Bergami: Conceptualization; Data curation; Formal analysis; Supervision; Validation; Writing - original draft; Writing - review & editing. Neelu Singh: Writing - original draft; Writing - review & editing. Ilaria Corsi: Conceptualization; Data curation; Formal analysis; Supervision; Validation; Writing - original draft; Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Absher, T.M., Ferreira, S.L., Kern, Y., Ferreira, A.L., Christo, S.W., Ando, R.A., 2019. Incidence and identification of microfibers in ocean waters in Admiralty Bay, Antarctica. Environ. Sci. Pollut. Res. 26, 292–298. https://doi.org/10.1007/s11356-018-3509-6.

Al-Thawadi, S., 2020. Microplastics and nanoplastics in aquatic environments: challenges and threats to aquatic organisms. Arabian J. Sci. Eng. 45, 4419–4440. https://doi.org/10.1007/s13369-020-04402-z.

Almela, P., Gonzalez, S., 2020. Are antarctic specially protected areas safe from plastic pollution? A survey of plastic litter at byers Peninsula, Livingston island, Antarctica. Adv. Polar Sci. 31, 284–290. https://doi.org/10.13679/j.advps.2020.0029.

Amaral-Zettler, L.A., Zettler, E.R., Mincer, T.J., 2020. Ecology of the plastisphere. Nat. Rev. Microbiol. 18, 139–151. https://doi.org/10.1038/s41579-019-0308-0.

Andrady, A.L., 2017. The plastic in microplastics: a review. Mar. Pollut. Bull. 119, 12–22. https://doi.org/10.1016/j.marpolbul.2017.01.082.

Antarctic Treaty Secretariat, 2019. ATCM XLII - CEP XXII Prague, Resolution 5 - Reducing Plastic Pollution in Antarctica and the Southern Ocean.

Aronson, R.B., Thatje, S., Mcclintock, J.B., Hughes, K.A., 2011. Anthropogenic impacts on marine ecosystems in Antarctica. Ann. N. Y. Acad. Sci. 1223, 82–107. https://doi.org/10.1111/j.1749-6632.2010.05926.x.

ASOC, 2017. Marine Debris: a Persistent and Emerging Threat to Antarctic Ecosystems (SC-CAMLR-XXXVI/BG/29).

Atkinson, A., Ward, P., Hunt, B.P.V., Pakhomov, E.A., Hosie, G.W., 2012. An overview of Southern Ocean zooplankton data: abundance, biomass, feeding and functional relationships. CCAMLR Sci 19, 171–218.

Audrézet, F., Zaiko, A., Lear, G., Wood, S.A., Tremblay, L.A., Pochon, X., 2021. Biosecurity implications of drifting marine plastic debris: current knowledge and future research. Mar. Pollut. Bull. 162, 111835. https://doi.org/10.1016/j.marpolbul.2020.111835.

Auman, H.J., Woehler, E.J., Riddle, M.J., Burton, H., 2004. First evidence of ingestion of plastic debris by seabirds at sub-Antarctic Heard Island. Mar. Ornithol. 32, 105–106.

Barnes, D.K.A., 2005. Remote islands reveal rapid rise of Southern Hemisphere sea debris. Sci. World J. 5, 915–921. https://doi.org/10.1100/tsw.2005.120.

Barnes, D.K.A., Walters, A., Gonçalves, L., 2010. Macroplastics at sea around Antarctica. Mar. Environ. Res. 70, 250–252. https://doi.org/10.1016/j.marenvres.2010.05.006.

Bergami, E., Krupinski Emerenciano, A., González-Aravena, M., Cárdenas, C.A., Hernández, P., Silva, J.R.M.C., Corsi, I., 2019. Polystyrene nanoparticles affect the innate immune system of the Antarctic sea urchin *Sterechinus neumayeri*. Polar Biol 42, 743–757. https://doi.org/10.1007/s00300-019-02468-6.

Bergami, E., Rota, E., Caruso, T., Birarda, G., Vaccari, L., Corsi, I., 2020a. Plastics everywhere: first evidence of polystyrene fragments inside the common Antarctic collembolan *Cryptopygus antarcticus*. Biol. Lett. 16, 20200093. https://doi.org/10.1098/rsbl.2020.0093.

Bergami, E., Manno, C., Cappello, S., Vannuccini, M.L., Corsi, I., 2020b. Nanoplastics affect moulting and faecal pellet sinking in Antarctic krill (*Euphausia superba*) juveniles. Environ. Int. 143, 105999. https://doi.org/10.1016/j.envint.2020.105999.

Bergmann, M., Mützel, S., Primpke, S., Tekman, M.B., Trachsel, J., Gerdts, G., 2019. White and wonderful? Microplastics prevail in snow from the alps to the arctic. Sci. Adv. 5, eaax1157. https://doi.org/10.1126/sciadv.aax1157.

Bessa, F., Ratcliffe, N., Otero, V., Sobral, P., Marques, J.C., Waluda, C.M., Trathan, P.N., Xavier, J.C., 2019. Microplastics in gentoo penguins from the Antarctic region. Sci. Rep. 9, 14191. https://doi.org/10.1038/s41598-019-50621-2.

Bhatt, P., Pathak, V.M., Bagheri, A.R., Bilal, M., 2021. Microplastic contaminants in the aqueous environment, fate, toxicity consequences, and remediation strategies. Environ. Res. 200, 111762. https://doi.org/10.1016/j.envres.2021.111762.

Bravo Rebolledo, E.L., van Franeker, J.A., 2015. Impact of Marine Debris on Antarctic Fur Seals *Arctocephalus gazella* at Cape Shirreff: Diet Dependent Ingestion and Entanglement Preliminary Results. IMARES Wageningen UR.

Cannon, S.M.E., Lavers, J.L., Figueiredo, B., 2016. Plastic ingestion by fish in the Southern Hemisphere: a baseline study and review of methods. Mar. Pollut. Bull. 107, 286–291. https://doi.org/10.1016/j.marpolbul.2016.03.057.

Cappello, S., Caruso, G., Bergami, E., Macrì, A., Venuti, V., Majolino, D., Corsi, I., 2021. New insights into the structure and function of the prokaryotic communities colonizing plastic debris collected in King George Island (Antarctica): preliminary observations from two plastic fragments. J. Hazard Mater. 414, 125586. https://doi.org/10.1016/j.jhazmat.2021.125586.

Carpenter, E.J., 1972. Polystyrene spherules in coastal waters. Science 178, 750–753. https://doi.org/10.1126/science.178.4062.750.

Caruso, G., 2020. Microbial colonization in marine environments: overview of current knowledge and emerging research topics. J. Mar. Sci. Eng. 8, 78. https://doi.org/10.3390/jmse8020078.

Caruso, G., 2019. Microplastics as vectors of contaminants. Mar. Pollut. Bull. 146, 921–924. https://doi.org/10.1016/j.marpolbul.2019.07.052.

Caruso, G., 2015. Microplastics in marine environments: possible interactions with the microbial assemblage. J. Pollut. Eff. Cont. 3, 2. https://doi.org/10.4172/2375-4397.1000e111.

CCAMLR, 2016. Conservation Measure 91-05 (2016): Ross Sea Region Marine Protected Area, CCAMLR Conservation Measures. Hobart, Australia.

CCAMLR Secretariat, 2019. SC-CAMLR-38/09 Outcomes from a Review of the CCAMLR Marine Debris Program. Hobart, Australia.

Chen, D., Hale, R.C., La Guardia, M.J., Luellen, D., Kim, S., Geisz, H.N., 2015. Hexabromocyclododecane flame retardant in Antarctica: research stations as sources. Environ. Pollut. 206, 611–618. https://doi.org/10.1016/j.envpol.2015.08.024.

Chen, X., Xiong, X., Jiang, X., Shi, H., Wu, C., 2019. Sinking of floating plastic debris caused by biofilm development in a freshwater lake. Chemosphere 222, 856–864. https://doi.org/10.1016/j.chemosphere.2019.02.015.

Cincinelli, A., Scopetani, C., Chelazzi, D., Lombardini, E., Martellini, T., Katsoyiannis, A., Fossi, M.C., Corsolini, S., 2017. Microplastic in the surface waters of the Ross Sea (Antarctica): occurrence, distribution and characterization by FTIR. Chemosphere 175, 391–400. https://doi.org/10.1016/j.chemosphere.2017.02.024.

Clarke, A., Barnes, D.K.A., Hodgson, D.A., 2005. How isolated is Antarctica? Trends Ecol. Evol. 20, 1–3. https://doi.org/10.1016/j.tree.2004.10.004.

COMNAP, Environmental Protection Expert Group, 2022, 17/01/2022. URL. https://www.comnap.aq/environmental-protection.

Convey, P., Barnes, D.K.A., Morton, A., 2002. Debris accumulation on oceanic island shores of the Scotia Arc, Antarctica. Polar Biol 25, 612–617. https://doi.org/10.1007/s00300-002-0391-x.

Corsi, I., Bergami, E., Caruso, G., 2021a. Special issue plastics in polar regions. Environ. Int. 149, 106203. https://doi.org/10.1016/j.envint.2020.106203.

Corsi, I., Bellingeri, A., Eliso, M.C., Grassi, G., Liberatori, G., Murano, C., Sturba, L., Vannuccini, M.L., Bergami, E., 2021b. Eco-interactions of engineered nanomaterials in the marine environment: towards an eco-design framework. Nanomaterials 11, 1–32. https://doi.org/10.3390/nano11081903.

Corsi, I., Bergami, E., Grassi, G., 2020. Behaviour and bio-interactions of anthropogenic particles in marine environment for a more realistic ecological risk assessment. Front. Environ. Sci. 8, 1–21. https://doi.org/10.3389/fenvs.2020.00060.

Cózar, A., Martí, E., Duarte, C.M., García-de-lomas, J., van Sebille, E., Ballatore, T.J., Eguíluz, V.M., González-Gordillo, J.I., Pedrotti, M.L., 2017. The Arctic Ocean as a dead end for floating plastics in the North Atlantic branch of the thermohaline circulation. Sci. Adv. 3, e1600582. https://doi.org/10.1126/sciadv.1600582.

Cunningham, E.M., Ehlers, S.M., Dick, J.T.A., Sigwart, J.D., Linse, K., Dick, J.J., Kiriakoulakis, K., 2020. High abundances of microplastic pollution in deep-sea sediments: evidence from Antarctica and the Southern Ocean. Environ. Sci. Technol. 54, 13661–13671. https://doi.org/10.1021/acs.est.0c03441.

Dawson, A., Kawaguchi, S., King, C.K., Townsend, K.A., King, R., Huston, W.M., Bengtson Nash, S.M., 2018a. Turning microplastics into nanoplastics through digestive fragmentation by Antarctic krill. Nat. Commun. 9, 1001. https://doi.org/10.1038/s41467-018-03465-9.

Dawson, A., Huston, W., Kawaguchi, S., King, C., Cropp, R., Wild, S., Eisenmann, P., Townsend, K., Bengtson Nash, S.M., 2018b. Uptake and depuration kinetics influence microplastic bioaccumulation and toxicity in antarctic krill (*Euphausia superba*). Environ. Sci. Technol. 52, 3195–3201. https://doi.org/10.1021/acs.est.7b05759.

De-la-Torre, G.E., Dioses-Salinas, D.C., Pizarro-Ortega, C.I., Saldaña-Serrano, M., 2020. Global distribution of two polystyrene-derived contaminants in the marine environment: a review. Mar. Pollut. Bull. 161, 111729. https://doi.org/10.1016/j.marpolbul.2020.111729.

do Sul, J.A.I., Barnes, D.K.A., Costa, M.F., Convey, P., Costa, E.S., Campos, L., 2011. Plastics in the Antarctic environment: are we looking only at the tip of the iceberg? Oecologia Aust 15, 150–170. https://doi.org/10.4257/oeco.2011.1501.11.

Eerkes-Medrano, D., Thompson, R.C., Aldridge, D.C., 2015. Microplastics in freshwater systems: a review of the emerging ,threats, identification of knowledge gaps and prioritisation of research needs. Water Res 75, 63–82. https://doi.org/10.1016/j.watres.2015.02.012.

Eriksen, M., Borgogno, F., Villarrubia-Gómez, P., Anderson, E., Box, C., Trenholm, N., 2020. Mitigation strategies to reverse the rising trend of plastics in Polar Regions. Environ. Int. 139, 105704. https://doi.org/10.1016/j.envint.2020.105704.

Eriksson, C., Burton, H., 2003. Origins and biological accumulation of small plastic particles in Fur seals from Macquarie Island. Ambio 32, 380–384. https://doi.org/10.1579/0044-7447-32.6.380.

Eriksson, C., Burton, J., Fitch, S., Schulz, M., van den Hoff, J., 2013. Daily accumulation rates of marine debris on sub-Antarctic island beaches. Mar. Pollut. Bull. 66, 199–208. https://doi.org/10.1016/j.marpolbul.2012.08.026.

Fang, C., Zheng, R., Zhang, Y., Hong, F., Mu, J., Chen, M., Song, P., Lin, L., Lin, H., Le, F., Bo, J., 2018. Microplastic contamination in benthic organisms from the Arctic and sub-Arctic regions. Chemosphere 209, 298–306. https://doi.org/10.1016/j.chemosphere.2018.06.101.

Fragão, J., Bessa, F., Otero, V., Barbosa, A., Sobral, P., Waluda, C.M., Guímaro, H.R., Xavier, J.C., 2021. Microplastics and other anthropogenic particles in Antarctica: using penguins as biological samplers. Sci. Total Environ. 788, 147698. https://doi.org/10.1016/j.scitotenv.2021.147698.

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., 2018. Antarctica's ecological isolation will be broken by storm-driven dispersal and warming. Nat. Clim. Change 8, 704–708. https://doi.org/10.1038/s41558-018-0209-7.

Gao, X., Huang, C., Rao, K., Xu, Y., Huang, Q., Wang, F., Ma, M., Wang, Z., 2018. Occurrences, sources, and transport of hydrophobic organic contaminants in the waters of Fildes Peninsula, Antarctica. Environ. Pollut. 241, 950–958. https://doi.org/10.1016/j.envpol.2018.06.025.

Garcia-Garin, O., García-Cuevas, I., Drago, M., Rita, D., Parga, M., Gazo, M., Cardona, L., 2020. No evidence of microplastics in Antarctic Fur seal scats from a hotspot of human activity in Western Antarctica. Sci. Total Environ. 737, 140210. https://doi.org/10.1016/j.scitotenv.2020.140210.

Geilfus, N.X., Munson, K.M., Sousa, J., Germanov, Y., Bhugaloo, S., Babb, D., Wang, F., 2019. Distribution and impacts of microplastic incorporation within sea ice. Mar. Pollut. Bull. 145, 463–473. https://doi.org/10.1016/j.marpolbul.2019.06.029.

Gheorghe, S., Lucaciu, I., Paun, I., Stoica, C., Stanescu, E., 2013. Ecotoxicological behavior of some cationic and amphoteric surfactants (biodegradation, toxicity and risk assessment). In: Chamy, R., Rosenkranz, F. (Eds.), Biodegradation - Life of Science. Intech Open, United Kingdom. https://doi.org/10.5772/56199, 43968.

Gigault, J., Halle, A. ter, Baudrimont, M., Pascal, P.Y., Gauffre, F., Phi, T.L., El Hadri, H., Grassl, B., Reynaud, S., 2018. Current opinion: what is a nanoplastic? Environ. Pollut. 235, 1030–1034. https://doi.org/10.1016/j.envpol.2018.01.024.

Golubev, S., 2020. Macroplastic in seabirds at Mirny, Antarctica. Birds (Lond.) 1, 13–18. https://doi.org/10.3390/birds1010003.

González-Pleiter, M., Edo, C., Velázquez, D., Casero-Chamorro, M.C., Leganés, F., Quesada, A., Fernández-Piñas, F., Rosal, R., 2020. First detection of microplastics in the freshwater of an antarctic specially protected area. Mar. Pollut. Bull. 161, 111811. https://doi.org/10.1016/j.marpolbul.2020.111811.

González-Pleiter, M., Lacerot, G., Edo, C., Pablo Lozoya, J., Leganés, F., Fernández-Piñas, F., Rosal, R., Teixeira-de-Mello, F., 2021. A pilot study about microplastics and mesoplastics in an Antarctic glacier. Cryosphere 15, 2531–2539. https://doi.org/10.5194/tc-15-2531-2021.

Gouin, T., Roche, N., Lohmann, R., Hodges, G.A., 2011. Thermodynamic approach for assessing the environmental exposure of chemicals absorbed to microplastic. Environ. Sci. Technol. 45, 1466–1472. https://doi.org/10.1021/es1032025.

Graham, E.R., Thompson, J.T., 2009. Deposit-and suspension-feeding sea cucumbers (Echinodermata) ingest plastic fragments. J. Exp. Mar. Biol. Ecol. 368, 22–29. https://doi.org/10.1016/j.jembe.2008.09.007.

Grassi, G., Gabellieri, E., Cioni, P., Paccagnini, E., Faleri, C., Lupetti, P., Corsi, I., Morelli, E., 2020. Interplay between extracellular polymeric substances (EPS) from a marine diatom and model nanoplastic through eco-corona formation. Sci. Total Environ. 725, 138457. https://doi.org/10.1016/j.scitotenv.2020.138457.

Gregory, M.R., 2009. Environmental implications of plastic debris in marine settings-entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. Philos. Trans. R. Soc. B Biol. Sci. 364, 2013–2025. https://doi.org/10.1098/rstb.2008.0265.

Gregory, M.R., Kirk, R.M., Mabin, M.C.G., 1984. Pelagic tar, oil, plastics and other litter in surface waters of the New Zealand sector of the Southern Ocean and on Ross Dependency shores. N. Z. Antarct. Rec. 6, 12–28.

Grover-Johnson, O., 2018. Findings from the continuous plankton recorder in the Ross Sea and the East antarctic regions (supervised project report ANTA604). https://ir.canterbury.ac.nz/bitstream/handle/10092/15837/Microplastics%20in%20the%20Southern%20Ocean.pdf?sequence=1&isAllowed=y.

Harper, P.C., Fowler, J.A., 1987. Plastic pellets in New Zealand storm-killed prions (*Pachyptila* spp.) 1958-1977. Notornis 34, 65–70.

Harrison, J.P., Sapp, M., Osborn, M.A., 2011. Interactions between microorganisms and marine microplastics: a call for research. Mar. Technol. Soc. J. 45, 12–20. https://doi.org/10.4031/MTSJ.45.2.2.

Hartmann, N.B., Hüffer, T., Thompson, R.C., Hassellöv, M., Verschoor, A., Daugaard, A.E., Rist, S., Karlsson, T., Brennholt, N., Cole, M., Herrling, M.P., Hess, M.C., Ivleva, N.P., Lusher, A.L., Wagner, M., 2019. Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris. Environ. Sci. Technol. 53 (3), 1039–1047. https://doi.org/10.1021/acs.est.8b05297.

Hasan Anik, A., Hossain, S., Alam, M., Binte Sultan, M., Hasnine, M.D.T., Rahman, M.M., 2021. Microplastics pollution: a comprehensive review on the sources, fates, effects, and potential remediation. Environ. Nanotechnol. Monit. Manag. 16, 100530. https://doi.org/10.1016/j.enmm.2021.100530.

Hernandez, L.M., Xu, E.G., Larsson, H.C.E., Tahara, R., Maisuria, V.B., Tufenkji, N., 2019. Plastic teabags release billions of microparticles and nanoparticles into tea. Environ. Sci. Technol. 53, 12300–12310. https://doi.org/10.1021/acs.est.9b02540.

Hoffmann, L., Eggers, S.L., Allhusen, E., Katlein, C., Peeken, I., 2020. Interactions between the ice algae Fragillariopsis cylindrus and microplastics in sea ice. Environ. Int. 139, 105697. https://doi.org/10.1016/j.envint.2020.105697.

Hughes, K.A., Constable, A., Frenot, Y., López-Martínez, J., McIvor, E., Njåstad, B., Terauds, A., Liggett, D., Roldan, G., Wilmotte, A., Xavier, J.C., 2018. Antarctic environmental protection: strengthening the links between science and governance. Environ. Sci. Pol. 83, 86–95. https://doi.org/10.1016/j.envsci.2018.02.006.

IAATO, 2020. Tourism statistics download. https://iaato.org/tourism-statistics-327mnsyd.

Isobe, A., Uchiyama-matsumoto, K., Uchida, K., Tokai, T., 2017. Microplastics in the Southern Ocean. Mar. Pollut. Bull. 114, 623–626. https://doi.org/10.1016/j.marpolbul.2016.09.037.

Jones-Williams, K., Galloway, T., Cole, M., Stowasser, G., Waluda, C., Manno, C., 2020. Close encounters - microplastic availability to pelagic amphipods in Sub-Antarctic and Antarctic surface waters. Environ. Int. 140, 105792. https://doi.org/10.1016/j.envint.2020.105792.

Katsumiti, A., Losada-Carrillo, M.P., Barros, M., Cajaraville, M.P., 2021. Polystyrene nanoplastics and microplastics can act as Trojan horse carriers of benzo(a)pyrene to mussel hemocytes in vitro. Sci. Rep. 11, 22396. https://doi.org/10.1038/s41598-021-01938-4.

Kelly, A., Lannuzel, D., Rodemann, T., Meiners, K.M., Auman, H.J., 2020. Microplastic contamination in east Antarctic sea ice. Mar. Pollut. Bull. 154, 111130. https://doi.org/10.1016/j.marpolbul.2020.111130.

Koelmans, A.A., Besseling, E., Foekema, E.M., 2014. Leaching of plastic additives to marine organisms. Environ. Pollut. 187, 49–54. https://doi.org/10.1016/j.envpol.2013.12.013.

Kuklinski, P., Wicikowski, L., Koper, M., Grala, T., Leniec-Koper, H., Barasiński, M., Talar, M., Kamiński, I., Kibart, R., Małecki, W., 2019. Offshore surface waters of Antarctica are free of microplastics, as revealed by a circum-Antarctic study. Mar. Pollut. Bull. 149, 110573. https://doi.org/10.1016/j.marpolbul.2019.110573.

Lacerda, A.L.d.F., Proietti, M.C., Secchi, E.R., Taylor, J.D., 2020. Diverse groups of fungi are associated with plastics in the surface waters of the Western South Atlantic and the Antarctic Peninsula. Mol. Ecol. 29, 1903–1918. https://doi.org/10.1111/mec.15444.

Lacerda, A.L.d.F., Rodrigues, L., dos, S., van Sebille, E., Rodrigues, F.L., Ribeiro, L., Secchi, E.R., Kessler, F., Proietti, M.C., 2019. Plastics in sea surface waters around the Antarctic Peninsula. Sci. Rep. 9, 3977. https://doi.org/10.1038/s41598-019-40311-4.

Laganà, P., Caruso, G., Corsi, I., Bergami, E., Venuti, V., Majolino, D., La Ferla, R., Azzaro, M., Cappello, S., 2019. Do plastics serve as a possible vector for the spread of antibiotic resistance? First insights from bacteria associated to a polystyrene piece from King George Island (Antarctica). Int. J. Hyg Environ. Health 222, 89–100. https://doi.org/10.1016/j.ijheh.2018.08.009.

Lambert, S., Wagner, M., 2016. Formation of microscopic particles during the degradation of different polymers. Chemosphere 161, 510–517. https://doi.org/10.1016/j.chemosphere.2016.07.042.

Lau, W.W.Y., Shiran, Y., Bailey, R.M., Cook, E., Stuchtey, M.R., Koskella, J., Velis, C.A., Godfrey, L., Boucher, J., Murphy, M.B., et al., 2020. Evaluating scenarios toward zero plastic pollution. Science 369, 1455–1461. https://doi.org/10.1126/science.aba9475.

Lee, Y.M., Cho, K.H., Hwang, K., Kim, E.H., Kim, M., Hong, S.G., Lee, H.K., 2016. Succession of bacterial community structure during the early stage of biofilm development in the Antarctic marine environment. Korean J. Microbiol. 52, 49–58. https://doi.org/10.7845/kjm.2016.6005.

Le Guen, C., Suaria, G., Sherley, R.B., Ryan, P.G., Aliani, S., Boehme, L., Brierley, A.S., 2020. Microplastic study reveals the presence of natural and synthetic fibres in the diet of King penguins (Aptenodytes patagonicus) foraging from South Georgia. Environ. Int. 134, 105303. https://doi.org/10.1016/j.envint.2019.105303.

Leistenschneider, C., Burkhardt-Holm, P., Mani, T., Primpke, S., Taubner, H., Gerdts, G., 2021. Microplastics in the weddell sea (Antarctica): a forensic approach for discrimination between environmental and vessel-induced microplastics. Environ. Sci. Technol. 55, 15900–15911. https://doi.org/10.1021/acs.est.1c05207.

Lespes, G., Faucher, S., Slaveykova, V.I., 2020. Natural nanoparticles, anthropogenic nanoparticles, where is the frontier? Front. Environ. Sci. 8, 1–5. https://doi.org/10.3389/fenvs.2020.00071.

Lo Giudice, A., Caruso, G., Rizzo, C., Papale, M., Azzaro, M., 2019. Bacterial communities versus anthropogenic disturbances in the Antarctic coastal marine environment. Environ. Sustain. Environ. Sustain. 2, 297–310. https://doi.org/10.1007/s42398-019-00064-2.

Manno, C., Peck, L.V., Corsi, I., Bergami, E., 2021. Under pressure: nanoplastics as a further stressor for sub-Antarctic pteropods already tackling ocean acidification. Mar. Pollut. Bull. 174, 113176. https://doi.org/10.1016/j.marpolbul.2021.113176.

Marsh, R., van Sebille, E., 2021. From the Southern Ocean to Antarctica and its changing ice shelves. In: Marsh, R., van Sebille, E. (Eds.), Ocean Currents. Elsevier, Amsterdam (The Netherlands), pp. 303–373. https://doi.org/10.1016/B978-0-12-816059-6.00006-1 (Chapter 8).

Materić, D., Kjær, H.A., Vallelonga, P., Tison, J.L., Röckmann, T., Holzinger, R., 2022. Nanoplastics measurements in Northern and Southern polar ice. Environ. Res. 208, 112741. https://doi.org/10.1016/j.envres.2022.112741.

Mishra, A.K., Singh, J., Mishra, P.P., 2021. Microplastics in polar regions: an early warning to the world's pristine ecosystem. Sci. Total Environ. 784, 147149. https://doi.org/10.1016/j.scitotenv.2021.147149.

Mountford, A.S., Morales Maqueda, M.A., 2021. Modeling the accumulation and transport of microplastics by sea ice. J. Geophys. Res. Ocean. 126, e2020JC016826. https://doi.org/10.1029/2020JC016826.

Munari, C., Infantini, V., Scoponi, M., Rastelli, E., Corinaldesi, C., Mistri, M., 2017. Microplastics in the sediments of Terra Nova Bay (Ross Sea, Antarctica). Mar. Pollut. Bull. 122, 161–165. https://doi.org/10.1016/j.marpolbul.2017.06.039.

Nelms, S.E., Galloway, T.S., Godley, B.J., Jarvis, D.S., Lindeque, P.K., 2018. Investigating microplastic trophic transfer in marine top predators. Environ. Pollut. 238, 999–1007. https://doi.org/10.1016/j.envpol.2018.02.016.

Nguyen, N.H.A., El-Temsah, Y.S., Cambier, S., Calusinska, M., Hrabak, P., Pouzar, M., Boruvka, M., Kejzlar, P., Bakalova, T., Gutleb, A.C., Sevcu, A., 2021. Attached and planktonic bacterial communities on bio-based plastic granules and micro-debris in seawater and freshwater. Sci. Total Environ. 785, 147413. https://doi.org/10.1016/j.scitotenv.2021.147413.

Oberbeckmann, S., Kreikemeyer, B., Labrenz, M., 2018. Environmental factors support the formation of specific bacterial assemblages on microplastics. Front. Microbiol. 8, 2709. https://doi.org/10.3389/fmicb.2017.02709.

Oberbeckmann, S., Labrenz, M., 2020. Marine microbial assemblages on microplastics: diversity, adaptation, and role in degradation. Ann. Rev. Mar. Sci 12, 209–232. https://doi.org/10.1146/annurev-marine-010419-010633.

Oberbeckmann, S., Osborn, A.M., Duhaime, M.B., 2016. Microbes on a bottle: substrate, season and geography influence community composition of microbes colonizing marine plastic debris. PLoS One 11, e0159289. https://doi.org/10.1371/journal.pone.0159289.

Onink, V., Wichmann, D., Delandmeter, P., van Sebille, E., 2019. The role of ekman currents, geostrophy, and Stokes drift in the accumulation of floating microplastic. J. Geophys. Res. Ocean. 124, 1474–1490. https://doi.org/10.1029/2018JC014547.

Overeem, I., 2003. sea ice: an introduction to its physics, chemistry, biology and geology. Arctic Antarct. Alpine Res. 35, 541. https://doi.org/10.1657/1523-0430(2003)035[0542:BR]2.0.CO;2.

Padeiro, A., Amaro, E., Dos Santos, M.M.C., Araújo, M.F., Gomes, S.S., Leppe, M., Verkulich, S., Hughes, K.A., Peter, H.U., Canário, J., 2016. Trace element contamination and availability in the Fildes Peninsula, king George island, Antarctica. Environ. Sci. Process. Impacts 18, 648–657. https://doi.org/10.1039/c6em00052e.

Peeken, I., Primpke, S., Beyer, B., Gütermann, J., Katlein, C., Krumpen, T., Bergmann, M., Hehemann, L., Gerdts, G., 2018. Arctic sea ice is an important temporal sink and means of transport for microplastic. Nat. Commun. 9, 1505. https://doi.org/10.1038/s41467-018-03825-5.

Pertierra, L.R., Hughes, K.A., Vega, G.C., Olalla-Tárraga, M.A., 2017. High resolution spatial mapping of human footprint across Antarctica and its implications for the strategic conservation of avifauna. PLoS One 12, 1–20. https://doi.org/10.1371/journal.pone.0168280.

Phillips, R.A., Waluda, C.M., 2020. Albatrosses and petrels at South Georgia as sentinels of marine debris input from vessels in the southwest Atlantic Ocean. Environ. Int. 136, 105443. https://doi.org/10.1016/j.envint.2019.105443.

Pradel, A., Gautier, M., Bavay, D., Gigault, J., 2021. Micro- and nanoplastic transfer in freezing saltwater: implications for their fate in polar waters. Environ. Sci. Process. Impacts 23, 1759–1770. https://doi.org/10.1039/D1EM00280E.

Puasa, N.A., Zulkharnain, A., Verasoundarapandian, G., Wong, C.Y., Zahri, K.N.M., Merican, F., Shaharuddin, N.A., Gomez-Fuentes, C., Ahmad, S.A., 2021. Effects of diesel, heavy metals and plastics pollution on penguins in Antarctica: a review. Animals 11, 2505. https://doi.org/10.3390/ani11092505.

Reed, S., Clark, M., Thompson, R., Hughes, K.A., 2018. Microplastics in marine sediments near Rothera research station, Antarctica. Mar. Pollut. Bull. 133, 460–463. https://doi.org/10.1016/j.marpolbul.2018.05.068.

Rochman, C.M., Hoh, E., Hentschel, B.T., Kaye, S., 2013. Long-term field measurement of sorption of organic contaminants to five types of plastic pellets: implications for plastic marine debris. Environ. Sci. Technol. 47, 1646–1654. https://doi.org/10.1021/es303700s.

Rowlands, E., Galloway, T., Cole, M., Lewis, C., Peck, V., Thorpe, S., Manno, C., 2021. The effects of combined ocean acidification and nanoplastic exposures on the embryonic development of Antarctic krill. Front. Mar. Sci. 8, 1080. https://doi.org/10.3389/fmars.2021.709763.

Rummel, C.D., Jahnke, A., Gorokhova, E., Kühnel, D., Schmitt-Jansen, M., 2017. Impacts of biofilm formation on the fate and potential effects of microplastic in the aquatic environment. Environ. Sci. Technol. Lett. 4, 258–267. https://doi.org/10.1021/acs.estlett.7b00164.

Ryan, P.G., 1987. The incidence and characteristics of plastic particles ingested by seabirds. Mar. Environ. Res. 23, 175–206. https://doi.org/10.1016/0141-1136(87)90028-6.

Ryan, P.G., de Bruyn, P.J.N., Bester, M.N., 2016. Regional differences in plastic ingestion among Southern Ocean Fur seals and albatrosses. Mar. Pollut. Bull. 104, 207–210. https://doi.org/10.1016/j.marpolbul.2016.01.032.

SCAR Plastic, A.G., 2019. Workshop: Plastic in the Polar Environment: Sources, Impacts and Solutions (28-29 October 2019, Hull, UK), SCAR Plastic-AG Workshop Report.

SCAR Plastic, A.G., 2018. Plastic in polar environments. URL. https://www.scar.org/science/plastic/home/.

Schirinzi, G.F., Llorca, M., Seró, R., Moyano, E., Barceló, D., Abad, E., Farré, M., 2019. Trace analysis of polystyrene microplastics in natural waters. Chemosphere 236, 124321. https://doi.org/10.1016/j.chemosphere.2019.07.052.

Secretariat of the Antarctic Treaty, 2019. Reducing Plastic Pollution in Antarctica and the Southern Ocean: Resolution 5 (2019) - ATCM XLII - CEP XXII, Prague. https://www.ats.aq/devAS/Meetings/Measure/705.

Sfriso, A.A., Tomio, Y., Rosso, B., Gambaro, A., Sfriso, A., Corami, F., Rastelli, E., Corinaldesi, C., Mistri, M., Munari, C., 2020. Microplastic accumulation in benthic invertebrates in Terra Nova Bay (Ross Sea, Antarctica). Environ. Int. 137, 105587. https://doi.org/10.1016/j.envint.2020.105587.

Sharma, S., Chatterjee, S., 2017. Microplastic pollution, a threat to marine ecosystem and human health: a short review. Environ. Sci. Pollut. Res. 24, 21530–21547. https://doi.org/10.1007/s11356-017-9910-8.

Singh, N., Granberg, M., Collard, F., Caruso, G., Lu, Z., Kögel, T., Gabrielsen, G.W., 2021. Microplastics in the realm of Svalbard: current knowledge and future perspectives (MIRES). In: Moreno-Ibáñez, M., Methlie Hagen, J.O., Hübner, C., Lihavainen, H., Zaborska, A. (Eds.), The State of Environmental Science in Svalbard – an Annual Report. Chapter 5. Norway: Svalbard Integrated Arctic Earth Observing System (SIOS), pp. 118–141. https://hdl.handle.net/10.5281/zenodo.4293836.

Stark, J.S., Raymond, T., Deppeler, S.L., Morrison, A.K., 2019. Antarctic seas. In: Sheppard, C. (Ed.), World Seas: an Environmental Evaluation. The Netherlands Elsevier, Amsterdam, pp. 1–43. https://doi.org/10.1016/B978-0-12-805068-2.00023-1.

Suaria, G., Perold, V., Lee, J.R., Lebouard, F., Aliani, S., Ryan, P.G., 2020a. Floating macro- and microplastics around the Southern Ocean: results from the antarctic circumnavigation expedition. Environ. Int. 136, 105494. https://doi.org/10.1016/j.envint.2020.105494.

Suaria, G., Achtypi, A., Perold, V., Lee, J.R., Pierucci, A., Bornman, T.G., Aliani, S., Ryan, P.G., 2020b. Microfibers in oceanic surface waters: a global characterization. Sci. Adv. 6, 23. https://doi.org/10.1126/sciadv.aay8493.

Tekman, M.B., Wekerle, C., Lorenz, C., Primpke, S., Hasemann, C., Gerdts, G., Bergmann, M., 2020. Tying up loose ends of microplastic pollution in the arctic:

distribution from the sea surface through the water column to deep-sea sediments at the HAUSGARTEN observatory. Environ. Sci. Technol. 54, 4079–4090. https://doi.org/10.1021/acs.est.9b06981.

Ter Halle, A., Jeanneau, L., Martignac, M., Jardé, E., Pedrono, B., Brach, L., Gigault, J., 2017. Nanoplastic in the North atlantic subtropical gyre. Environ. Sci. Technol. 51, 13689–13697. https://doi.org/10.1021/acs.est.7b03667.

Tirelli, V., Suaria, G., Lusher, A.L., 2020. Microplastics in polar samples. In: Rocha-Santos, T., Costa, M., Mouneyrac, C. (Eds.), Handbook of Microplastics in the Environment. Springer-Nature, Cham, Switzerland, pp. 1–48. https://doi.org/10.1007/978-3-030-10618-8_4-1.

Tocháček, J., Láska, K., Bálková, R., Krmíček, L., Merna, J., Tupý, M., Kapler, P., Poláček, P., Čížková, K., Buráň, Z., 2019. Polymer weathering in Antarctica. Polym. Test. 77, 105898. https://doi.org/10.1016/j.polymertesting.2019.105898.

Trathan, P.N., Hill, S.L., 2016. The importance of krill predation in the Southern Ocean. In: Siegel, V. (Ed.), Biology and Ecology of Antarctic Krill, Advances in Polar Ecology. Springer, Berlin, Germany, pp. 321–350. https://doi.org/10.1007/978-3-319-29279-3_9.

United Nations Environment Programme, 2021. Southern Ocean united nations decade [WWW document]. URL. https://www.sod.ecade.org/working-groups/.

van Franeker, J.A., Bell, P.J., 1988. Plastic ingestion by petrels breeding in Antarctica. Mar. Pollut. Bull. 19, 672–674. https://doi.org/10.1016/0025-326X(88)90388-8.

van Sebille, E., Aliani, S., Law, K.L., Maximenko, N., Alsina, J.M., Bagaev, A., Bergmann, M., Chapron, B., Chubarenko, I., Cózar, A., et al., 2020. The physical oceanography of the transport of floating marine debris. Environ. Res. Lett. 15, 23003. https://doi.org/10.1088/1748-9326/ab6d7d.

van Sebille, E., Wilcox, C., Lebreton, L., Maximenko, N., Hardesty, B.D., van Franeker, J.A., Eriksen, M., Siegel, D., Galgani, F., Lavender Law, K., 2015. A global inventory of small floating plastic debris. Environ. Res. Lett. 10, 124006. https://doi.org/10.1088/1748-9326/10/12/124006.

Vázquez, O.A., Rahman, M.S., 2021. An ecotoxicological approach to microplastics on terrestrial and aquatic organisms: a systematic review in assessment, monitoring and biological impact. Environ. Toxicol. Pharmacol. 84, 103615. https://doi.org/10.1016/j.etap.2021.103615.

Waller, C.L., Griffiths, H.J., Waluda, C.M., Thorpe, S.E., Loaiza, I., Moreno, B., Pacherres, C.O., Hughes, K.A., 2017. Microplastics in the Antarctic marine system: an emerging area of research. Sci. Total Environ. 598, 220–227. https://doi.org/10.1016/j.scitotenv.2017.03.283.

Waluda, C.M., Staniland, I.J., 2013. Entanglement of Antarctic Fur seals at Bird Island, South Georgia. Mar. Pollut. Bull. 74, 244–252. https://doi.org/10.1016/j.marpolbul.2013.06.050.

Waluda, C.M., Staniland, I.J., Dunn, M.J., Thorpe, S.E., Grilly, E., Whitelaw, M., Hughes, K.A., 2020. Thirty years of marine debris in the Southern Ocean: annual surveys of two island shores in the Scotia Sea. Environ. Int. 136, 105460. https://doi.org/10.1016/j.envint.2020.105460.

Wang, X., Huang, W., Wei, S., Shang, Y., Gu, H., Wu, F., Lan, Z., Hu, M., Shi, H., Wang, Y., 2020. Microplastics impair digestive performance but show little effects on antioxidant activity in mussels under low pH conditions. Environ. Pollut. 258, 113691. https://doi.org/10.1016/j.envpol.2019.113691.

Webster, N.S., Negri, A.P., 2006. Site-specific variation in Antarctic marine biofilms established on artificial surfaces. Environ. Microbiol. 8, 1177–1190. https://doi.org/10.1111/j.1462-2920.2006.01007.x.

Wu, P., Huang, J., Zheng, Y., Yang, Y., Zhang, Y., He, F., Chen, H., Quan, G., Yan, J., Li, T., Gao, B., 2019. Environmental occurrences, fate, and impacts of microplastics. Ecotoxicol. Environ. Saf. 184, 109612. https://doi.org/10.1016/j.ecoenv.2019.109612.

Yu, Y., Mo, W.Y., Luukkonen, T., 2021. Adsorption behaviour and interaction of organic micropollutants with nano and microplastics – a review. Sci. Total Environ. 797, 149140. https://doi.org/10.1016/j.scitotenv.2021.149140.

Zettler, E.R., Mincer, T.J., Amaral-Zettler, L.A., 2013. Life in the “plastisphere”: microbial communities on plastic marine debris. Environ. Sci. Technol. 47, 7137–7146. https://doi.org/10.1021/es401288x.

Zhang, M., Haward, M., McGee, J., 2020. Marine plastic pollution in the polar south: responses from antarctic treaty system. Polar Rec 56, E36. https://doi.org/10.1017/S0032247420000388.