



# The feeding mode effect: influence on particle ingestion by four invertebrates from Sub-Antarctic and Antarctic waters

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## Abstract

Microplastic (MP) pollution is a significant threat to marine environments not only due to its widespread presence but also because of the alarming emergence of ingestion records among benthic organisms. In this study, MP prevalence was assessed in the stomach of the crustaceans *Lithodes santolla* and *Grimothea gregaria* and the gastropods *Nacella deaurata* and *N. concinna*. Particles were analyzed with Fourier-transform infrared (FTIR) spectroscopy. Overall, the analysis revealed that the particles were mainly microfibers composed of cellulose/rayon (60%), followed by MPs (30%), and undetermined not registered in the library (10%). Higher prevalence was found in marine benthic grazers compared to scavengers, with the latter showing low particle prevalence in their stomach contents. Grazers presented a significantly higher abundance per individual but a lower size of ingested particles compared to scavengers. When grouped by trophic levels, tertiary consumers presented significantly lower abundances per individual but larger sizes of the ingested particles. Pearson's correlations showed no significant associations between particle abundance/size and species body size. The results of this study may suggest that continued MP pollution in marine environments and the associated accidental ingestion by marine organisms will alter the energy flow and organic matter availability in benthic food webs, with species that perform certain functional traits more susceptible to being affected.

**Keywords** Microplastic pollution · Benthic organisms · Microfibers · Cellulose · FTIR · Trophic level

## Introduction

Marine ecosystems are currently threatened by various pollutants such as heavy metals, sewage, crude oil spills, nutrient loads, and plastics, all endangering ocean life (Häder et al. 2020). Of particular concern are plastics, which barely degrade despite the harsh conditions of marine environments (Villarrubia-Gómez et al. 2018; Berlino et al. 2021). Primarily derived from human activities such as improper waste disposal

and industrial processes, plastics have emerged as one of the most prevalent and damaging contaminants affecting marine biota (Lusher et al. 2017a; Covernton et al. 2019; Krüger et al. 2020; Xue et al. 2020; Bringer et al. 2021; Lebreton et al. 2022). Microplastics (MPs) are of particular concern due to their small size, ranging from less than 5 mm to 1 µm, as defined by Crawford and Quinn (2017). Mostly originating from the degradation of larger plastic items, their durability and the challenges associated with their removal make them one of the most ubiquitous and, therefore, troubling forms of marine pollution (Villarrubia-Gómez et al. 2018; Picó and Barceló 2019). Plastic particles can enter food webs through accidental ingestion either by both pelagic and benthic organisms (Cole et al. 2011; Besseling et al. 2013; Hall et al. 2015; Courteney-Jones et al. 2017; Mizraji et al. 2017; Scherer et al. 2017; Setälä et al. 2016; Pinheiro et al. 2020; Urbina et al. 2023) or by accidentally attaching to external organs, such as gills, during respiration (Watts et al. 2014; Gray and Weinstein 2017; Leads et al. 2019). Growing research on the impacts of plastics across various species and habitats

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## Highlights

- Sub-Antarctic benthic species predominantly ingested blue microfibers.
- Cellulose and rayon were the most common particle types found in grazers and scavengers.
- MPs found in remote areas highlight the role of ocean circulation on their transport.
- Feeding mode determines susceptibility to particle intake.

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highlights the particular vulnerability of benthic organisms (Lusher et al. 2017a; Cera et al. 2020; Berlino et al. 2021; Darabi et al. 2021). The seabed, and by extension benthic habitats, function as significant reservoirs for MPs, where both biological and physical processes drive accumulation and concentration (Jorquera et al. 2022). Specific substrates such as sediments, coarse organic matter, and surfaces like stones can foster microbial film growth, which facilitates the attachment of MPs. While stones may not inherently retain particles due to their coarse nature, the biofilms that develop on their surfaces can enhance the adherence of MPs, thereby contributing to the pollutant load in benthic areas (Haegerbaeumer et al. 2019; Kalčíková and Bundschuh 2022).

Although MP studies often focus on regions with moderate to high anthropogenic pressure, it is important to note that remote and ecologically vulnerable areas such as polar and subpolar habitats are also at risk due to the endemic and sensitive species they harbor (Horton and Barnes 2020; Tecklin et al. 2024). In the Chilean fjords and channels, for instance, which are generally considered pristine (Tecklin et al. 2024), much of the floating marine debris comprises plastics from local sources, such as shellfish and salmon aquaculture (Hinojosa and Thiel 2009), as well as distant sources transported by ocean currents (Jorquera et al. 2022). MPs have also been detected in remote Chilean fjord areas, far from urban centers, likely due to local currents and nearby salmon farming (Castillo et al. 2020; Jorquera et al. 2022). The Antarctic Peninsula, another remote hotspot of benthic biodiversity (Grange and Smith 2013), faces risks from plastic pollution due to tourism, fishing, and inadequate wastewater treatment on Antarctic stations, where human presence is constant (Jones-Williams et al. 2020). These findings underscore an urgent need for comprehensive action to protect these fragile ecosystems.

The field and laboratory assessments of MP pollution have unveiled intricate interactions between MPs and pelagic and benthic organisms, considering several functional traits. These traits, which refer to specific characteristics or behaviors that influence an organism's performance or survival, are important as they shed light on the complex nature of the problem. Among these traits, feeding mode, habitat, and body size have been the most extensively studied (Setälä et al. 2016; Scherer et al. 2017; Piarulli et al. 2020; Xu et al. 2020; Bertoli et al. 2022).

A comprehensive literature review has revealed that functional traits related to performance, such as somatic growth, reproduction, and metabolism, are more severely affected than those linked to behavior and feeding activity (Berlino et al. 2021). However, the effects are species-specific and strongly tied to the feeding mode of benthic biota, particularly bacterivores, filter feeders, and shredders (Berlino et al. 2021). Feeding mode appears to influence MP occurrence in benthic organisms more than body size

(Bour et al. 2018; Fang et al. 2021). This highlights the importance of anatomical characteristics, such as the buccal cavity and digestive tract, in determining how different species encounter and process MPs in their environment. These anatomical traits, observed in various benthic taxa like bivalves, crustaceans, and nematodes (Fueser et al. 2019; Ward et al. 2019; Carreras-Colom et al. 2022; Pantó et al. 2024), complement the understanding of MP ingestion mechanisms and may also influence the size of ingested MPs, which often scales with an organism's body mass (Jâms et al. 2020). Additionally, mobility and spatial occurrence likely play a role in MP uptake, as sessile species, such as barnacles and bivalves, may experience greater exposure to coastal pollutants like MPs due to their proximity to pollutant sources and limited ability to avoid contaminated areas like intertidal environments (Thushari et al. 2017).

Building on these findings, feeding mode and body size, as previously discussed, remain particularly relevant for interpreting an organism's likelihood of encountering and processing MPs. Among these traits, feeding mode is especially crucial in determining susceptibility to MP ingestion, with filter-feeding organisms, including benthic macrofauna (e.g., bivalves and crustaceans) and pelagic megafauna (e.g., chondrichthyans and large marine mammals), being at the highest risk due to the large volumes of water they filter. For instance, these filter feeders have been found to ingest microbeads, microfibers, and microfragments made of various polymers, such as polystyrene, polypropylene, and polyethylene (Setälä et al. 2016; Germanov et al. 2018; Urbina et al. 2023).

Omnivores may ingest a greater variety of MPs due to their less selective diet, an aspect studied mainly in fish (Mizraji et al. 2017; Garcia et al. 2020). Additionally, deposit feeders and detritivores are susceptible to ingesting MPs due to their sedimentary habitats (Wright et al. 2013). Grazers with strong buccal structures, such as echinoids and crustaceans, can fragment and modify the structure of MPs, making them smaller and more bioavailable in the food web (Watts et al. 2015; Parolini et al. 2020). Conversely, scavengers and visual predators may incidentally ingest MPs when their prey is contaminated, leading to trophic transfer to higher levels (Van Colen et al. 2020; Trestrail et al. 2020). Thus, the trophic level plays a significant role in the distribution of MPs in marine biota. Lower trophic levels occupied by different feeding modes may exhibit higher MP concentrations in stomach contents (Hurt et al. 2020; Sfriso et al. 2020), while biomagnification may be reflected in higher trophic levels as MP concentrations increase in the environment (Gao et al. 2024).

Research on MP ingestion in Sub-Antarctic and Antarctic macroinvertebrates remains limited, with most studies focusing on Chilean and Argentinian Patagonian environments and only a few on Antarctica. Key contributions

include records of MP ingestion in species such as the southern king crab *Lithodes santolla* (Andrade and Ovando 2017) and the intertidal limpet *Nacella magellanica* (Ojeda et al. 2021), assessments of MP prevalence and selective ingestion by mussels and small fishes (Ríos et al. 2020), documentation of ingestion within marine protected areas (Cossi et al. 2021), and a comprehensive analysis of MP contamination in Terra Nova Bay, which included polymer characterization across various feeding strategies in benthic species (Sfriso et al. 2020). Despite these valuable insights, a comprehensive understanding of MP ingestion in these regions remains elusive, underscoring the need for further research.

This study delved into the potential MP ingestion by two scavenger crustaceans, *Lithodes santolla* and *Grimothea gregaria*, and two grazing gastropods, *Nacella concinna* and *Nacella deaurata*, all of which are not only abundant but also ecologically pivotal in Sub-Antarctic and Antarctic ecosystems. These species play critical roles in their respective ecosystems: *L. santolla*, a highly mobile species and a generalist, has a diet that includes crustaceans, bivalves, hydrozoans, algae, fish, cephalopods, and gastropods, indicating a broad trophic niche (Andrade et al. 2022). The squat lobster *G. gregaria* plays a key ecological role in Sub-Antarctic food webs, largely due to its feeding strategy and abundance in benthic aggregations (Lovrich and Thiel 2011). It is capable of moving across the water column, feeding on small crustaceans, macroalgae, polychaetes (Romero et al. 2004, 2006), and particulate organic matter (POM). Its ecological role is comparable to that of krill (*Euphausia superba*), serving as prey for various benthic and pelagic predators (Vinuesa and Varisco 2007; Haro et al. 2016; Harris et al. 2016). The feeding behavior of limpets from the genus *Nacella* is diverse, including cropping and browsing on macroalgae and epilithic microalgae, as well as ingesting small prey and suspended particulate organic matter (SPOM). The diet is influenced by habitat (subtidal, lower intertidal, and mid-intertidal zones), availability of food, and feeding structures like the radula in grazing individuals, which facilitate access to different food sources (Ruppert et al. 2004; Choy et al. 2011; Andrade and Brey 2014; Rosenfeld et al. 2018). Both gastropod species studied, *N. concinna* and *N. deaurata*, display an omnivorous diet that includes green microalgae and brown and red algae. Additionally, some individuals consume invertebrates such as foraminifera, mollusks, and arthropods (Andrade and Brey 2014; Rosenfeld et al. 2018). In terms of ecological interactions, *Nacella* limpets are prey for various predators. In the Magellan region, the asteroid *Cosmasterias lurida* and the steamer-duck *Tachyeres pteneres* feed on these limpets, while in the Antarctic Peninsula, the kelp gull *Larus dominicanus* is a known predator for them (Silva et al. 1999). Historically, *Nacella* limpets have also contributed to the human diet, highlighting their significance in various food webs (Morello et al. 2012).

The Patagonian fjords and Antarctic Peninsula, the focus of our study, are of immense ecological importance. The fjords serve as biodiversity hotspots, characterized by unique environmental conditions that support a wide range of marine species and diverse marine life (Escribano et al. 2003; Quiroga et al. 2022). The Antarctic Peninsula, home to sensitive and endemic species (Grange and Smith 2013), represents a critical environment for assessing pollution impacts, given its relatively pristine state and rising anthropogenic pressures. Similarly, the Patagonian fjords are highly dynamic ecosystems that are increasingly being recognized for their vulnerability to anthropogenic influences. Although MP contamination in both regions has been increasingly documented in recent years—particularly in surface waters and sediments—experimental studies are just beginning to provide valuable insights into the interactions between MPs and specific benthic invertebrate species (Gonzalez-Pineda et al. 2025). However, direct evidence from individuals in their natural habitats remains scarce.

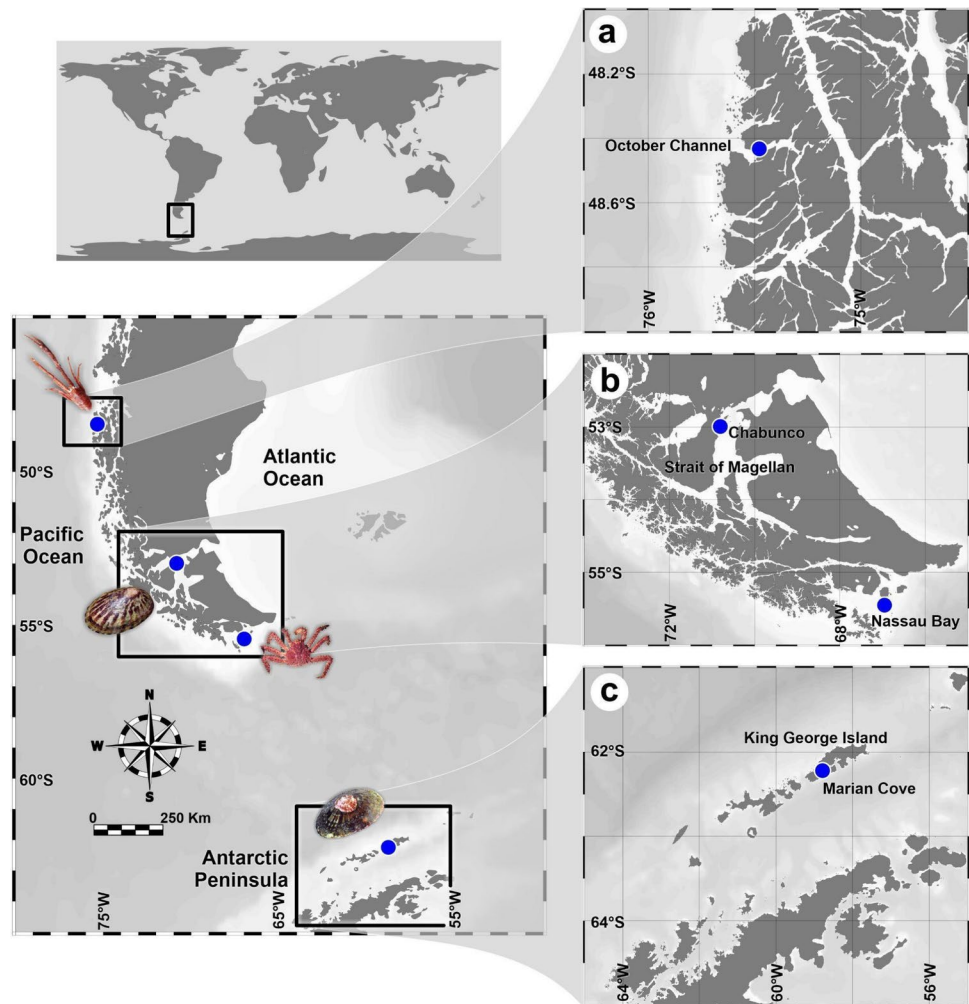
Employing new evidence we have collected, we hypothesized that particle abundance found in the stomach content of benthic species would correlate with body size but not necessarily vary across trophic levels. Additionally, we anticipated significant differences in particle abundance among feeding modes and variations in ingested plastic particles' shape and chemical composition. By examining the prevalence of potential plastic particles in species from these regions and using functional traits as explanatory variables, our research aims to provide region-specific data that can serve as a foundation for future studies exploring the ecological implications of MP pollution in their natural environment.

## Materials and methods

### Sample collection

Fieldwork was conducted in four locations that included the Central Patagonian Zone (October Channel; 48°41'28"S; 75°11'56"W), Chabunco in the Sub-Antarctic Magellan Strait (52°59'14"S; 70°48'31"W), Nassau Bay (55°41'67"S; 67°66'67"W), and in a rapidly deglaciating fjord in the West Antarctic Peninsula (Marian Cove, King George Island; 62°12'42"S; 58°45'5"W) (Fig. 1). Southern king crabs, *L. santolla*, were collected using fishing traps deployed from a fishing vessel between September and November of 2017, at depths ranging from 20 to 40 m in Nassau Bay. Squat lobsters (*G. gregaria*) were collected in the October Channel (Katalalixar National Reserve) in July 2018 using a vertical conical zooplankton net with a length of 1.20 m, a mouth diameter of 30 cm, and a mesh size of 300 µm. Samples were collected at a depth of 3 m,

**Fig. 1** Sampling locations (blue circles) in the Southern Patagonian Zone (a), in Sub-Antarctic Strait of Magellan and Nassau Bay (b), and in Marian Cove glacier, King George Island, West Antarctic Peninsula (c)



and the duration of each sampling period varied depending on the time needed for individuals to enter the net. Limpets (*N. concinna* and *N. deaurata*) specimens were manually collected in January 2018 in Marian Cove and in September 2019 in Chabunco, respectively, during low tide in the intertidal zone (refer to Table 1). After being collected, all specimens were frozen for subsequent transportation to the Laboratorio de Ecología Funcional of the Instituto de la Patagonia, Universidad de Magallanes, where the analyses took place.

### Sample treatment and analysis

To ensure reliable and accurate results, precautions were taken to prevent cross and airborne contamination, following well-established protocols (Lusher et al. 2017b; Bour et al. 2018; Hermesen et al. 2018). This involved thorough sterilization of all laboratory equipment prior to use (e.g., tweezers, Petri dishes), the use of disposable gloves and cotton clothing, regular and rigorous surface cleaning, and the establishment of separate areas for sample analysis.

**Table 1** Sampled species by feeding mode, *n* numbers, habitat, trophic level, body size, and mass of analyzed specimens. TL=trophic level, where 1° primary consumer, 2° secondary consumer, and 3° tertiary

consumer; BL=body length (mm); MBL=mean body length (mm); BW=body weight (g); MBW=mean body weight (g)

Species	Feeding mode	<i>N</i> stomachs	Region	TL	BL (mm)	MBL (mm)	BW (g)	MBW (g)
<i>Nacella concinna</i>	Grazer	12	Antarctic	1°	2.46–4.65	4.11	1.94–13.11	9.86
<i>Nacella deaurata</i>	Grazer	12	Sub-Antarctic	1°	2.44–4.83	4.65	1.27–14.96	4.81
<i>Lithodes santolla</i>	Scavenger	149	Sub-Antarctic	3°	54–140	94.81	100–1700	711
<i>Grimothea gregaria</i>	Scavenger	41	Sub-Antarctic	2°	3–27	3.14	0.49–1.10	0.81



Petri dishes not in use were diligently covered with glass and aluminum to prevent any potential airborne contamination. Procedural blanks were included, as recommended by previous studies (Bessa et al. 2019), and dried filters were observed using a stereoscopic microscope to check for possible contamination. The results revealed no contamination in the blank samples on Petri dishes. Additionally, each specimen was defrosted and rinsed with pre-filtered deionized water to remove any external debris that could have potentially interfered with subsequent analyses, following the method described by Lusher et al. (2017b).

Body size (in centimeters) and body mass (in grams) measurements were taken for each specimen, along with records of feeding mode, habitat, and trophic level (refer to Table 1). Each individual's stomach was extracted and placed in a sterile Petri dish. Stomach contents were obtained by scraping the internal walls with tweezers, and such contents were then examined under a stereomicroscope. Food items for diet analyses were separated from the visible plastic particles. Potential MPs in the sample were carefully collected using forceps or a needle for tiny particles and, following a standardized protocol (Lusher et al. 2017b), stored in Eppendorf tubes with 70% ethanol for a subsequent micro-Fourier-transform infrared (FTIR) analysis. All particles found were counted and measured by their total length to the nearest millimeter and photographed under a stereoscopic microscope. A non-qualitative analysis was conducted on each species where particles were found, using classification criteria based on shape, texture, and color (Hidalgo-Ruz et al. 2012). The prevalence of particles was calculated as the percentage of specimens containing at least one particle in their stomach for each species (Bessa et al. 2019). The number of particles per individual was compared among species, feeding mode, and trophic levels. Trophic levels were obtained from the most recent available literature.

### Micro-Fourier transform infrared (FTIR) analysis

All samples from which particles were identified and isolated were sent to the Laboratorio de Fisiología Animal Comparada at the Universidad de Concepción for Micro FTIR analysis. Due to budget restrictions, a sub-sample of five stomach contents per species was analyzed under a micro-FTIR (Fourier-transform infrared analysis, Spotlight 400 FTIR Imaging System PerkinElmer). Fiber spectra were obtained by diffuse reflectance, and attenuated total reflectance was used for fragments. All protocols followed during the analysis have been described in previous studies (Jorquera et al. 2022; Correa-Araneda et al. 2022). A total of 69 samples from all four species were analyzed.

Particles were extracted and placed on a potassium bromide disc under a stereomicroscope (Nikon SMZ18).

Polymer spectra were obtained for each isolated sample, ranging from 4000 to 650  $\text{cm}^{-1}$ , with a resolution of 4  $\text{cm}^{-1}$ . These spectra were then compared to those found in a polymer library to identify the type of polymer present (Perez-Venegas et al. 2020). The equipment automatically performed a baseline correction by subtracting  $\text{CO}_2$  and humidity ( $\text{H}_2\text{O}$ ) signals.

### Statistical analysis

To assess potential differences in particle abundances and sizes among species, feeding modes, and trophic levels, a permutational multivariate analysis of variance (PERMANOVA) was performed using Euclidean distance and 999 permutations. This method was chosen since the data did not meet parametric assumptions and showed variation in sample size. When appropriate, a Wilcoxon multiple comparisons test with Bonferroni p-adjustment was subsequently performed. Pearson correlation coefficients were calculated to investigate correlations between particle abundances, sizes, and body size of each species. Data were log-transformed to reduce statistical noise and adjust the correlation. Descriptive statistics and graphical representations were generated using the RStudio software (Posit Team 2024) and the *vegan* and *ggplot* packages. To explore the relationship between particle shapes and polymer types across species, we employed principal component analysis (PCA) using the PAST software version 4.09b (Hammer et al. 2001). The PCA was set with a variance–covariance matrix, and a bootstrap procedure with  $N=100$  was applied to assess the stability of the components.

## Results

### Prevalence, abundance, and size of particle among species

Among the 214 individuals collected and analyzed, particles were found in all species, with a higher prevalence in the limpets *N. deaurata* (100%, 12/12 individuals) and *N. concinna* (100%, 12/12 individuals), compared to *L. santolla* (32%, 48/149 individuals) and *G. gregaria* (31%, 13/41 individuals). In total, 427 particles were isolated from the four species, with the highest quantities observed in *L. santolla* and *N. concinna*, accounting for 182 and 118 particles, respectively. In *G. gregaria*, 70 particles were found, and in *N. deaurata*, 57 particles were found, all from the stomach contents (Table 2).

The number of particles detected per individual varied from 1 to 38, depending on the species. In the case of *N. deaurata*, the average was 4.8 particles (SD = 2.8) per individual, while in *N. concinna*, it was 9.8 particles (SD = 9.5

**Table 2** Characteristics of particles, including shape (microfibers/fragments), and texture (balls/porous fragments/smooth fragments) identified in the stomach contents of the four species collected from Sub-Antarctic and Antarctic regions

Species	Particle shape	No. of particles	Particle texture	No. of particles
<i>Nacella deaurata</i>	Microfibers	52	Balls	1
	Fragments	5	Porous fragments	2
	Total	57	Smooth fragments	3
<i>Nacella concinna</i>	Microfibers	111	Balls	1
	Fragments	7	Porous fragments	6
	Total	118	Smooth fragments	1
<i>Grimothea gregaria</i>	Microfibers	66	Balls	1
	Fragments	4	Porous fragments	2
	Total	70	Smooth fragments	1
<i>Lithodes santolla</i>	Microfibers	171	Balls	1
	Fragments	11	Porous fragments	11
	Total	182	Smooth fragments	0

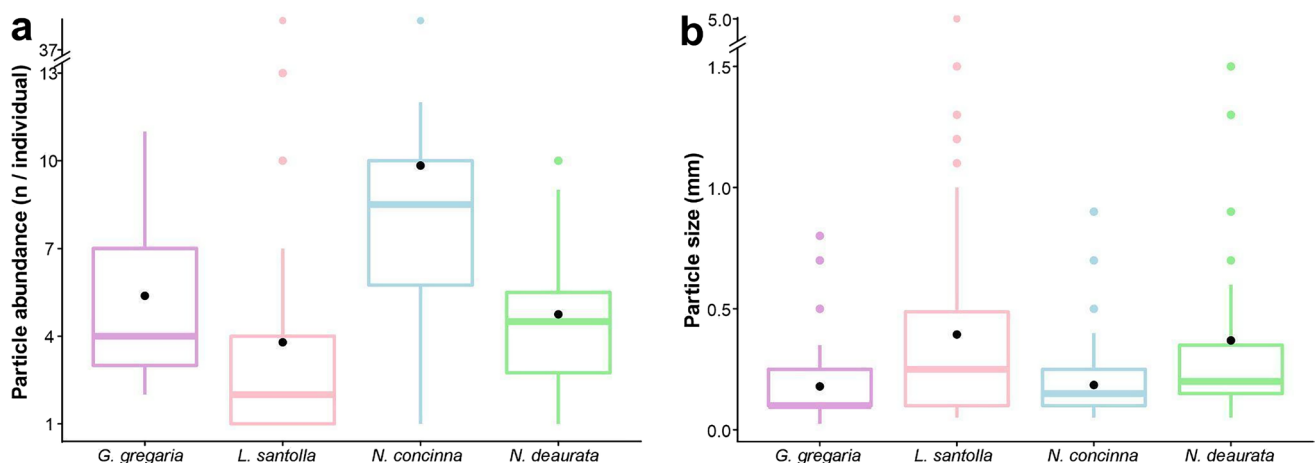
particles) per individual. *Lithodes santolla* had an average of 3.8 particles (SD=5.8 particles) per individual, and *G. gregaria* had 5.6 particles (SD=3 particles) per individual (Fig. 2a). Statistical analyses showed significant differences between species in terms of the abundance of particles per individual (PERMANOVA  $R^2=0.11$ ,  $F=3.51$ ,  $p<0.05$ ; Table 3). *Lithodes santolla* had a significantly lower abundance of particles per individual than *N. concinna* and *G. gregaria* (Wilcoxon pairwise comparison  $p<0.05$ ; Table 3).

The size distribution of particles ranged from 0.025 to 5 mm (maximum length), with an average length of 0.30 mm (SD=0.4 mm). The largest mean size was found in *L. santolla* (mean=0.39 mm, SD=0.5 mm), followed by *N. deaurata* (mean=0.37 mm, SD=0.4 mm). Smaller sizes were found in *N. concinna* (mean=0.18 mm, SD=0.1 mm) and *G. gregaria* (mean=0.18 mm, SD=0.1 mm) (Fig. 2b). Significant differences were found between the different species (PERMANOVA  $R^2=0.07$ ,  $F=10.47$ ,  $p<0.05$ ; Table 3). *Lithodes santolla* and *N. deaurata* had significantly larger

particles compared to *N. concinna* and *G. gregaria* (Wilcoxon pairwise comparison  $p<0.05$ ; Table 3).

### Particle features in the stomach contents of benthic organisms

Most of the particles detected consisted of microfibers (93.7%), while plastic fragments accounted only for a smaller proportion (6.3%). Southern king crabs had the highest concentration of microfibers, comprising 40% of the total fiber count. Fragments were present in small quantities across all four benthic species, representing less than 10% of the total count. Based on texture, the majority of the particles can be categorized as porous fragments (70%), followed by smooth fragments (16.7%) and fiber balls (13.3%). Porous fragments were the most prevalent texture in all species except *N. deaurata*. The remaining microfibers were not associated with any specific texture but were found as individual particles (Table 2).



**Fig. 2** a Abundance and b size of particles found per species. Box plots show the median values in bold lines and quartiles

**Table 3** PERMANOVA analysis (and Wilcoxon pairwise comparisons with a Bonferroni *p*-adjustment method) comparing abundance and size of particles by species and functional traits. Values in bold indicate statistically significant differences. TL=trophic level; GG=*G. gregaria*; LS=*L. santolla*; NC=*N. concinna*; ND=*N. deaurata*

PERMANOVA test—abundance of particles				PERMANOVA test—size of particles			
Factor	<i>R</i> <sup>2</sup>	<i>F</i>	<i>p</i> -value	Factor	<i>R</i> <sup>2</sup>	<i>F</i>	<i>p</i> -value
Species	0.11	3.51	<b>0.02</b>	Species	0.07	10.45	<b>0.001</b>
Feeding mode	0.06	4.92	<b>0.02</b>	Feeding mode	0.01	5.56	<b>0.02</b>
TL	0.06	2.82	<b>0.05</b>	TL	0.05	10.86	<b>0.001</b>
Wilcoxon pairwise comparisons (Bonferroni <i>p</i> -adj)				Wilcoxon pairwise comparisons (Bonferroni <i>p</i> -adj)			
	<i>p</i> -value				<i>p</i> -value		
GG×LS			<b>0.02</b>	GG×LS			<b>6.3e−05</b>
NC×LS			<b>0.004</b>	NC×LS			<b>2.6e−05</b>
ND×LS			0.18	ND×LS			1
NC×GG			0.68	NC×GG			1
ND×GG			1	ND×GG			<b>0.0004</b>
ND×NC			0.25	ND×NC			<b>0.0004</b>
Wilcoxon pairwise comparisons (Bonferroni <i>p</i> -adj)				Wilcoxon pairwise comparisons (Bonferroni <i>p</i> -adj)			
	<i>p</i> -value				<i>p</i> -value		
Secondary×primary			1	Secondary×primary			0.07
Tertiary×primary			<b>0.001</b>	Tertiary×primary			<b>0.002</b>
Tertiary×secondary			<b>0.01</b>	Tertiary×secondary			<b>3.1e−05</b>

Particles displayed a variety of colors, including black, blue, brown, green, gray, orange, pink, red, transparent, light green, and white. Blue and black were the predominant colors, accounting for 50% and 15% of the total, respectively. Blue-colored microfibers were the most commonly found among the benthic species studied, with *N. deaurata* at 46%, *N. concinna* at 34%, *L. santolla* at 56%, and *G. gregaria* at 65%. Other colors, such as gray, green, orange, red, white, and yellow, accounted for less than 25% of the total. Notably, *L. santolla* had the highest color diversity and *G. gregaria* had the lowest (Fig. 3a–d).

### Composition of particles in the benthic organisms

The polymeric origin of the particles was identified in samples analyzed across the four species (*N. deaurata*=29 particles; *N. concinna*=17 particles; *G. gregaria*=11 particles; *L. santolla*=12 particles). Cellulose/rayon-like particles were the most abundant, accounting for 59% of the total, followed by other polymers (30%), while a smaller proportion (10%) was classified as undetermined (Fig. 4a). Among the identified polymer particles, polyethylene terephthalate (PET) was the most prevalent at 15%, followed by nylon at 6%, acrylic at 6%, and polypropylene (PP) at 4% (Fig. 4b).

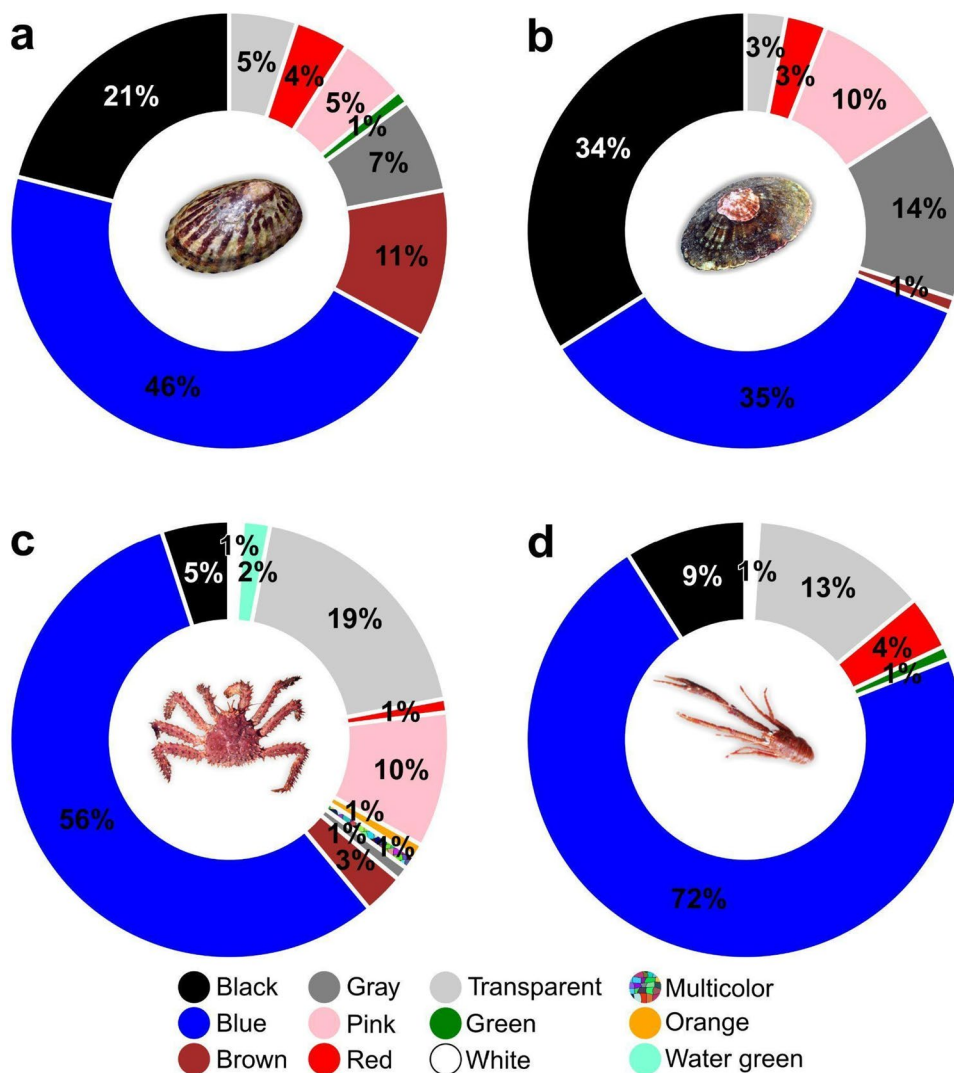
In terms of species-specific analyses (Fig. 5a–d), limpets *N. deaurata* and *N. concinna* primarily ingested cellulose/rayon particles, accounting for 62% and 70%, respectively. Additionally, *N. deaurata* showed the presence of MPs composed of PET (21%) and acrylic (3%). *Nacella concinna* also exhibited acrylic (6%) and nylon (6%) MPs.

Notably, undetermined particles of polymeric origin were found exclusively in the limpet species, representing 14% in *N. deaurata* and 18% in *N. concinna*. Conversely, cellulose/rayon microfibers dominated in crustaceans from the Sub-Antarctic region (*L. santolla* and *G. gregaria*) but at lower percentages (41% and 55%, respectively). In contrast to limpets, both crustacean species showed the presence of polypropylene (PP) MPs, with a higher proportion in *L. santolla* (17%) compared to *G. gregaria* (9%). Acrylic MPs were found in *G. gregaria* (Fig. 6a), accounting for a higher proportion (18%) than both limpet species, while nylon was predominantly found in *L. santolla* (25%; Fig. 6b) compared to *N. concinna*. Representative photographs of MPs found in *G. gregaria* and *L. santolla* are displayed in Fig. 6a–b, providing both visual and spectral data for these identified polymers, with an acrylic blue fiber in *G. gregaria* and a polyamide (nylon) gray fiber in *L. santolla*.

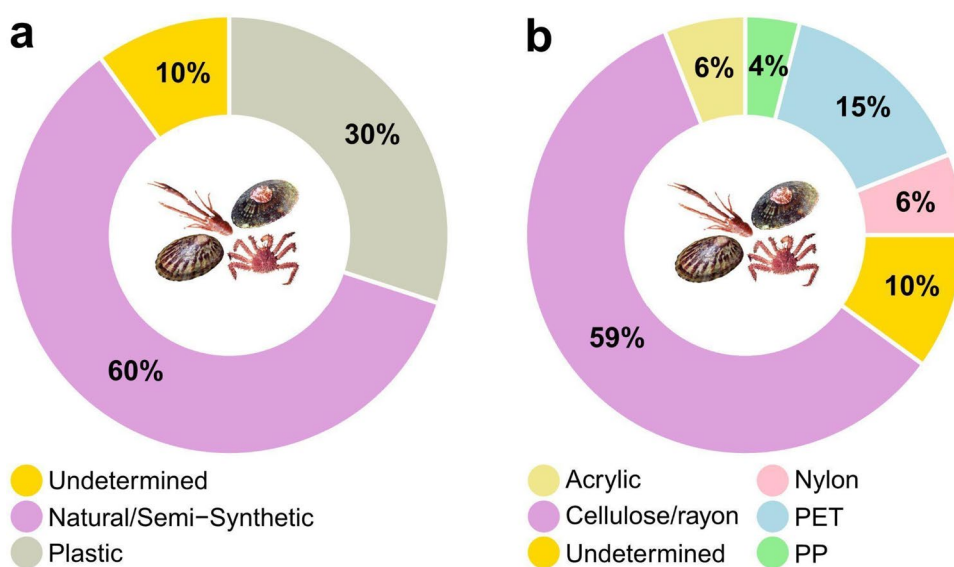
### Correlations between particles abundance/size and benthic organism body size

Pearson correlation analyses did not reveal a significant association between organism body mass and the abundance/size of the particles found in the stomach contents (Table 4). Although particle size was negatively correlated with body size in *L. santolla* ( $R = -0.15$ ,  $p$ -value = 0.05), the correlation was weak and not considered robust enough to indicate a significant effect.

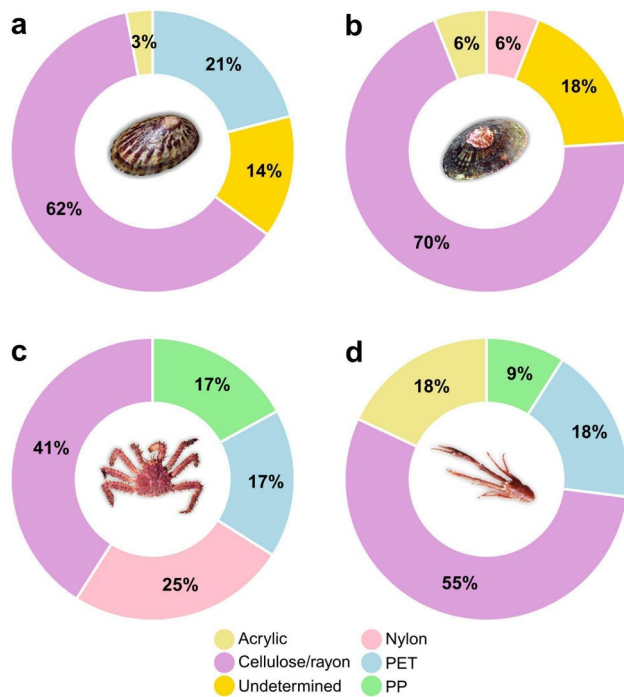
**Fig. 3** Proportion of each particle color found across all benthic species **(a)** *N. deaurata*, **(b)** *N. concinna*, **(c)** *L. santolla*, and **(d)** *G. gregaria*



**Fig. 4** **a** General characterization of particles across all benthic organisms and **b** polymer identification polypropylene (PP), nylon, acrylic, undetermined, polyethylene terephthalate (PET), and cellulose/rayon







**Fig. 5** Composition and proportion of particles across all benthic species: **a** *N. deaurata*, **b** *N. concinna*, **c** *L. santolla*, and **d** *G. gregaria*

### Feeding mode, trophic level versus abundance/size of particles

Our study revealed significant differences in the number and size of ingested particles between the two feeding modes observed (Table 3). Grazers showed a higher abundance of particles per individual (mean = 7.29 particles, SD = 1.49 particles) compared to scavengers (mean = 4.13 particles, SD = 0.68 particles) (Fig. 7a). In terms of particle size, scavengers had a significantly larger average size of 0.33 mm (SD = 0.03 mm) (ranging from 0.025 to 5 mm). In contrast, grazers had an average size of 0.25 mm (SD = 0.03 mm) (ranging from 0.05 to 2.5 mm) (Fig. 7b) (PERMANOVA  $R^2 = 0.06$ ,  $F = 4.92$ ,  $p < 0.05$ ; Table 3).

In terms of particle abundance among trophic levels, our findings showed that primary consumers had the highest particle abundance per individual (mean = 7.29 particles, SD = 7.30 particles), followed by secondary consumers (mean = 5.38 particles; SD = 2.96 particles) and tertiary consumers (mean = 3.79 particles; SD = 5.73 particles) (Fig. 8a). Statistical analyses indicated significant differences (PERMANOVA  $R^2 = 0.06$ ,  $F = 2.82$ ,  $p < 0.05$ ; Table 3), with tertiary consumers also showing a significantly lower abundance of particles per individual compared to primary and secondary consumers (Wilcoxon Pairwise Comparison  $p < 0.05$ ; Table 3). These analyses

reveal a higher particle abundance in the lower trophic levels compared to higher ones (Table 3).

Regarding particle sizes, the results showed that tertiary consumers ingested larger particles (mean = 0.39 mm; SD = 0.50 mm), followed by primary consumers (mean = 0.25 mm; SD = 0.28 mm) and secondary consumers (mean = 0.18 mm; SD = 0.15 mm) (Fig. 8b). Statistical analyses indicated significant variations (PERMANOVA  $R^2 = 0.05$ ,  $F = 10.86$ ,  $p < 0.05$ ; Table 3), with tertiary consumers having significantly larger particles compared to primary and secondary consumers (Wilcoxon Pairwise Comparison  $p < 0.05$ ; Table 3).

### Compositions of particles between feeding modes

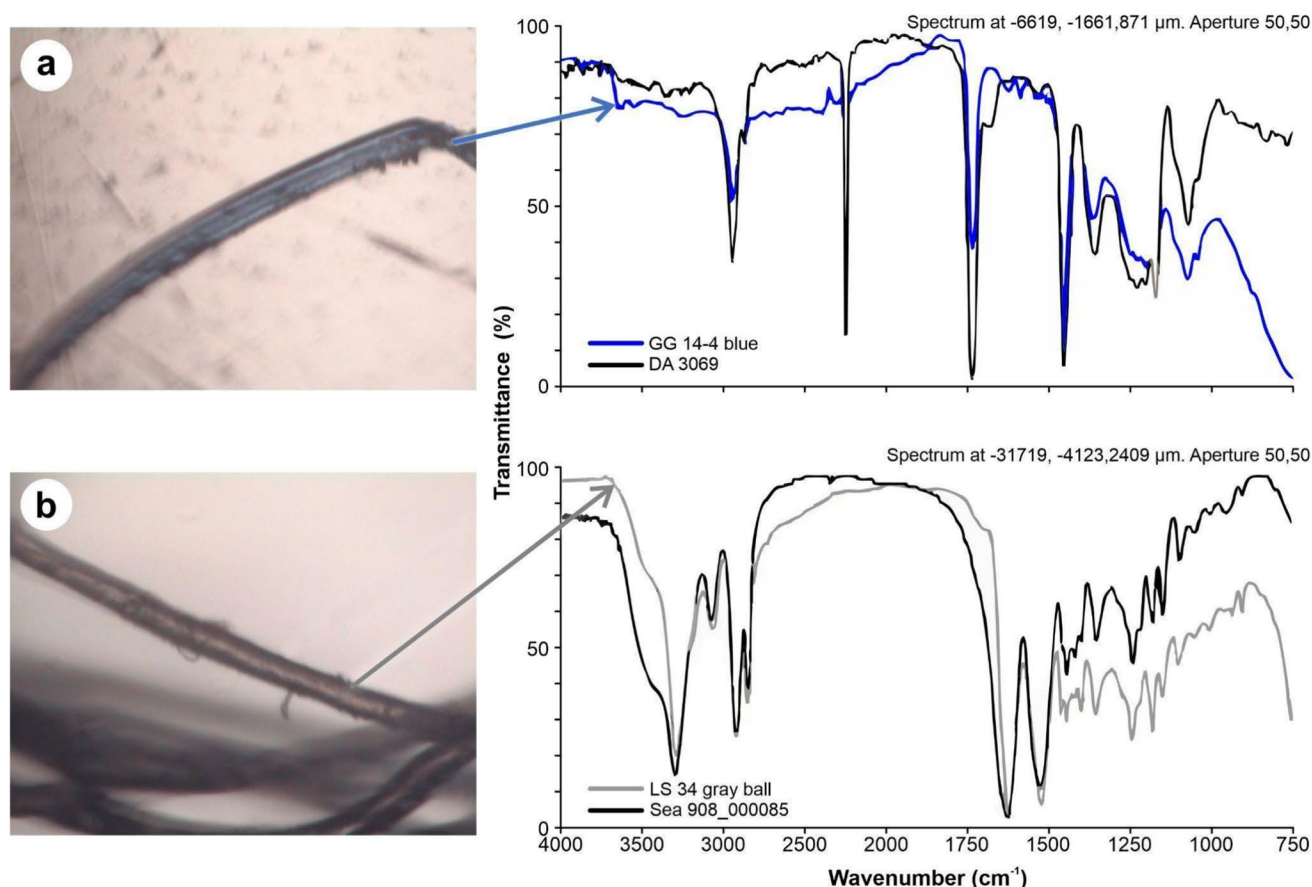
Cellulose/rayon emerged as the dominant material (Fig. 9a–b). Furthermore, this material was more prevalent and had a higher proportion among grazers than scavengers (65% and 48%, respectively). In grazers, PET MPs exhibited a higher proportion than acrylic and nylon, with nylon being the least frequently detected polymer type (Fig. 9a). Among scavengers, PET was the second most prevalent MPs type (17%). Notably, nylon and PP showed similar proportions in scavengers (Fig. 9b). Acrylic and nylon MPs were detected in both groups but showed higher proportions in scavengers than grazers.

Based on the polymer type and shape, the principal component analysis (PCA) (Fig. 10) revealed that species (PCA 1) accounted for 40.43% of the contributions. In comparison, feeding mode (PCA 2) accounted for 24.04%, effectively identifying three distinct groups along the axes. Microfibers were the predominant type of MPs across all species, with some variations. Ball-shaped fibers and fragments were primarily associated with *L. santolla*, while fibers were predominantly linked to limpets *N. deaurata*, *N. concinna*, and *G. gregaria*. Polymer compositions exhibited more significant variability between species, with nylon and PP predominantly associated with *L. santolla*, and acrylic and PET resulting more common in *G. gregaria*. Additionally, the PCA results indicated that the composition of cellulose/rayon MPs was particularly associated with grazers.

## Discussion

### Insights into particle ingestion patterns

This study provides new insights into the ingestion of MPs, cellulose, and rayon microfibers by benthic organisms from different communities belonging to various trophic levels and feeding modes, highlighting the anthropogenic pressure in Sub-Antarctic and Antarctic coastal waters. These



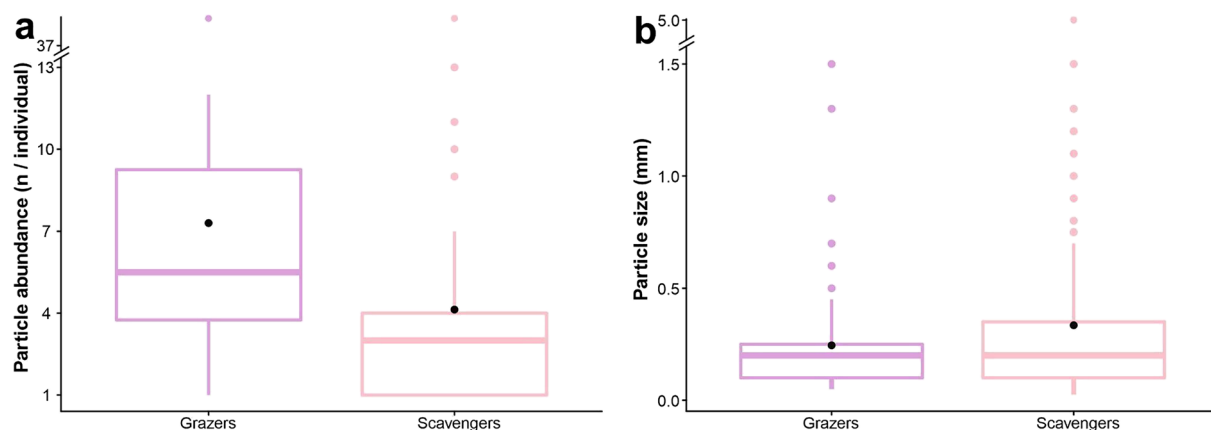
**Fig. 6** Pictures and spectra of two polymers identified: **a** acrylic blue fiber from *G. gregaria* (GG) and **b** polyamide (nylon) gray fiber from *L. santolla* (LS)

findings expand the spatial coverage of previous studies (Andrade and Ovando 2017; Sfriso et al. 2020; Cossi et al. 2021; Ojeda et al. 2021) and incorporate ecological complexity by examining benthic species with diverse functional traits, such as feeding mode, trophic level, and mobility, which are further discussed. These traits can influence MP prevalence, abundance, and characteristics—such as shapes, sizes, and colors—within these ecosystems.

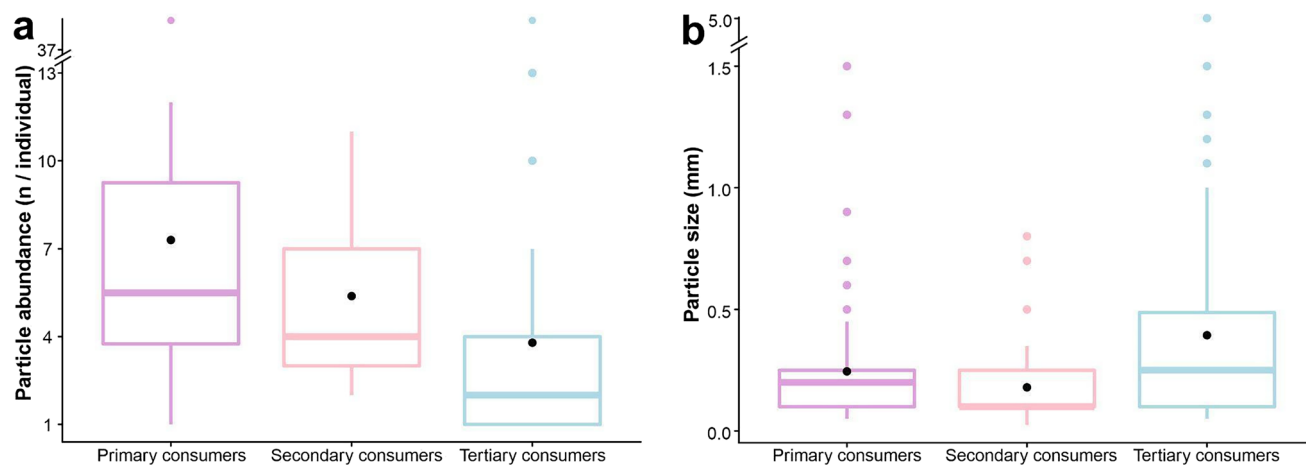
**Table 4** Pearson's correlations between particle abundance/size and benthic organism body size

Species body size (cm)	Particle abundance (n/ind)		Particle size (mm)	
	Pearson correlation	<i>p</i> -value	Pearson correlation	<i>p</i> -value
<i>Nacella deaurata</i>	0.32	0.33	−0.12	0.39
<i>Nacella concinna</i>	0.21	0.54	0.047	0.61
<i>Grimothea gregaria</i>	0.097	0.77	0.19	0.11
<i>Lithodes santolla</i>	−0.04	0.83	−0.15	0.05

We extracted 427 particles from the stomach of the studied specimens, revealing significant variations in particle abundance across different trophic levels and feeding modes. At lower trophic levels, primary consumers exhibited a higher prevalence and abundance of particles compared to those consumers that occupy higher trophic levels. This variation may be attributed to differences in feeding habits, mobility, and the anatomy of the feeding apparatus of the studied species, all of which could influence their exposure and susceptibility to ingesting MPs (Porter et al. 2023). While feeding mode and habitat appear to influence particle ingestion, the small variance explained by these factors in our analysis suggests that additional, unmeasured variables contribute to the observed patterns. One such variable could be body size. Although our results did not show a significant species-specific effect, body size may still capture broader interspecific differences. As highlighted by Berlino et al. (2021), encounter probabilities and ingestion patterns are likely influenced by body size, with smaller species potentially ingesting smaller particles due to physical constraints, while larger species may experience cumulative effects through trophic interactions. Such interspecific

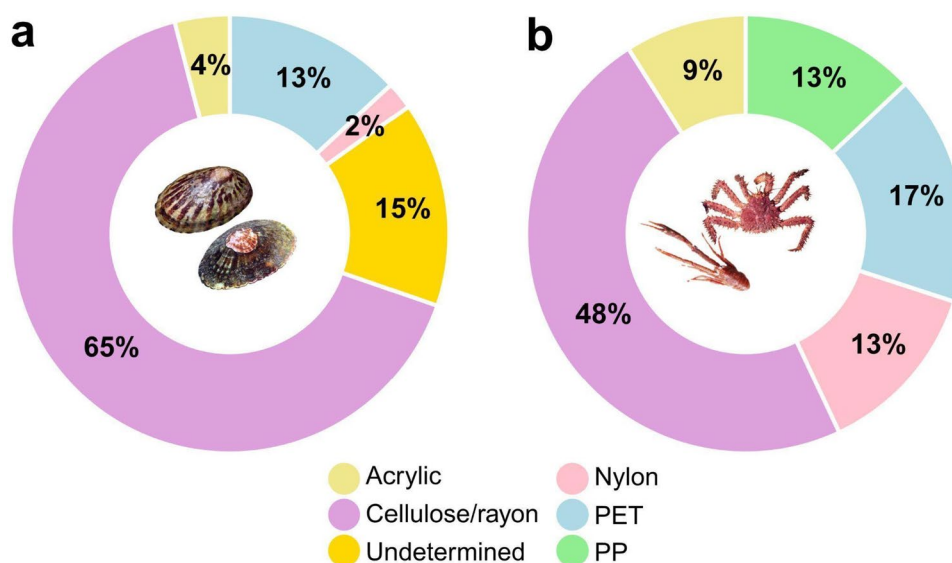


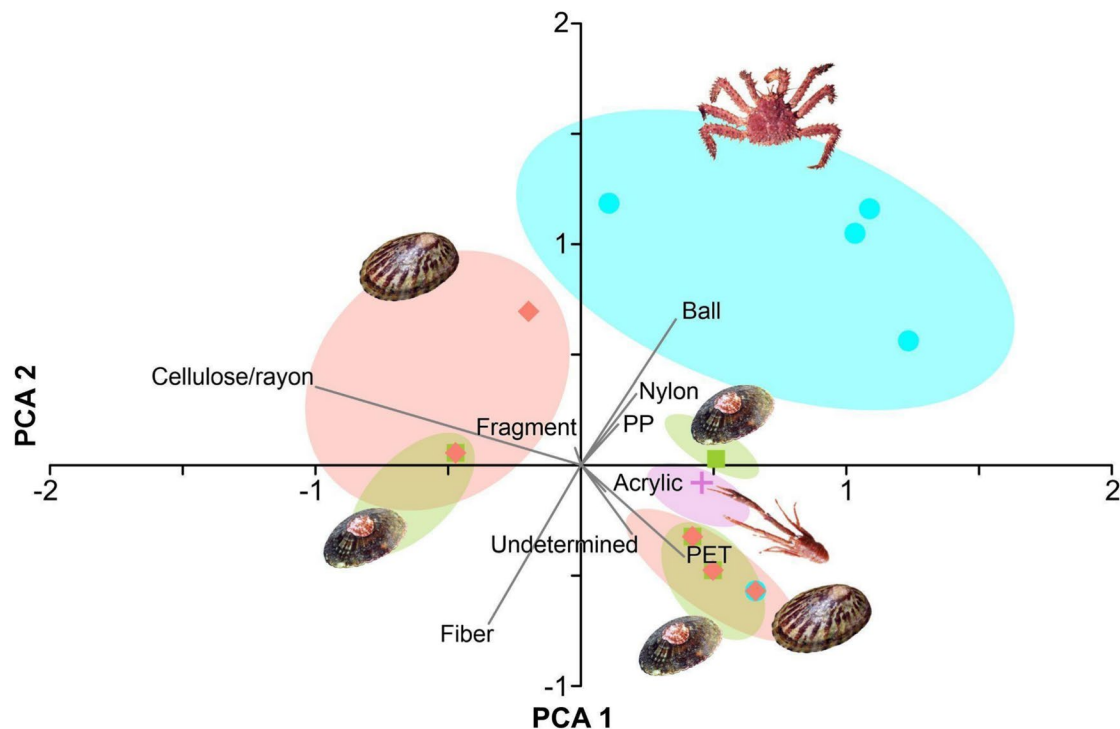
**Fig. 7** **a** Abundance and **b** size of particles found per feeding mode in all the benthic organisms collected from each site located in the Sub-Antarctic and Antarctic Peninsula region. Box plots show the median values in bold lines and quartiles



**Fig. 8** **a** Abundance and **b** size of particles found per trophic level in all the benthic organisms collected from each site located in the Sub-Antarctic and Antarctic Peninsula region. Box plots show the median values in bold lines and quartiles

**Fig. 9** Polymer types between feeding modes. The graphic shows the proportion of each polymer type to the total particles analyzed from **a** grazers and **b** scavengers





**Fig. 10** The principal component analysis conducted on stomach content samples revealed a biplot that represents both explanatory variables (polymeric composition, shape, and texture) and the observations for each species in a two-dimensional space. Arrows indicate the most influential explanatory variables, with their length reflect-

ing their relative weight and contribution to the solution. The species are color-coded as follows: pink represents *N. deaurata*, light green represents *N. concinna*, cyan represents *L. santolla*, and purple represents *G. gregaria*

variability underscores the complexity of the impacts of MPs. It is worth considering whether transit times, related to the size of the digestive tract, could influence the abundance and size of plastic particles found in the studied species, as this could negatively impact their health and fitness. For instance, previous studies have shown that due to the complexity of their digestive tract, crustaceans retain MPs, preventing their egestion alongside food, as observed in northern hemisphere langoustine (Welden and Cowie 2016). While this provides a useful reference, no data are currently available for the species analyzed in this study to further explore this assumption.

Future research should investigate this by comparing MP occurrences across different sections of the digestive tract and conducting controlled feeding experiments to provide deeper insights into retention patterns and physiological effects. Studies have previously reported a positive correlation between body size and MP abundance in marine pelagic organisms (Jâms et al. 2020; Covernton et al. 2021), suggesting that body size may influence the size and abundance of ingested plastic particles (Hamilton et al. 2021; Jiang et al. 2022). However, research on how body size affects MP ingestion in benthic organisms remains limited. Incorporating body size as an explanatory trait in experimental designs,

along with larger sample sizes and a wider range of animal sizes, could enhance our understanding of the factors driving particle ingestion.

### Dominance of microfibers in benthic species

Microfibers were the most prevalent type of MPs ingested across all studied benthic species, irrespective of trophic level or feeding mode. This suggests that microfiber ingestion is primarily driven by their ubiquitous availability in marine environments, closely linked to the production and disposal practices of the textile and clothing industries (Liu et al. 2021), as well as residual water from household laundry (Mahara et al. 2022). Due to their small size and buoyancy, microfibers are highly mobile in the water column and sediments, increasing the likelihood of exposure for benthic organisms (Mishra et al. 2019). These findings highlight that environmental exposure and habitat-specific conditions likely play a more significant role in shaping microfiber ingestion patterns than functional traits such as trophic level or feeding mode.

Limpets, as grazers with low mobility, relatively small body size, and the ability to scrape food from substrates using their specialized feeding apparatus (i.e., radula),



exhibited slightly higher microfiber ingestion than the scavenger species studied. These traits, thus, increase limpets' susceptibility to MP accumulation (Ojeda et al. 2021). In contrast, scavengers such as *G. gregaria* and *L. santolla* showed lower ingestion compared to grazers. This lack of a clear relationship with functional traits indicates that the size and physical properties of microfibers make them equally accessible to diverse benthic species. Instead, differences in ingestion may be influenced by localized environmental factors, such as the concentration and distribution of microfibers in specific habitats.

These findings highlight the importance of prioritizing particle availability (i.e., quantity, type, and distribution) and environmental exposure in future research. While functional traits like feeding mode and trophic level provide valuable context, the ingestion of microfibers appears to be primarily driven by their size, mobility, and ubiquitous presence in marine environments, rather than by body size or species-specific characteristics. Direct measurements of microfiber concentrations in benthic habitats will be crucial to advancing our understanding of the dynamics of microfiber ingestion by benthic species in these ecosystems.

### Environmental sources and implications for benthic ecosystems

The dominance of microfibers, particularly semi-synthetic cellulose/rayon, is likely associated with their higher abundance in coastal environments across the Patagonian fjords and Antarctic Peninsula. Microfibers have been recognized as the most common type of MPs found along shorelines and coastal areas worldwide (Salvador Cesa et al. 2017; Barrows et al. 2018), including Antarctica and the Southern Ocean (Rota et al. 2022). The world's surface oceans are estimated to contain between 90,000 and 380,000 metric tons of MPs (Suaria et al. 2020). Their widespread presence and easy transport by ocean currents make them readily available to marine organisms, increasing the likelihood of ingestion (Lusher et al. 2013; Wright et al. 2013; Fang et al. 2018). MPs often aggregate with organic and inorganic particles, increasing their size and density, which leads to quicker settling onto benthic sediments (Zhang 2017). In coastal environments, where suspended sediments and detrital particles are abundant, this aggregation and subsequent sedimentation are likely key factors shaping the distribution and long-term fate of MPs.

Moreover, sediments serve as a primary sink for MPs, as they can accumulate MP levels of 1 to 2 orders of magnitude higher than in overlying waters (de Smit et al. 2021). Burrowing organisms, together with habitat-forming species such as corals and macroalgae, play a critical role in burying MPs within the sediment matrix. Their activity creates pathways that facilitate the long-term incorporation of MPs into

the sedimentary environment, making them accessible to benthic fauna (Coppock et al. 2021; de Smit et al. 2021). In this context, the benthic species examined in this study can interact with MPs while feeding in sedimentary habitats. For example, *N. concinna* and *N. deurata* may ingest MPs during non-selective grazing (Choy et al. 2011; Andrade and Brey 2014), *G. gregaria* may ingest MPs directly as a deposit feeder that consumes sediments (Romero et al. 2004), and *L. santolla* may acquire MPs both through its benthic prey and potentially while foraging in sediments, as observed for this species (Andrade et al. 2022) and other lithodid crabs in the Northern Hemisphere (Falk-Petersen et al. 2011).

It is also important to keep in mind that natural water-insoluble polymers like cellulose have been found to attach to algal biomass (Zanchetta et al. 2021). Interestingly, certain groups of macroalgae are known to produce substantial amounts of this bio-polymer. Green algae, for instance, have been identified as a rich and significant source of native cellulose derived from their cell walls in varying quantities (Mihiranyan 2011). Notably, *Ulva lactuca*, a dominant species in intertidal environments of the Magellan region (Ríos and Mutschke 1999), exhibits a remarkable ability to colonize intertidal and subtidal habitats within fjords and channels (Rodríguez et al. 2021). This context suggests that some cellulose-based fibers found in benthic environments may originate from natural sources like *U. lactuca*, underscoring the importance of distinguishing between natural and synthetic polymers in fiber analyses to accurately assess their ecological implications.

Studies have found *U. lactuca* abundant in cellulose content (Yaich et al. 2015). As a result, *U. lactuca* has been suggested as a fundamental fueling source for benthic biota in Sub-Antarctic marine environments, particularly for grazers species (Andrade et al. 2016). The prevalence of cellulose in the composition of particles isolated from the stomach contents of grazer limpets aligns with their potential dietary preference for macroalgae. Similar findings were observed for the diet of the limpet *N. concinna* in the Antarctic environment (Choy et al. 2011), and the prevalence of cellulosic particles in this study.

While dietary preferences for macroalgae in *Nacella* limpets could explain the higher prevalence of cellulosic particles in their stomach contents, other particles classified as MPs were also present, although in low quantities. For example, Marian Cove, part of the heavily populated Maxwell Bay, is impacted by human activity and far from a pristine environment. It hosts multiple scientific stations with permanent staff conducting year-round activities, as well as numerous research vessels in the surrounding waters. The activities associated with human presence and the hydrodynamic conditions of the area may contribute to the accumulation of MPs in wastewater discharges from the stations into the natural environment (Kim et al. 2023). This state

of affairs in Marian Cove could, thus, be linked to the MPs found in *N. concinna*, such as acrylic and nylon, as well as undetermined particles.

### Ecological implications of MPs in benthic food webs

While the ingestion of MPs by benthic organisms in polar regions underscores the pervasiveness of this contaminant in remote ecosystems, the direct consequences of MP pollution on benthic macrofauna and their ecological functions remain uncertain and require further investigation. Such research is necessary because benthic macrofauna are integral to numerous ecological processes, including sediment bioturbation, organic matter cycling, energy transfer, and nutrient fluxes (Welsh 2003). As ecologically significant functional components, benthic macrofauna play a crucial role in maintaining ecosystem dynamics. They are an essential part of the food web, not only as prey but also as predators, connecting different trophic levels and regulating energy flow within the ecosystem (Gili and Coma 1998; Bolam et al. 2002; Trebilco et al. 2020).

MP ingestion presents several potential threats to these vital organisms and the processes they support. Physical impacts, such as damage to the digestive tract, reduced food consumption, weight loss, and decreased growth rates, have been documented in marine organisms (Li et al. 2021; Jeyavani et al. 2022; Besseling et al. 2013; Wright et al. 2013; Urbina et al. 2023). Chemical impacts are equally concerning, as MPs can act as vectors for toxic substances that may bioaccumulate in tissues, potentially reducing fecundity (Sussarellu et al. 2016) and causing energy depletion (Wright et al. 2013; Watts et al. 2015; Urbina et al. 2023). Additionally, negative effects on subsequent generations have been observed (Sussarellu et al. 2016). These effects suggest that MP ingestion could disrupt the ecological roles of benthic macrofauna, such as nutrient cycling and energy transfer, potentially leading to cascading impacts within the marine ecosystem.

The effects of MPs within food webs are difficult to predict, but evidence indicates that their ingestion may influence their bioavailability, promoting sedimentation as marine snow (Porter et al. 2018) and leading to further accidental consumption by marine organisms, in a cyclic process. Following ingestion, the fate of MPs varies depending on their physical properties and the organism's physiology. Certain particles may be expelled in fecal matter, particularly in species that produce visible fecal pellets (Redondo-Hasselerharm et al. 2018; Parolini et al. 2020), while others may pass through the digestive tract and accumulate in tissues, as observed in several benthic species. These pathways can significantly influence the bioavailability of MPs within the food web, shaped by both trophic and

non-trophic interactions, and amplify their distribution within marine communities (D'Avignon et al. 2023).

Few studies have explored the retention of MP-associated hazardous substances in marine organisms across different feeding modes. Bioaccumulation patterns may vary depending on the species and the physical and chemical properties of the particles (Avio et al. 2015; Pittura et al. 2018). Future research should investigate these dynamics under realistic environmental conditions, as recommended by Miller et al. (2020). Laboratory experiments incorporating natural sedimentary and hydrodynamic conditions could provide deeper insights into how MPs interact with marine biota. These efforts will be critical for understanding the full extent of MPs impacts on marine ecosystems, particularly in polar and sub-Antarctic regions.

### Sources and pathways of MP pollution

Remote areas in the Patagonian fjords and channels, as well as the entire Antarctic region, are widely regarded as pristine environments with low anthropogenic pressures compared to populated areas (Hughes et al. 2011; Castillo et al. 2020; Horton and Barnes 2020; Tecklin et al. 2024). Several studies have failed to find a spatial correlation between the sources of MPs and their abundance, primarily due to the influence of oceanographic drivers, such as currents, on the distribution and dispersal of pollutants. However, a strong correlation has been observed between localized anthropogenic activities (e.g., aquaculture) and MPs in marine sediments (Jorquera et al. 2022).

Although field studies on MP occurrence in marine invertebrates from the Magellan region and Patagonian fjords and channels are still limited, previous research in Nassau Bay, Southern Patagonia, indicated that the crustacean *L. santolla* primarily ingested tiny blue fibers (Andrade and Ovando 2017). Our study expands upon these findings by characterizing these plastic fibers as acrylics, nylon, PET, and PP polymers. According to the literature, these polymers likely originate from fishing gear and nylon ropes (Thushari et al. 2017), as well as from the clothing production industry and, in the case of acrylics, boat painting operations (Gibson 2017; Halstead et al. 2018), all common activities in Southern Chile.

Fishing activities are common in that region, and they can introduce significant amounts of MPs, particularly fibers, into the marine environment, as fishing gear is predominantly made of plastic (Andrady 2011). The extent of plastic pollution derived from fishing gear remains to be properly quantified due to the heterogeneity in gear types and fishing efforts, as well as inadequate monitoring practices (Kuczenski et al. 2022). For instance, the abrasion of plastic ropes during commercial fishing, especially when in contact with the seafloor, can release MPs into the environment

(Syversen et al. 2022), making fishing gear one of the primary sources of MPs in the marine realm (Lusher et al. 2017a). Environmental, operational, behavioral, contingency, and management factors may contribute to the abandonment, loss, and discard of fishing gear at sea, leading to their sinking into the seafloor and causing damage to benthic habitats through abrasion, dragging, and entanglement (Richardson et al. 2021). The degradation of these discarded materials, thus, can potentially release MPs (Wright et al. 2021), making them available for accidental ingestion by marine organisms.

In our study, the most densely populated area is near Chabunco, located on the coast of the Magellan Strait. This area is likely subjected to anthropogenic pressure due to its proximity to an industrial zone (Cabo Negro) and aquaculture activities, which may introduce pollutant particles into the local environment and its biota. Abundant species of macroalgae are commonly found throughout the coast (Newcombe and Cárdenas 2011; Mansilla et al. 2013; Cárdenas and Montiel 2015), serving as important food sources for various organisms, such as limpets (Andrade and Brey 2014; Rosenfeld et al. 2018). Therefore, the species *N. deaurata* is more likely to ingest particles through grazing on algae and directly or indirectly ingesting particles. Research has shown that MPs accumulate on macroalgae through passive mechanisms such as adherence and entanglement (Huang et al. 2023). Tissues that are intermittently submerged and exposed to air create favorable conditions for direct MPs adhesion (Huang et al. 2023). On a finer scale, the polysaccharide components of the macroalgal mucus layer significantly enhance MPs attachment to algal surfaces (Gutow et al. 2016; Zhang et al. 2022), and the presence of epibionts may further strengthen this effect (Li et al. 2022). Additionally, the architectural complexity and cuticle characteristics of macroalgal canopies aid in the accumulation and eventual burial of MPs in the underlying sediment by trapping particles on their surfaces and promoting sedimentation around the canopy (de Smit et al. 2021).

This result could be particularly relevant, as we only obtained undetermined spectra for certain particles in the limpets *N. deaurata* and *N. concinna*. For these specific grazer species, the significance of macroalgae on their diets has been demonstrated (Choy et al. 2011; Andrade and Brey 2014), and the diversity of macroalgae species might explain the challenge in identifying polyamide or nylon using FTIR when a biofilm covers it (Uurasjärvi et al. 2020), which naturally occurs on the surface of macroalgal fronds.

Moreover, studies in the Antarctic indicate that atmospheric and oceanic transport can carry MPs from distant sources, including southern South America, into otherwise pristine regions (Cunningham et al. 2022). This suggests that MPs, especially fibers, may enter remote ecosystems through multiple pathways (e.g., air, seawater, sediment), with coastal and deep-sea areas potentially acting as sinks.

Therefore, sources like atmospheric deposition and emissions from coastal populated areas, as well as research stations and vessels should all be considered in assessing MP contamination in remote polar environments.

Despite the absence of human settlements, benthic organisms such as *G. gregaria* on the coast of the Katalalixar National Reserve area contained MPs, including acrylic, PET, and PP microfibers, in their gut contents. This crustacean, which inhabits the entire Patagonian fjords and channel region, may serve as an effective biomonitoring organism. The types and quantities of MPs in its stomach contents could reflect environmental exposure to these pollutants. In Central Patagonia, these polymers likely originate from oceanic sources, with MPs potentially entering the channels via subsurface marine waters from the Gulf of Penas. Maritime activities in this area, including boat paint acrylic particles, are a significant source of these pollutants (Castillo et al. 2020). The uptake of MPs by *G. gregaria*, a secondary consumer, appears to result from incidental and direct ingestion related to its habitat. Given its ecological role as a key species in Patagonian food webs (Ricciardelli et al. 2020; Andrade et al. 2024), *G. gregaria* is an ideal candidate for monitoring MPs, allowing for the identification of taxa most at risk. Moreover, some habitats are underrepresented in environmental monitoring due to sampling challenges but analyzing organisms like *G. gregaria*, which inhabit these areas, can help assess the prevalence of MPs and the risks for associated taxa. Unlike traditional environmental sampling, which provides a snapshot of current conditions, gut content analyses in *G. gregaria* provide data on longer-term exposure by detecting MPs in the ingestion and offer a more comprehensive view over approximately 12 h, depending on gut transit times. This temporal integration provides insights into MP exposure over a given period, complementing broader monitoring programs. Such data can guide targeted mitigation efforts and help refine strategies for managing MP pollution in vulnerable ecosystems.

## Challenges and limitations

Our study provides information on the particle prevalence and composition of MPs in benthic organisms from the Sub-Antarctic and Antarctic regions, highlighting their presence even in these remote and supposedly pristine environments. This evidence underscores the pervasive nature of plastic pollution. We observed variations in the types and numbers of MPs among species, trophic levels, and feeding modes. Additionally, our findings highlight the importance of considering habitat-specific factors, such as diet preferences and mobility, to understand the likelihood of benthic organisms ingesting MPs.

Although the chemical composition of most particles was identified, a percentage remained undetermined due

to limited spectral quality or the absence of corresponding data in our library. This limitation highlights the need for expanded reference libraries and improved spectral resolution in future studies. Addressing these factors could enhance identification accuracy, allowing for a more comprehensive understanding of particle composition and its potential implications.

While further research is needed to fully grasp MPs' ecological and physiological impacts on marine organisms, our study contributes valuable insights for understanding patterns of MP ingestion in the studied organisms. This understanding complements the growing body of knowledge on this global issue as it is crucial to assess and mitigate the impact of plastic pollution to preserve the health and integrity of marine ecosystems.

Considering the relative sample sizes necessary to assess particle prevalence in the studied invertebrates, it is apparent that variations in sampling among different species could introduce complexities into the analysis. The discrepancy in sample sizes presents challenges in ensuring the robustness and comparability of findings across species. Additionally, the inconsistent sampling across seasons and years may potentially obscure temporal trends or patterns, which were beyond the scope of this study.

It is essential to acknowledge that the samples originate from remote locations such as the Antarctic and sites like Katalixar and Nassau Bay, which are only sporadically accessible due to logistical constraints. These methodological limitations underscore the need for careful interpretation of the data and emphasize the importance of acknowledging and addressing these constraints in discussing the study's outcomes.

## Future research directions

There is an urgent need to evaluate MPs' potential adverse effects at the physiological level, particularly among key species occupying lower trophic levels within marine food webs. Laboratory studies have documented both lethal and sublethal effects on various invertebrates, including mollusks and crustaceans, albeit mainly limited to inland waters (see therein Azevedo-Santos et al. 2021). Our results provide valuable insights into the interactions between MPs and benthic communities in the Antarctic and Sub-Antarctic region, highlighting significant variations in ingestion patterns across species and trophic levels. These findings offer guidelines for prioritizing target species in future research on the ecotoxicity of MPs. This means that efforts should be placed on species already known to ingest MPs and who play key roles within the benthic food web, as mentioned here, since their ecological performance may be impacted by the chemicals in MPs. Such insights have the potential to further enable inferences about possible cascading effects at the community

level across the studied habitats in the Sub-Antarctic and Antarctic regions. This information should be considered when assessing the broader impacts of MPs on marine organisms (Bour et al. 2018), including potential implications for fisheries.

Further research that investigates the potential exposure pathways of anthropogenic pollutants in specific locations is also needed. Future studies should include assessments of the effects of MP concentrations on a variety of benthic species with different feeding traits and habitat preferences. Such investigations would provide critical insights into how MPs influence the ecological functioning and habitat quality of marine environments, ultimately shedding light on the overall health status of ecosystems impacted by anthropogenic pollutants. Furthermore, other morphological and developmental factors, such as oral cavity size (Fueser et al. 2019), advanced life cycle stages (Scherer et al. 2017), and intestinal area in the case of herbivorous fish (Jacob et al. 2020), can also influence the size, quantity, and sensitivity of organisms when ingesting plastic particles. These functional and biological traits should be considered as well in future research efforts, as they provide critical context for interpreting exposure pathways and assessing the broader ecological implications of MPs pollution.

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**Author contribution** Conceptualization: C. A., T. S., B. P., and M. U.; methodology: C. A., B. P., and T. S.; data curation: C. A., C. R., and B. P.; software: C. A., T. S., and C. R.; formal analysis: C. A., B. P., T. S., and M. U.; validation: C. A., C. A. V., and M. U.; resources: C. A., C. A. V., and M. U.; writing—original draft preparation: C. A. and T. S.; writing—review and editing: C. A., T. S., C. R., B. P., C. A. V., and M. U.; visualization: C. A., T. S., C. A. V., C. R., and M. U.; project administration: C. A.; funding acquisition: C. A., C. A. V., and M. U. All authors have read and agreed to the published version of the manuscript.



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**Data availability** Data will be made available under request.

## Declarations

**Ethics approval** The authors declare that all applicable national guidelines for sampling of organisms for the research have been followed and all necessary approvals have been obtained.

**Consent to participate** Not applicable.

**Consent for publication** Not applicable.

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