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Assessment of plastic debris and biofouling in a specially protected area of the Antarctic Peninsula region

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ABSTRACT

The aim of this paper is to characterize the plastic and to study a potential relationship between plastic debris characteristics and the presence of fouling biota in an Antarctic Specially Protected Area Robert Island, on the Antarctic peninsula region. A combination of lab-based sorting, advanced spectral analysis and general linear modelling was used to assess the abundance and type of plastic debris washed up on the shore. Observations recorded 730 debris items, with 85 % being plastic. Polystyrene (PS) and Polyethylene terephthalate (PET) were the dominant plastics (61 %). Biofouling was observed on 25 % of plastic debris, with debris complexity and degradation significantly increasing the likelihood of fouling occurring. There was no correlation found between biofouling type and plastic polymer type. Findings raise concerns that even with the highest level of environmental protection, an external marine-based source of pollution can intrude the coastal habitat, with uncertain consequences to local flora and fauna.

1. Introduction

Since the global commercialisation of plastics in the 1960s, production of synthetic materials has consistently increased (Geyer et al., 2017). As of 2022, global plastic production now equals over 400 million tonnes per year (PlasticsEurope, 2023). Through incorrect waste disposal, discarded plastic can infiltrate water systems, eventually ending up in the ocean (Salinas et al., 2024). If they are positively buoyant, debris such as this can be carried in surface waters, propelled by oceanographic forcers such as prevailing wind and currents (Gallagher et al., 2024, Salinas et al., 2024, Barnes et al., 2009). Capable of travelling trans-oceanic distances, plastic debris now has a cosmopolitan distribution (Barnes et al., 2009; Thompson et al., 2009; Rech et al., 2016). The longevity of plastics within the environment is particularly concerning, persisting for centuries before breaking down (Sin and Tueen, 2022). There are multiple risks associated with plastic in the water column. These include but are not limited to; animal entanglement (Arnould and Croxall, 1995; Brown and Niedzwecki, 2020), transport of invasive species via organism “rafting” (Barnes, 2002; Gregory, 2009), ghost fishing (Lively and Good, 2019), bioaccumulation through the food chain (in the form of smaller micro/nano plastic) (Miller et al., 2020) and leaching of persistent organic pollutants when they begin to degrade (Rios et al., 2007).

Antarctica, the southernmost continent in the world, is home to a rich diversity of flora and fauna, that have remained relatively undisturbed for millennia (Dalziel et al., 2013). As such, both marine and terrestrial ecosystems are particularly vulnerable to external perturbations (Convey and Peck, 2019). Previously considered “biologically isolated”, due to strong oceanographic and atmospheric barriers such as the Polar Frontal Zone (Convey et al., 2002), it has recently been observed that surface particles can percolate via storm-produced surface waves and eddies, at relatively high frequency (Fraser et al., 2018). Floating microplastics originating from lower latitudes have been confirmed to reach areas north of the multi-front structure of the Southern Ocean (SO). This phenomenon has been supported by recent research findings. Murphy et al. (2021) discussed the global connectivity of Southern Ocean ecosystems, highlighting how benthic and intertidal species can traverse Southern Ocean fronts and reach Antarctic waters by rafting with buoyant materials at the ocean's surface (Murphy et al., 2021).

Moreover, Suaria et al. (2021) delved into the dynamics of transport, accumulation, and export of plastics at oceanic fronts, shedding light on how plastics move within oceanic systems, which could explain the presence of floating microplastics in regions north of the Southern Ocean

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multi-front structure (Suaria et al., 2021). Additionally, Lozoya et al. (2022) presented new evidence of Southern Ocean connectivity through their study on stranded pellets in Fildes Peninsula, King George Island, Antarctica. This research contributes to the understanding of how materials, including microplastics, can travel across vast distances in the Southern Ocean (Lozoya et al., 2022). Plastic debris has been recorded from benthic sediments to surface waters (Jones-Williams et al., 2020; Lacerda et al., 2019), in glacial ice (González-Pleiter et al., 2021) and in snow (Aves et al., 2022) in Antarctica, becoming ubiquitous in the polar environment.

The sub-Antarctic islands, unlike higher latitudes and continental antarctica, are not immune to biological invasions, with 6 species non-native species recorded to be living within these waters (McCarthy et al., 2019). The South Shetland Islands (SSI), as well as Antarctic Peninsula Region, receive 7-fold more tourist voyages than anywhere else on the continent (McCarthy et al., 2022). Anthropogenic activities will be more concentrated, putting increased strain on the ecosystem in these areas.

Beached anthropogenic debris has been recorded within other SSI ASPAs (Almela and González Herrero, 2020; Finger et al., 2021), at levels equal to areas without any mitigation measures in place (Pertierra et al., 2013; Waluda et al., 2020). This suggests ASPAs are still vulnerable to external pollution, despite strict controls to minimise on-land disturbance. However, surveys of beached debris within Antarctica are limited, with inconsistencies in sampling rate and methodology (Waluda et al., 2020; Eriksson et al., 2013; Finger et al., 2021). In that sense the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) Marine Debris Program Guidelines provide a framework for managing and reducing marine debris in the Southern Ocean. These guidelines focus on regular monitoring and data collection using standardized methods, reporting debris data to CCAMLR, and sharing information amongst member countries. The guidelines emphasize prevention and mitigation measures, such as implementing waste management practices on ships and research stations, and complying with international regulations like MARPOL Annex *V*. Additionally, they promote research on the impacts of marine debris and raise awareness amongst stakeholders. These efforts aim to protect the Antarctic marine ecosystem and ensure sustainable resource use (CCAMLR, 2017).

Plastic debris in the oceans not only affects marine life through ingestion and entanglement but also serves as a substrate for biofouling, where organisms attach and grow on the plastic surfaces (Mendoza et al., 2021). Marine plastic litter biofouling is a significant issue that poses threats to marine ecosystems and biodiversity because drifting plastic can serve as a vector for the dispersion of invasive species by transporting them attached to it (García-Gómez et al., 2021). Biota has been observed to colonise plastic debris by attaching to the debris surface within multiple locations of the Southern Ocean (Barnes and Fraser, 2003, Lacerda et al., 2020, Cappello Cappello et al., 2021).

The Northwestern peninsula of Robert Island was designated an Antarctic Specially Protected Area (ASPA112) in 2002 by the Antarctic Treaty Secretariat (ATS) (ATS, 2012). This designation is the highest level of environmental protection the ATS can provide, prohibiting any human activity unless absolutely necessary, or for monitoring purposes. The Coppermine peninsula was given this protection due to the outstanding diversity of flora and fauna that reside there, which include multiple species of birds, seals, and penguins. Additionally, over 20 different species of moss have been recorded, forming one of the largest known continuous carpets in the continent (ATS, 2012). There is only one small research base existing on Robert Island, located within the ASPA112, with a maximum occupancy of 5 people. Operations are limited, with any work conducted requiring a permit. Therefore, any pollution that exists within this ASPA, particularly along the coastline, is likely to have come from an external source or from some local historical sources.

As Chile is the proposing country of the ASPA 112, during the austral summer of 2023, Chile conducted a cleaning operation of all the debris deposited along the coastline of this ASPA, which once collected was transported to the city of Punta Arenas, Chile. In this context, the aim of this work is first to characterize the collected debris, specifically plastics, and to document biofouling of plastic debris, to understand a potential relationship between plastic debris type and characteristics and the presence of fouling biota.

Finally, this study aims to add to a growing body of literature to better understand the type of plastic debris that is present within an isolated Antarctic Coastline. This study will provide insight of the external sources of pollution impacting ASPA, that cannot be fully controlled.

2. Area of study

The study area is in Robert Island, part of the South Shetland Island Archipelago on the northern tip of Western Antarctic Peninsula region (WAP). ASPA112 is located within the southern section of Robert Island, covering the entire Coppermine peninsula (Fig. 1).

3. Material and methods

The cleaning operation was carried out along a transect (see Fig. 1C) extended from the western tip of Coppermine cove, in a north-westerly direction to the tip of the peninsula. The coastline consisted of two pebbled bays, with large boulders scattered throughout. The beach is predominantly composed of pebbles with a diameter ranging from approximately 10 to 20 cm. The granulometry indicates a coarse, well-rounded, and uniform composition, typical of areas with high-energy wave action that sorts and smooths the rocks. The pebbles give the beach a stable and consistent texture. The overall sediment structure is characterized by minimal presence of finer particles, resulting in a

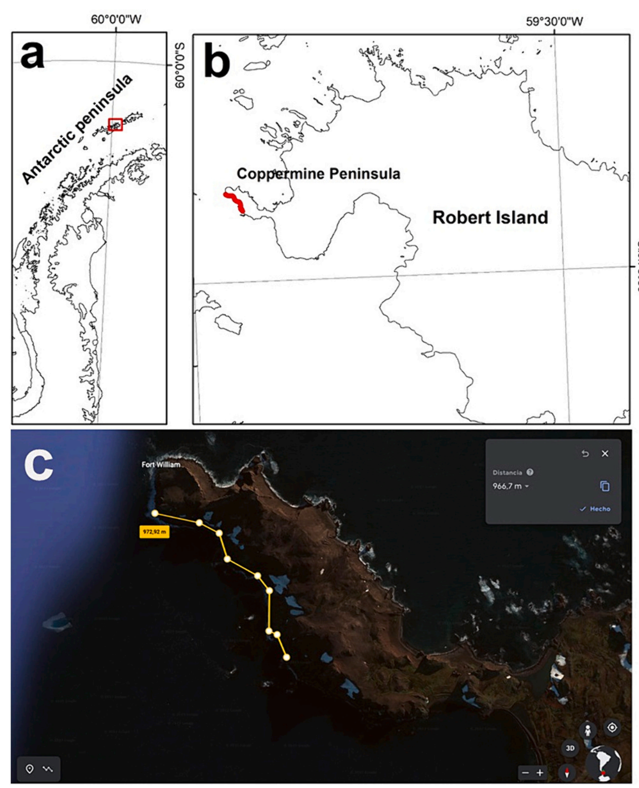

Fig. 1. a) Antarctic peninsula region with the location of the area of study highlighted in red, b) Robert island and Coppermine peninsula where de ASPA 112 is located and c) view of the cleaning area and the transect in yellow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

porous and well-draining surface (Fig. 2).

Due to the regulations of the ASPA, the access route was chosen carefully, so as not to disturb the large quantities of nesting seabirds. Beach debris was identified visually, by pairs of surveyors. The beach was surveyed from the waterline up to the upper strand line, along a GPS-plotted transect. The total length of the survey transect was 966.7 m of a variable width that could not be measured during the cleaning operation. This was surveyed once over the course of 7 days, from 12/01/2023 to 19/01/2023, in smaller sections. The Anthropogenic debris of any type that was identified was collected, in accordance with the CCAMLR marine debris program guidelines (CCAMLR, 2017). All debris was compiled into waterproof, red jute bags. These were taken via boat to Luis Risopatron base, where they were unloaded then transported to the INACH marine biology lab complex in Punta Arenas, Chile.

Debris pieces were initially sorted bag-by-bag, the contents of each bag photographed in one overall image. Non-plastic debris pieces were weighed with Sartorius m-prove AY-4000 portable balance or a mechanical bathroom scale for larger objects. The length measurement was taken using a measuring tape, then their category/subcategory type recorded onto the CCAMLR marine debris spreadsheet for anthropogenic debris monitoring, before being discarded. Each piece of debris determined to be majority plastic was given a label, photographed and its maximum length was recorded. Plastic debris weight was recorded with the same scales as mentioned previously. Small pieces too light to be detected by the Sartorius m-prove AY-4000 portable balance (<0.1 g) were weighed using the RADWAG AS 220/C/2 analytical balance. Plastic debris was then separated into different items (Table 1).

Following initial sample sorting, the physical characteristics of each plastic debris were recorded according to the parameters given in the Table 1.

Plastic debris was also scanned for signs of biofouling visually for a time of at least 30 s, to ensure that the whole surface was seen. If there were any signs, such as coloration/staining or presence of attached flora/fauna, it was recorded. These plastic debris pieces were then sorted into biofouling/non biofouling. A further classification of fouling biota type was recorded, based on their phenotypic differences. A table defining each classification, alongside a visual example, is in the appendix (Table S1). Pieces that had identified biota but were of unknown plastic composition were cut with a scalpel, to an area of ~1cm^2. Each of these small samples were placed into separate plastic falcon tubes, depending on their classified biofouling type. These samples were used for spectral analysis.

Each sample piece was cut into smaller, ~0.5cm^2 squares, to fit the maximum number possible onto a cellulose-acetate anodisc filter (25 mm, 0.2 μm pore size) for spectral analysis. On average, 16 pieces (±1) were scanned at a time. A Fourier-transform infrared spectrometer (μFTIR, Agilent Technologies, Cary 620 microscope coupled with a Cary

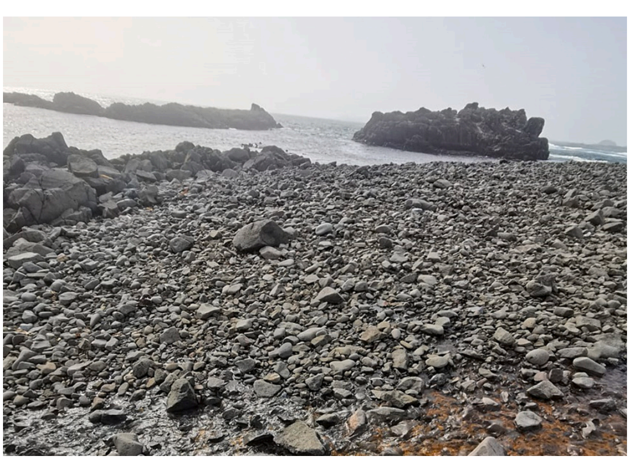

Fig. 2. View of the coastline of the ASPA 112.

Table 1
Description parameters used to describe the plastic litter in this study.

Plastic items	Polystyrene Foams Ropes/fishing gear Small fragments/pieces/bottle caps Miscellaneous Sheeting/films Bottles/piece of bottles/strapping Paint fragments
Size	Small (<2.5 cm), Medium (2.5-10 cm), Large (>10 cm-1 m) and Very large (>1 m).
Colour	White, Black, Red, Blue, Transparent, Green, Yellow, Metallic, Brown and Other colors
Biofouling	Refers to any organism that is seen attached to debris, regardless of taxonomic domain.
Polymer type	PE: Polyethylene PP: Polypropylene PET: Polyethylene terephthalate HDPE: High-density polyethylene PVC: Polyvinyl chloride PS: Polystyrene PU: Polyurethane Mix: Mixed plastics Unknown: Unknown plastics
Physical characteristics	Rugosity: Y/N for rough/smooth Flexibility: Y/N for flexible/rigid Visual degradation level: 1–5 scale, where 1 was pristine, and 5 was at a point of breaking apart and almost unrecognizable

670 μFTIR spectrometer and 128 × 128 focal plane array detector) was used to create infrared (IR) spectra, to identify polymer candidates. The scanning method performed, alongside the parameters of the FT-IR, is similar to that used in Wilkie Johnston et al. (2023). A background scan was first taken of a blank anodisc, involving 64 co-added scans with 8 cm^{-1} spatial resolution binned at 4 intervals. The sample anodisc was then visual imaged in full, to ensure all plastic candidates were captured, and an IR scanning box was drawn to encapsulate them all into a scan. This area was scanned in transmission mode, creating 16 co-added scans, with a wavenumber range from 3650 to 1250 cm^{-1}. The Fig. 3 summarizes this procedure.

In order to identify polymer composition from IR spectra, the final FT-IR map must be processed and matched to a polymer library. For this study, "Purency Microplastics Finder", by Purency GmbH, was used. This automatic microplastic detection software utilizes machine learning to enable fast and reliable polymer identification, using a 21-polymer class library (Keys et al., 2022; Rendell-Bhatti et al., 2023; Wontor et al., 2023). The resulting outcome of Purency processing is colour coded into a spatial map, identical to the original visual pane, for easy comparison. Each colour relates to a different polymer. A confidence value (relevance) threshold of 0.6 was used. This value relates to the prediction certainty of the algorithm to match each individual spectra point to a polymer within the library (Keys et al., 2022). Studies which have previously utilised this software employed a lower relevance value of >0.5 to classify a polymer match (Mylius et al., 2023). Individuals from each of the fouling categories/sub-categories were chosen for further analysis. If there were > 1 pieces, a piece was selected at random from the group. The focus of this step was to identify potential families/species. If a selected sample was unclear, another from the group may be selected.

Samples were first imaged under the Leica S6 D stereomicroscope (magnifications x0.63-x4). A sample of the biofouling organism was then extracted from the debris piece using tweezers and a scalpel. The smallest piece possible was removed, to make it the most likely for successful identification under the subsequent transmitted light microscope, which has a light source below the stage. It was placed onto a glass slide, then fixed with Nikon Type A microscopy oil and a class cover slip. A Zeiss Axiolab 5 transmitted light microscope with mounted Zeiss Axiocam 208 colour camera was then used to analyse and

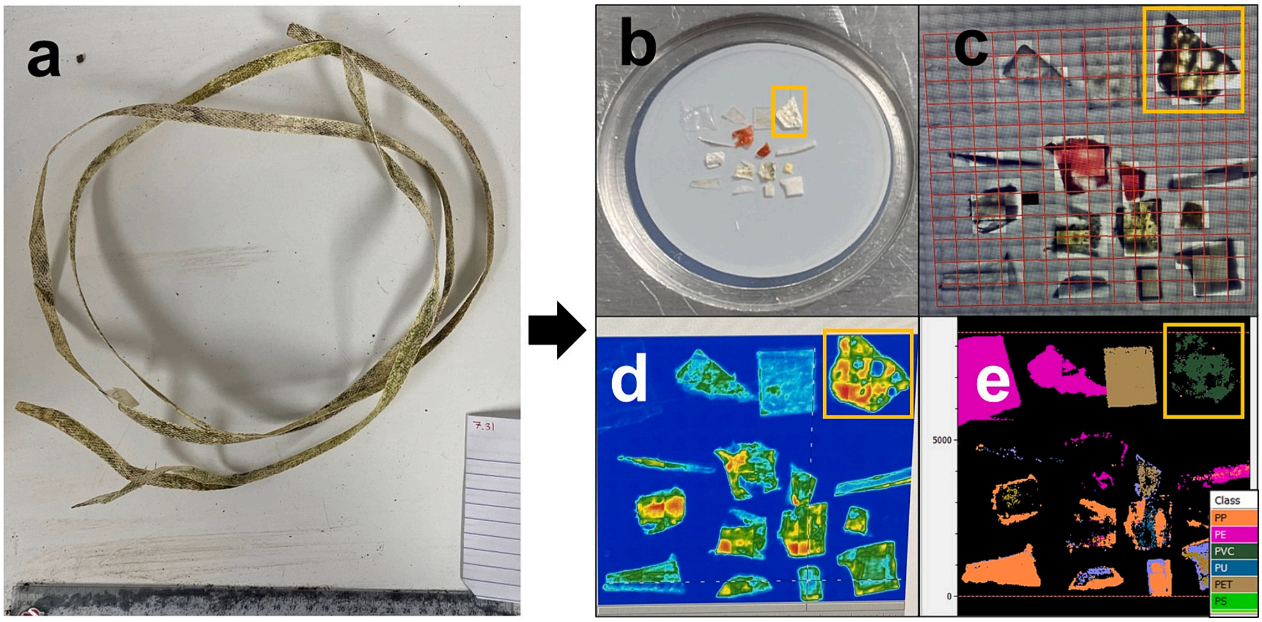

Fig. 3. Spectral Analysis flowthrough. (a) Initial Polymer Piece to be scanned, white open strapping with unknown polymer composition. (b) Small 0,1 cm2 piece mounted onto anodisc for scanning. (c) Identification of debris piece under initial visible image scan. (d) Heat map produced following FT-IR scan. (e) Colour coded spatial map, produced from FT-IR spectra using microplastics finding software Purency (GmbH). Key to polymer type is shown on bottom left of pane. Yellow boxes identify location of polymer piece. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

photograph the extracted organisms at varying magnification levels (x10, x20, x40 and x100). Due to the degraded state of some biota, no families could be identified. The literature was also not accurate enough, and to empirically define a biota type without identifying phenotypic features.

Statistical analyses and all data visualization were performed using R studio (version 2023.6.1). An exploratory data analysis approach was taken. General physical characteristics of plastic debris found were assimilated into a summary table. To test if biofouling was found on pieces with certain characteristics, a multivariate general linear model with binomial distribution was created. Fisher's exact test was also used, to test for any correlations between biota fouling type and polymer composition. The *p*-value threshold for statistical significance was set at $p < 0.05$.

A logistic regression model was developed, to evaluate if any physical characteristics of debris influenced the presence of fouling biota. For the purpose of this model, the length variable was treated as categorical (using CCAMLR classifications used in Fig. 4). The final model was a general linear model with binomial distribution, and included the variables complexity, type, degradation and colour.

4. Results

Of all anthropogenic debris collected on the ASPA 112 in Coppermine peninsula (730 total), 85 % ($n = 621$) pieces were plastic. Of the non-plastic debris, the majority were machined wood ($n = 34$), followed by metal ($n = 20$) (see Supplementary Material for a more detailed non-plastic debris summary, Table S2). Considering the total items of marine debris it resulted in a rate of 0.74 items/m.

Plastic debris mainly consisted of consumer products (32 % by number), followed by miscellaneous items (29 % by number). These included items such as plastic fragments ($n = 56$), foam ($n = 54$), paint fragments ($n = 21$) and burnt plastic ($n = 3$). The debris type that was the most abundant on mass was fishing gear (39.41 kg, 53.4 % of total debris mass). White was the most abundant debris colour ($n = 258$), followed by clear ($n = 155$). A range of languages were recorded on all debris types except for packaging bands and polystyrene. The most popular language recorded was Chinese ($n = 19$) and English ($n = 15$), with consumer products recording the greatest number of different languages (see Table 2).

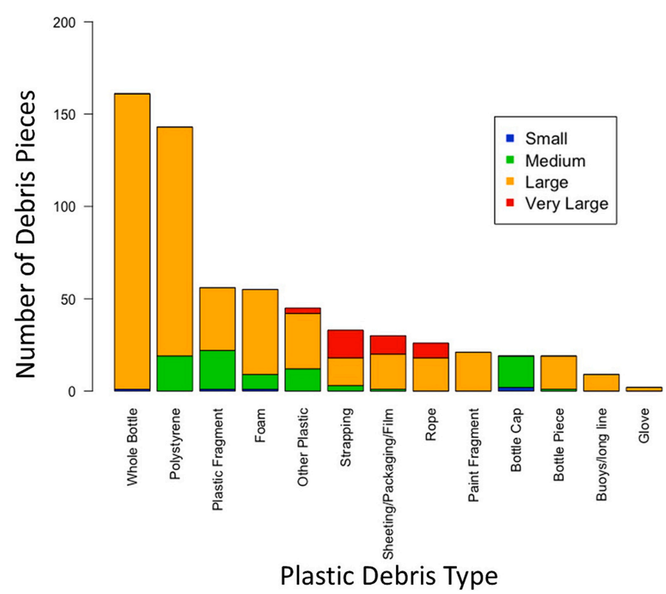

Fig. 4. Stacked bar chart illustrating each type of debris found. Bars are individually split into different length classifications, according to CCALMR size classifications. A colour key for sizes is included in the top right of the graph.

Following CCAMLR size classifications for debris (Table 1), plastic debris was split into size categories based on their maximum length. For all debris types, the most abundant size category was large >10 cm-1 m ($n = 496$). Overall sample size for length presentation was $\boldsymbol{n} = \boldsymbol{619}$, due to 2 debris pieces missing length classification. The most common debris items were whole bottles ($n = 161$) and polystyrene pieces ($n = 143$) (Fig. 4).

Fouling biota was observed on 25.28 % ($n = 157$) of plastic pieces (Fig. 5). Out of 157 plastic debris with fouling biota presence, only 58 pieces were of known polymer composition. 92 out of 99 unknown

Table 2
Summary table of plastic debris collected. Debris is split into categories according to their broad use. Summary table layout based off Waluda et al.'s (2020) results presentation.

Debris type	Number of pieces	% (By number)	Mass (kg)	% (By mass)	Colors (in order of abundance)
Consumer Products	203	32.69	14.59	19.77	Clear, white, blue, yellow, brown, green, orange, pink
Fishing Gear	35	5.64	39.42	53.4	White, orange, green, blue, grey, red, yellow
Miscellaneous	181	29.16	13.52	18.32	White, black, grey, blue, brown, green, red, clear, orange, yellow, pink, purple
Packaging Bags/Sheets	27	4.35	2.12	2.88	Clear, white, blue, brown, grey, black
Packaging Bands	33	5.31	0.18	0.25	White, blue, yellow, green, clear, black
Polystyrene	142	22.87	3.98	5.4	White
TOTAL	**621**	**100**	**73.82**	**100**	–

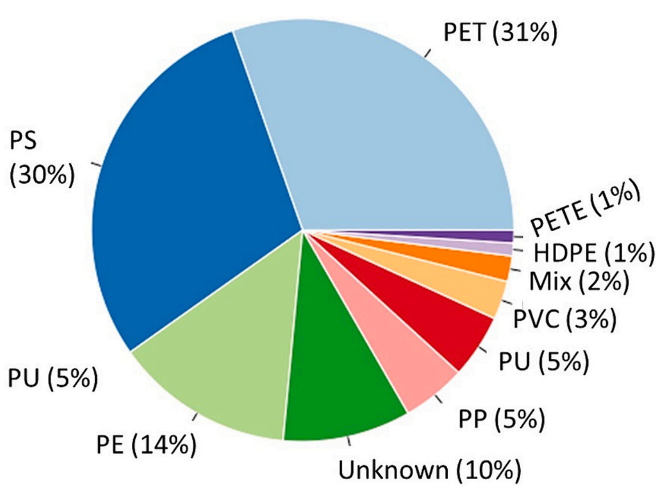

Fig. 5. Abundances of polymer types of the debris pieces with fouling biota, $n = 157$.

plastic debris pieces were scanned, as 7 samples were either lost through handling errors or during transport from Chile to the UK. The 7 lost pieces were included in analyses as part of the category "unknown". Including previously known plastic polymer types, ten types of polymers were identified (Fig. 5). Plastic debris with fouling biota were majorly polyethylene terephthalate (PET) 31 % (*n* = *48*), followed closely by polystyrene (PS) 30 % (*n* = *46*). Three debris pieces had a mix of polymer types. In two cases, the mix was of PS and polyethylene (PE). For one piece, this mix was PS, PE, and PET.

The most common biofouling type was green film (*n* = *55*) (Fig. 6). Fisher's exact test, with 100,000 simulations, was used to determine if polymer type influenced the type of biota found. A chi-squared test was not used, as the observed frequencies of some cells were < 5. There was no correlation found between any polymer and any biofouling type ($p > 0.5$).

Assessing model fit, our model accounted for one of the highest variances of all models evaluated, outputting a McFadden's pseudo-R^2 of 0.136. When comparing against other potential models under Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC), this model indicated the best fit. Multicollinearity between variables was not present, verified by a variance inflation factor (VIF) test. This model also did not severely violate any assumptions, nor included points that were deemed "outliers."

Using this model, it was determined that debris complexity significantly increased the presence of fouling biota ($p = 2.89\text{e-}05$). Degradation state only significantly increased biota fouling presence under the highest level of degradation ($p = 0.0109$). Debris type did not significantly influence the presence of biota ($p > 0.05$); however, fishing rope had more biofouling than other categories ($p = 0.0501$).

5. Discussion

A total of 730 pieces of anthropogenic debris were collected, over a distance of just under 1000 m, which means a rate of 0.74 Items/m. Anfuso et al. (2020) and Vesman et al. (2024) both reported similar abundances of 0,87 Items/m and 0.32 Items/m respectively nearby King George Island, with transect lengths of 820 and 1895 m. These abundances are higher than observed in Livingston Island, Torres et al. (1997) reporting a debris abundance of >0.11 Items/m within one season, 1995/1996 at Cape Shirreff. Nevertheless, it is important to consider that the results of our study were obtained during one week of cleaning, whereas the study by Torres et al. (1997) spanned an entire summer season in a 14 km long coastline finding about 1500 items. Salinas et al. (2024) reported 638 items along a 5.47 km (0.12 Items/m) stretch of coastline in Punta Arenas, Strait of Magellan, of which 37.5 % were plastic. In every study mentioned previously, plastic has been the dominant material of debris collected, accounting for 37.5–94.5 % of items (Salinas et al., 2024; Vesman et al., 2024). This study determined 85 % of debris to be plastic, matching the similar proportional abundances found in most other sites studied in the Southern Ocean (Vesman et al., 2024).

Within an ASPA of Livingston Island, recent surveys have detected a much lower debris abundance (0.008–0.04 items/m), than was observed in this study (Almela and González Herrero, 2020). Debris recorded in Antarctic Specially Managed Area (ASMA) in Admiralty Bay, King George Island were predominantly wood (49 %), with plastic accounting for 16 % of the 186 items recorded, again, a much lower abundance of debris compared to this study, despite its close proximity to five international research stations (Sander et al., 2009).

Finger et al. (2021) recorded 17 pieces of packaging bands within ASPA133, of which 59 % were longer than 30 cm. Of the strapping bands recorded in this study (*n* = 33), only 1 was uncut, but 81.25 % of the open strapping were >30 cm length. This is particularly concerning, considering the strict regulations established by the CCAMLR marine debris programme in 1989 (CCAMLR, 2017). Packaging bands are currently banned for use on bait boxes within the Southern Ocean under CCAMLR conservation measure 26–01 and must be cut to a length < 30 cm before disposal, to reduce the risk of animal entanglement (Waluda et al., 2020; CCAMLR, 2017; Zhang et al., 2020). This measure comes under the wider "General Environmental Protection Measure During Fishing", which was adopted by CCAMLR in 2006, which broadly disallows any disposal of plastic waste into the Antarctic Treaty Area. Amongst its exceptions, however, is the "accidental loss of equipment on board" (Zhang et al., 2020). This may be utilised by illegal fishing operations as a loophole to discard of waste more easily, instead of waiting until they reach port.

The most abundant colour of debris found was white (*n* = 258), followed by clear/transparent (*n* = 157). The least abundant colour was purple (n = 2). This contradicts Lavers et al. (2016), who tested the factors that influence detection rates of beach debris, observing that white is commonly the hardest colour to find, whilst blue was the easiest. This could be because the substrate colour in the ASPA 112 is dark, making light-colored plastics and waste easier to see due to their contrast.

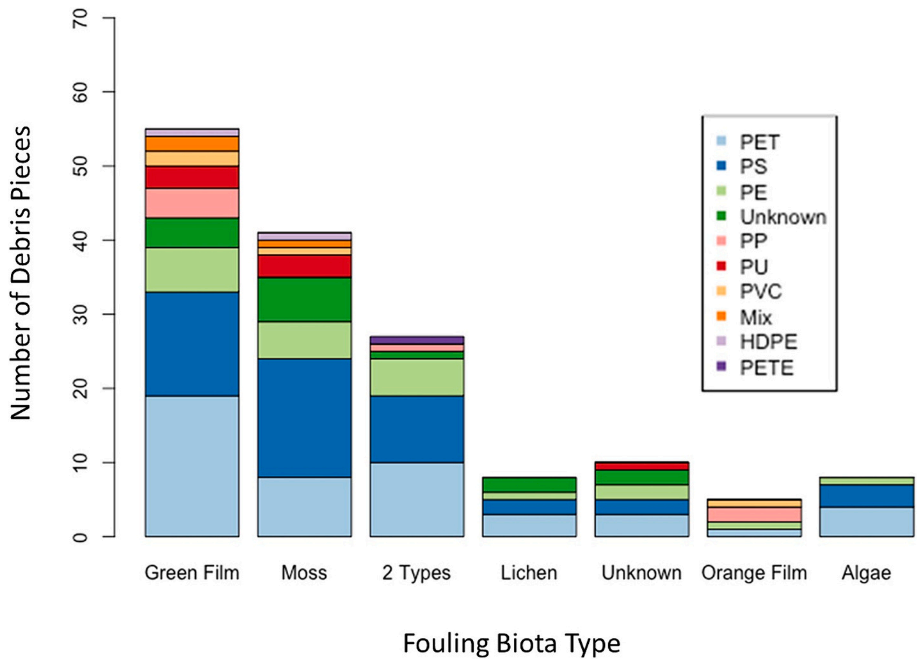

Fig. 6. Stacked bar chart matching the different polymer types of debris pieces with different fouling biota they displayed. A colour coded key to each polymer type is in the top right of the graph.

Plastic bottles were the most abundant debris type recorded on the Coppermine Peninsula (26 % of total plastic debris). This is similar to other studies (Gallagher et al., 2024; Slip and Burton, 1991; Finger et al., 2021), who noted their plastic debris collection to be >50 % bottles. Recent date stamps on bottles stranded on inaccessible island (~2 years) suggest that these drinking bottles have come from a local source, likely ship traffic within the region (Ryan et al., 2019), or even from research stations. This is concerning, when under Annex 5 of the International Convention of the Prevention of Pollution from Ships (MAPROL 73/78), the dumping of plastics from vessels is banned (Chen, 2015). The large range of languages present on consumer debris ($n = 7$) suggest an international problem with the local disposal of plastic waste. The SSIs have one of the highest densities of research stations of the whole continent, housing 10/76 active Antarctic research stations (Finger et al., 2021). Increased isolation of certain stations may also have a disproportionate input to local pollution sources. Due to their lack of resource, disposing rubbish in smaller bases and field camps is more difficult to undertake (Pertierra et al., 2013; Clarke et al., 2005). Marine debris studies at both higher and lower latitudes along the Antarctic peninsula have not been able to attribute plastic debris found to local research activities however, suggesting this may not be the predominant source (Convey et al., 2002; Waluda et al., 2020). Finger et al. (2021) suggested that a large proportion of waste HDPE found on Nelson Island was a result of a nearby dumping of waste on the Fildes peninsula 9–10 years earlier (2010/11) (Peter et al., 2013). Using an oceanographic dispersal model, plastic debris <7 years old floating around the Antarctic Peninsula region has been suggested to have originated from sources within the SO (Lacerda et al., 2019). This study found the largest debris type by mass to be fishing gear. According to do Sul et al. (2011) and Finger et al. (2021), local fishing operations are suggested as the largest input of marine debris in the SO, and local shipping traffic levels are linked to debris abundance on coastlines.

Barrientos Island, part of the Aitcho island group, is situated opposite the Coppermine peninsula, roughly 3.4 km from the study area. From 2017 to 2023, it is one of the top twenty most-visited landed site visits in Antarctica for tourists (IAATO, 2023). Landing operations have been suggested to impact the local environment through unintentional dropping/leaving of personal items behind (Lynch et al., 2010). Eriksson et al. (2013) described the one of the main factors for debris accumulation on beaches with Antarctica to be prevailing wind. If the beach is windward facing, it will accumulate more debris, as was observed by Waluda et al. (2020). Generally, the South Shetland Islands are subject to prevailing westerly winds, with little interannual variability (Van Wessem et al., 2015). As this coastline is southwest facing, it is likely subject to increased debris accumulation due to prevailing wind. Almela et al. (2020) also found debris to accumulate higher on the western side of Livingston Island, which is also subject to the same prevailing wind direction, being part of the SSIs. Additionally, islands within this archipelago are surrounded by annual sea ice during Austral Winter, which may act as a further barrier aiding debris retention on the coastline during winter (Anfuso et al., 2020; Gallagher et al., 2024). Due to its close proximity, land-based debris here may be taken out by the tide, dispersed into the local surface waters, eventually ending up on the Coppermine peninsula, and retained within its pebbly cove.

Fouling biota was present on 25.28 % of all plastic beach debris. It is generally accepted that buoyant plastic debris can float on surface waters for years to decades (Van Sebille et al., 2012) however, some studies have suggested that a significant portion of this is lost into deeper waters much sooner (Cózar et al., 2014; Eriksen et al., 2014). Fazey and Ryan (2016) hypothesise this may be due to biofouling, which increases the density of debris material, causing it to become negatively buoyant and sink. The density of polymers found were both positively and negatively buoyant, depending on type (Table S2). Buoyancy of plastic debris is dependent on its specific structure, not just polymer type, with highly buoyant plastics being in forms of foams and sealed bottles (Ryan, 2015). The majority of debris pieces with biofouling were < 100 cm in size. In theory, smaller plastic pieces will sink out of the water column from biofouling faster than larger pieces, due to a smaller surface area needing to be colonised before the buoyancy is overturned from positive to negative (Ryan, 2015).

Although no non-native species were identified as biofouling, it does not mean that they weren't present, especially because more specific studies would need to be carried out, such as eDNA studies to determine invasive species presence or absence attached to the plastics.

The succession of biofouling communities is complex, but the initial colonisation of substrates is by biofilm (Cooksey and Wigglesworth-

Cooksey, 1995). The high proportion of debris with green film fouling (35 % of total fouling) suggests that these pieces were subject to the early stages of biofouling. Biofilm was recorded on plastic debris within an ASPA on the Harmony Point, a coastline 26 km Northeast from the study area, on pieces of eroded polystyrene (Finger, 2021). This is in line with study observations, recording the second largest portion of green film on polystyrene ($n = 14$).

Moss was the second most abundant fouling biota category on plastic debris ($n = 41$). Pieces covered with moss were likely to be beached at this location for multiple years, due to the slow growth rate of this flora in Antarctica (1-5 mm/ year) (Finger et al., 2021; Ochyra et al., 2008). In this study, a large piece of wood was observed to be enwrapped within a developing moss mat (Fig. 6E). Southern Giant petrels commonly build their nest with moss, as well as pebbles (Conroy, 1972). If moss were to cover a piece of plastic debris, it may be mistakenly picked up and incorporated into their breeding area. Moss was mainly found on charcoal pieces ASPA113, Nelson Island (Finger et al., 2021), but in this study, the main debris type fouled with moss was expanded polystyrene foam (EPS).

Complexity and high levels of degradation were found to increase the presence of fouling biota on plastic. Not only do both of those characteristics increase the surface area available for the organism to attach, but it also provides an increase of crevices and corners, which may aid in helping establish roots (for moss) or holdfast (in the case of algae). Biofilms also benefit from an increase in surface cavities when excreting their adhesive for attachment (Berglin and Gatenholm, 1999). Marine bacteria have been observed to respond to a specific level of roughness on physical surfaces when attaching and creating a biofilm (Kerr and Cowling, 2003). Surface degradation of plastics has also been hypothesised to accelerate under biofilm formation (O'Brine and Thompson, 2010). Lesser degraded debris may have been in the water column for a shorter period, decreasing their chance of being fouled by biota.

The lack of significance surrounding other physical characteristics (e.g., debris colour, transparency, and length) suggest that surface morphology is the main component surrounding organism attachment. Although the only significant interactions identified by the model were debris complexity and high degradation, there were 4 more variable categories identified that may have lesser effects ($p < 0.1$). It is important to consider that these variables may also influence the presence of fouling biota on plastic debris. Fishing gear, for example, was found to increase biofouling at $p = 0.0501$, which is very close to the significance threshold used. This debris type is amongst the most common observed within Antarctic beach debris surveys (Waluda et al., 2020), including within ASPA126 on Livingston Island of the South Shetlands (Almela et al., 2020). Albatrosses and Petrels have been observed to consume anthropogenic items originating from fishing vessels around South Georgia (Phillips and Waluda, 2020).

This study found PET to be the most abundant polymer type identified within bio fouled debris. Anfuso et al. (2020) also found PET to be amongst the most abundant polymer found on King George Island. This may be due to the abundance of bottles, which are commonly manufactured with this polymer type (78.8 % of global bottled water production) due to its ability to be fully recycled (IBWA, 2024). PET properties include high strength, low permeability, heat resistance and transparency, making it a popular choice for a wide range of packaging types (Sin and Tueen, 2022). PS was the next most common polymer recorded, primarily in its expanded foam form (EPS). This debris type is commonly used in food packaging to keep items cold or warm for sustained periods, or as a building material due to its insulating ability. It can also be used as protective packaging, utilised for its light weight in worldwide operations (Sin and Tueen, 2022). Our results indicate that there is no correlation between polymer type and biofouling type ($p = 0.6835$), which aligns with Pauli et al. (2017). These authors observed that the composition of the fouling biota community changes on debris in response to habitat (e.g., beached, surface water, benthic). In contrast, Subías-Baratau et al. (2022) did find a correlation between plastic type and biofouling type; however, this latter assertion would need to exclude habitat response.

During debris collection, a synthetic fishing rope entangling a penguin carcass was observed (Fig. 7), an occurrence previously documented in Antarctica for penguins (Golubev, 2020) and for fur seals in other regions of the Southern Ocean (Arnould and Croxall, 1995; Rebolledo and van Franeker, 2015; Torres et al., 1997).

The South Shetland Islands, are particularly vulnerable to anthropogenic pressures, due to the high level of shipping traffic that encircles the surrounding waters (Lynch et al., 2010). Non-native species introductions are therefore much likelier here than in more remote places at higher latitudes. Invasive species have been recorded within Islands of similar latitudes to the study area (McCarthy et al., 2019; Cárdenas et al., 2020), meaning the future identification of biota to species level will be important. Employing phylogenetic analysis techniques (Cárdenas et al., 2020), or utilising SEM micro imagery to morphologically identify fouling biota (Lacerda et al., 2019; Subías-Baratau et al., 2022), have both been techniques successfully used in previous studies.

6. Conclusions

The finding and cleaning of 730 pieces of plastic waste and others on the coastline of ASPA 112 highlights that protected areas of this type are vulnerable to debris and plastic pollution originating from outside sources.

Around 25 % of plastic debris had fouling biota. This suggests that plastic debris has persisted in the surface water column then on the beach for long enough to be colonised. The most abundant fouling biota type, "green film", suggests debris pieces were in the primary phases of colonisation, likely by microorganisms or microbes. The exact fate of plastic debris is uncertain, but with longer retention rates on more

Fig. 7. Penguin carcass entangled with a rope.

sheltered coasts such as this study location, it raises concerns of the impacts long-term assimilation of plastic debris may have on an area of great ecological relevance.

Policy makers play a crucial role in implementing protection measures for peninsular areas like the Coppermine region, specifically addressing the threat of marine-sourced debris from external sources.

Finally, in Antarctica, due to the challenging meteorological conditions and logistical limitations, it is difficult to follow, for example, the OSPAR (2010) methodology to calculate accurate litter items/m^2, which is undoubtedly optimal for comparing results between different studies. It is necessary to explore a standard methodology that would allow us to obtain results comparable to abundance data in terms of items/m^2. This could be achieved by incorporating remote sensing technologies and the use of Unmanned Aerial Vehicles (UAV).

The use of UAVs equipped with high-resolution and thermal infrared cameras can provide detailed images of the coastal areas surface, allowing for the identification and quantification of plastic debris without the need for extensive on-the-ground surveys. By leveraging these innovative methodologies, researchers can enhance the detection and quantification of marine litter (Goddijn-Murphy, 2024; Goddijn-Murphy et al., 2022; Tasseron et al., 2021; Almeida et al., 2022). UAVs can cover large areas quickly and efficiently, which is particularly useful in remote and harsh environments like Antarctica. Satellite imagery can also play a crucial role in monitoring plastic pollution. Advanced satellite sensors can detect larger accumulations of debris (Salgado-Hernanz et al., 2021; Tasseron et al., 2021), and machine learning and deep learning algorithms can be developed to analyse these images and estimate the density and distribution of plastic litter (Jia et al., 2023). This approach would allow for frequent monitoring over large geographic areas, providing valuable data on temporal changes and trends in plastic pollution.

Combining these remote sensing technologies with ground-truthing efforts, where field teams verify the data collected by drones and satellites, can enhance the accuracy and reliability of the results, reducing the time and workforce required for traditional methods. Establishing guidelines for image resolution, sampling frequency, and data analysis will ensure consistency and comparability of results across different studies. By integrating these innovative approaches, we can overcome the limitations of traditional methodologies and achieve a more comprehensive and efficient quantification of plastic pollution in challenging environments like Antarctica.

CRediT authorship contribution statement

Laura Wilkie Johnston: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Clara Manno:** Writing – review & editing, Software, Methodology, Investigation. **Carla Ximena Salinas:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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