



Surface waters meso- and micro-litter around the Western Antarctic Peninsula: Are the South Shetland Islands a pollution hotspot?

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ABSTRACT

Not even the most remote and pristine oceanic regions, such as the Southern Ocean, are immune to the impacts of marine litter. This study presents novel data on surface waters meso- and micro-litter along the Western Antarctic Peninsula and Livingston Island (South Shetland Islands) across two summer campaigns (2022–2023), providing one of the broadest assessments of marine debris in Antarctica (62° S to 67° S). Litter was detected at all sampling sites, with abundances ranging from 0.019 ± 0.033 to 0.193 ± 0.104 items m^{-3} along the Western Antarctic Peninsula (average: 0.086 ± 0.082 items m^{-3}). The South Shetland Islands exhibited significantly higher litter abundances compared to higher-latitude sites. Our results show that litter distribution correlates with human activity intensity, with latitude and the personnel density of nearby research stations as key influencing factors. The South Shetland Islands emerged as an Antarctic marine litter hotspot, likely driven by the concentration of Antarctic facilities and other anthropogenic activities. Litter was primarily composed of synthetic fibres, especially polyester and nylon, pointing to local human sources. Additionally, a decrease in marine litter was observed at Livingston Island between campaigns, with abundance declining from 0.235 ± 0.152 items m^{-3} to 0.116 ± 0.033 items m^{-3} . This highlights the need for ongoing monitoring to capture interannual variability, avoid seasonal biases, and better understand marine litter dynamics in the Southern Ocean to guide conservation efforts. These findings underscore human impact in Antarctica and the urgent need for better waste management and stricter environmental regulation enforcement.

1. Introduction

Marine litter is a global issue, affecting even the most remote and pristine marine environments, including the Southern Ocean (Tirelli et al., 2020; Caruso et al., 2022; Da Silva et al., 2023). Marine litter includes micro-litter (items with a maximum dimension of 5 mm), meso-litter (items ranging from 5 to 250 mm), and macro-litter (>250 mm) (Ryan et al., 2019), comprising a wide range of synthetic, semi-synthetic, and naturally derived materials (Kroon et al., 2018). These contaminants have been identified in both abiotic and biotic matrices within the Antarctic marine environment, particularly in

seawater (Caruso et al., 2022; Rota et al., 2022; Da Silva et al., 2023). Plastic debris is of particular concern, as over 400 million tonnes of plastic are produced globally each year, yet only around 7 % is recycled (O'Neill and Lawler, 2021; Thacharodi et al., 2024, Plastics Europe, 2024). Moreover, it is estimated that 4.9 trillion tonnes of plastic litter have been mismanaged and released into the oceans (O'Neill and Lawler, 2021; Thacharodi et al., 2024). In this context, Antarctica, despite its remoteness and high level of protection, may be experiencing an emerging trend of debris accumulation. Therefore, assessing the extent and underlying drivers of litter waste, with a particular focus on plastics, is crucial for understanding and protecting Antarctic fragile

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ecosystems.

Marine litter, particularly meso- and microplastics, pose a significant threat to ecosystems and wildlife due to their persistence in the environment. These particles often contain chemical additives and they can also adsorb and transport hydrophobic persistent organic pollutants and heavy metals (Cao et al., 2021; Wang et al., 2024). Thus, its ingestion can lead to various physical and chemical hazards, disrupting feeding, reproduction, and survival (Li et al., 2016). In Antarctica, litter and micro-litter has been detected across a diverse range of organisms, including benthic invertebrates (Sfriso et al., 2020; Gonzalez-Pineda et al., 2024), planktonic species such as Antarctic krill (Dawson et al., 2018; Wilkie Johnston et al., 2023), and top predators like penguins (Bessa et al., 2019; Le Guen et al., 2020; Fragão et al., 2021), seals and other birds (Poeta et al., 2017; Battisti et al., 2019; Cebuhar et al., 2024). These findings underscore the significant risks faced by Antarctic biota.

Once in the Southern Ocean, south of the Antarctic Circumpolar Current, marine litter may become trapped and accumulate, particularly in coastal waters and fjords (Lacerda et al., 2019; Mountford and Morales Maqueda, 2021; Onink et al., 2021; Buckingham et al., 2022). Growing evidence indicates that local human activities, including fisheries, tourism, military operations, and scientific research, are significant sources of pollution in Antarctica (Caruso et al., 2022; Rota et al., 2022). Much of this activity is concentrated in the northernmost latitudes of the Western Antarctic Peninsula (WAP), particularly in the South Shetland Archipelago, due to its proximity to South America. This region, a historical tourist destination, also hosts numerous scientific stations (Aronson et al., 2011; Waller et al., 2017; Tejedo et al., 2022). Despite the lack of studies addressing this issue, the potential impact of marine litter transported from distant sources, through oceanic currents and, in the case of microplastics, via atmospheric pathways, may also represent a significant but overlooked factor influencing local marine pollution dynamics (Waller et al., 2017; Caruso et al., 2022).

Over the past decade, there has been a notable increase in assessments of marine litter contamination in the waters of the Southern Ocean, mainly focusing on micro-litter. Most studies have concentrated on the WAP (Absher et al., 2019; Lacerda et al., 2019; Jones-Williams et al., 2020; Garza et al., 2023; Antacli et al., 2024), the Ross Sea (Cincinelli et al., 2017; Zhang et al., 2022), the Weddell Sea (Leistenschneider et al., 2021, 2024), and the surrounding circumpolar waters (Kuklinski et al., 2019; Suaria et al., 2020b). Among the Subantarctic Islands, King George Island has received increasing scientific attention (Absher et al., 2019; Antacli et al., 2024), with also a report from Livingston Island (LV) (Monràs-Riera et al., 2023). Despite these advances, available data remain limited and fragmented, especially in the case of meso-litter, with most studies lacking a comprehensive analysis of the primary sources driving contamination, such as tourism, fisheries, military, and research activities.

This study aimed to investigate the presence of marine litter in the surface waters along the WAP by conducting a wide range survey across multiple sites between 62° S and 67° S. Additionally, we investigated the dynamics of marine litter during the summer seasons of two consecutive years (2022–2023) in the southern region of Livingston. This area hosts two research stations: the Spanish and Bulgarian research stations, and it receives tourism, particularly False Bay (IAATO, 2024). This region is also directly influenced by the Bransfield Front Current, which may transport plastics from the broader marine system (Sangrà et al., 2011; Moffat and Meredith, 2018; Monràs-Riera et al., 2023). Our objective was to analyse the distribution and characteristics of marine litter on a finer spatial scale and over a broader temporal scale than previously reported, while also exploring the potential conditioning factors, such as anthropogenic activity and environmental conditions. Thus, we evaluated potentially influencing litter distribution variables such as latitude, proximity and personnel capacity of research stations and tourism load. We hypothesize that areas with high human activity, particularly the South Shetland Islands, will exhibit higher waste levels due to increased tourism, the presence of numerous Antarctic facilities, and maritime

traffic among other factors (Aronson et al., 2011; Tejedo et al., 2022; Da Silva et al., 2023). Overall, we aimed to provide novel insights into the abundance, dynamics, and sources of marine litter in Antarctica, an understudied yet increasingly vulnerable region. This work represents one of the most extensive assessments of surface water litter conducted in the Southern Ocean to date, helping to fill key data gaps in a region often overlooked for global pollution research.

2. Materials & methods

2.1. Study site and sample collection

Samples were collected during two CHALLENGE summer campaigns from the surface waters of Livingston Island (LV; South Shetland Islands, Antarctica) and Western Antarctic Peninsula (WAP) in February–March 2022 and January–February 2023, respectively. At the 2022 campaign in LV, four sampling sites were studied in its southern region (Fig. 1). Along the WAP, samples were collected at fourteen sampling points between latitudes 62° and 67°S (Fig. 1). Due to logistical and environmental constraints of Antarctic fieldwork, sampling was limited to accessible coastal sites. While efforts were made to sample a range of coastal sites with varying levels of human activity, it was not possible to identify pristine control sites that were completely free from the influence of research stations or tourism. At each site, three transects were performed. Sampling in each transect was conducted under calm seawater conditions using a Manta Trawl net with a rectangular opening of 0.6 m × 0.25 m and a mesh size of 250 µm. The net was towed from the bow of a rigid inflatable boat using a metallic structure (Fig. S1) to prevent disturbance and contamination from the boat and to manage the presence of ice. The net was rinsed previously from its external side with abundant pressurized water to avoid contamination. Coordinates were recorded at the beginning and the end of each trawl (Table S1). A flowmeter was attached to the Manta Trawl to calculate the transect length, area, and volume of water sampled. We multiplied the transect distance, by the width (0.6 m) of the mouth of the manta, to estimate the total area sampled (Table S1). Also, we multiplied the latter by the approximate height of the trawl that was submerged during sampling (0.20 m) to estimate the total volume of water in which samples were collected (Table S2). The net was towed at a speed of 2–3 kn for periods of 10–30 min in each transect (Table S1). After this period, the net was raised on board and rinsed with pressurized seawater to accumulate the entire sample in the cod end and transferred to glass bottles of 1 L on board. Then, in the laboratory, samples were carefully filtered through a 125 µm sieve to ensure micro-litter retention and avoid contamination, and stored in glass bottles of 500 mL with filtered 50 % ethanol for further laboratory analyses.

2.2. Digestion procedure, litter extraction and characterisation

Once in the laboratory, samples were filtered through a 125 µm sieve and placed into a glass beaker by rinsing with filtered distilled water to process the entire sample. For the digestion, 3:1 (w/v) H₂O₂ 33 % was added to the beaker, which was rapidly covered with aluminium foil, and left at 40 °C overnight. The content was then filtered on a 1.2 µm pore glass fibre filter (GF/C Whatman 47 mm) with a glassware vacuum filtering system (Glassco®, All-glass filter-holder assembly). Filters were kept in Petri dishes and left to dry at room temperature until analysed. Filters were examined with a stereomicroscope (Olympus SZX10) connected to a digital camera (Olympus SC30) and litter items were visually identified. Pictures of each item were taken and processed through the Olympus CellSens Standard software. The type (fibre; fragment), size, and colour of each item were determined through detailed visual identification. Each colour category encompassed a range of similar shades. Items lacking any discernible colour were classified as transparent, while those displaying indistinct colour traces and visible signs of degradation were classified as weathered. The size of each item was

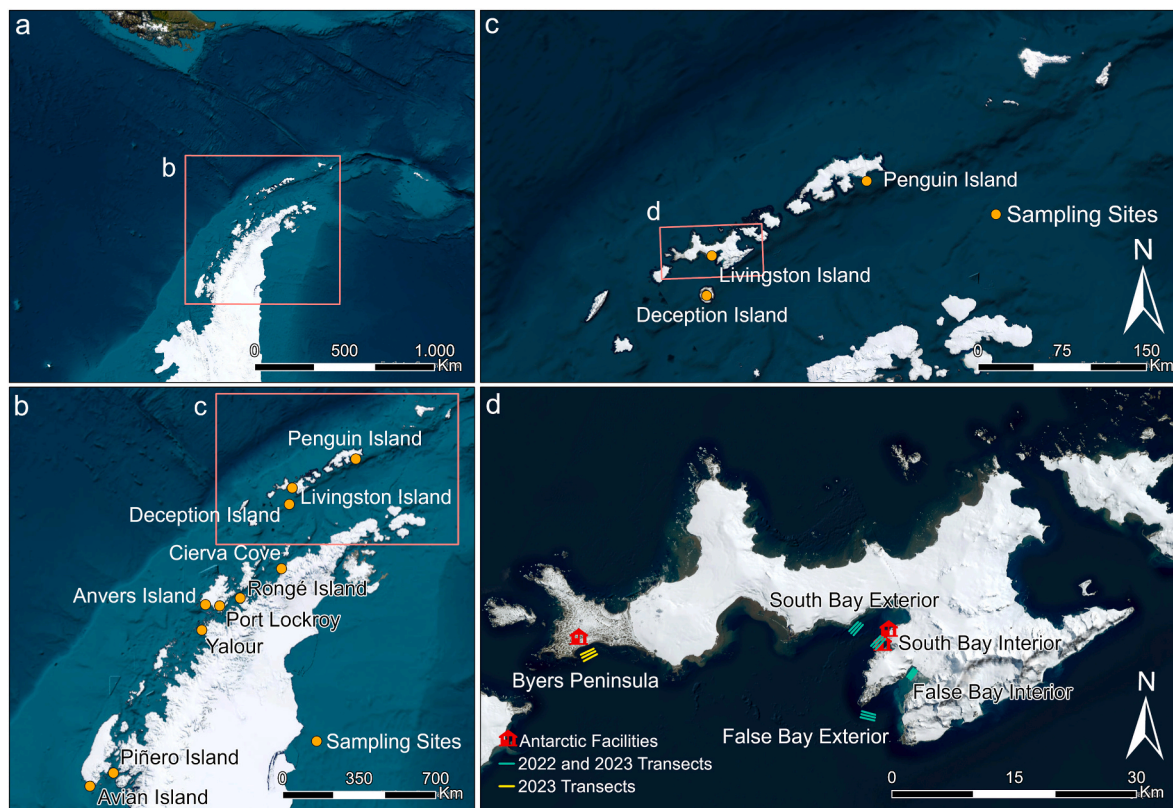


Fig. 1. Map of the sampling areas. a, Western Antarctic Peninsula with the relative location of the sampled area (red square); b, Western Antarctic Peninsula sampled area, with sampling points in orange, with the relative location of the South Shetland Islands (red square); c, South Shetland Islands sampled area, with sampling points in orange, with the relative location of Livingston Island (red square); d, Livingston Island schematic distribution of the sampling transects. Transects sampled during both campaigns (2022 and 2023) are shown in sky blue, while transects unique to the second campaign (2023) are shown in yellow. Map constructed with ArcGIS software (v 10.8).

measured along its longest axis. Items <5 mm were categorized as micro-litter, while those ranging from 5 to 20 mm were categorized as meso-litter, according to published definitions (Ryan et al., 2019; Galgani et al., 2023). We further classified the items into size ranges of 0.5 mm, from 0 mm to 18.5 mm. Items smaller than 0.25 mm were excluded to avoid inaccuracies, as the manta net mesh size was 250 μ m.

2.3. Polymer identification of the marine litter

Analysis of the micro-litter was conducted by using imaging-Fourier Transform Infrared (FTIR) at the CCiT-UB Services at the Universitat de Barcelona. All putative items, were handpicked from the filter papers using ultrafine laboratory tweezers and placed between two CaF_2 slides. Thermo SCIENTIFIC NICOLET iN10 MX for transmission in two CaF_2 slides with an MCT detector of 50 μ m of overture, 4 cm^{-1} spectral resolution and 4000 to 800 cm^{-1} spectral range was used. Polymer composition was determined by comparing the obtained profiles to the CCiT-UB OMNIC polymer spectral database.

2.4. Contamination protocol and quality control

To prevent contamination during the process, the samples were manipulated in a contamination-restricted fume hood. The samples were always handled by the same person, who wore a 100 % cotton white lab coat and thoroughly washed laboratory gloves before each analysis. The work surface was cleaned before and after each sampling procedure. Whenever possible, the materials used were primary glass and metal. This material was cleansed using a 1 % HNO_3 solution and rinsed several times with filtered distilled water. Quality control steps were followed in accordance with the protocol described by Monrás-Riera et al. (2023),

incorporating additional refinements to further optimize the process.

To quantify and account for potential contamination during sample processing, procedural blanks were carried out using Milli-Q water as a control, following the same sampling steps as the actual samples. Milli-Q water (~ 750 mL), previously stored in cleaned 1 L glass bottles, was transferred to cleaned 1 L glass bottles on board during the cruise. The control samples underwent the same procedures as the actual samples, including filtration through a 125 μ m sieve and storage in filtered 50 % ethanol. In the laboratory, the control samples were subjected to the digestion process, litter extraction, and characterisation. Additionally, a Petri dish containing moistened filter paper was exposed under the hood during sample handling and near the dissection microscope during visual sorting. This served as a control to monitor airborne contamination during laboratory work. All control samples were processed using the same methodology applied to seawater samples. To account for external contamination, each sample was conservatively adjusted by subtracting the number of items identified in the corresponding controls, based on their shape, colour, and polymer composition (Tables S3 and S4) (Miller et al., 2021; Monrás-Riera et al., 2023; Munno et al., 2023).

2.5. Statistical analyses

2.5.1. Litter distribution along the Western Antarctic Peninsula

To assess the distribution patterns and characteristics of the items, the number of debris items was standardized to the filtered water volume (m^3) of each transect. To examine the distribution of litter along the WAP, data were analysed using the non-parametric Kruskal-Wallis rank-sum test, with each study site treated as a factor and the transects as replicates.

To further study the litter distribution along the WAP and their

potential source influences, we considered the following variables. 1) *Latitude*, used as an indicator of broad-scale activity. Latitude encompasses marine and terrestrial activities, which are mostly concentrated around the South Shetland Islands and decrease towards higher latitude zones (Aronson et al., 2011; Tejado et al., 2022; Da Silva et al., 2023; Albarrán et al., 2024). 2) *Nearest station distance (m)* and 3) *Nearest station capacity* (maximum personnel capacity), are included as indicators of local activity. The distance was analysed to study the potential litter reach from the nearest station, while capacity was included to explore whether personnel abundance influences debris contamination (COMNAP, 2024). 4) *Tourism*, taken as an indicator of local marine and land activity. Using IAATO site visit activity data for 2022–2023 (International Association of Antarctica Tour Operators, 2024), we aimed to examine the influence of tourist load. 5) *Nearest historical site distance (m)*, referring to historical Antarctic stations that may be visited by tourists. These sites, recognized for their cultural and historical significance, are included as a proxy for local touristic impact (COMNAP, 2024). 6) *Number of stations within a 10 km area*, is used as an indicator of local activity since it approximates human activities occurring near the studied beach. 7) *Number of stations within a 100 km area*, used as an indicator of global activity, serves as a proxy for broader activities occurring around the studied site (Table 1).

A general linear model was conducted to investigate potential relationships between the explanatory variables (independent variables) and items abundance (dependent variable). This analysis used the average densities of each sampling site across the WAP. To address multicollinearity, the analysis was performed using two separate models: 1) *Latitude and Distance model*, which included latitude, distance to the nearest station, tourism, and historical site distance. 2) *Number of Stations model*, which included the number of stations within a 10 km and a 100 km radius, as well as nearest station capacity and tourism. These two models were chosen because latitude, distance to the nearest station, and historical site distance were highly correlated with the number of stations within a given area and to nearest station capacity (Pearsons correlation >0.70) when these variables were included together.

Furthermore, we investigated whether marine litter abundance differed specifically between the South Shetland Islands sites and the more southern sampling sites using a non-parametric pairwise Wilcoxon rank-sum test. All statistical tests were conducted following standard procedures in ecological data analysis (Dytham, 2011) and were carried

out using R version 4.1.2 (RStudio).

2.5.2. Litter in Livingston Island

To evaluate temporal dynamics at LV, we conducted a non-parametric permutational analysis of variance (PERMANOVA), using data from two cruises (2022 and 2023) and the same LV sampling sites as fixed factors and transects as replicates, to assess significant differences in debris abundance between campaigns and sampling sites. We further analysed variations between years in the litter characteristics (size ranges, colours, and polymer types) by performing a non-parametric Kruskal-Wallis rank-sum test with sampling year as a factor and each characteristic group as replicates. To verify assumptions of normality and homogeneity of variance, we applied the Shapiro-Wilk test and Levene's test, respectively.

3. Results

3.1. Abundance and characteristics of marine litter along the Western Antarctic Peninsula

In the 2023 campaign a total of 471 items were retrieved from all samples analysed along the Western Antarctic Peninsula (WAP), collected across a surface area of 27661 m² and 5569 m³ of filtered seawater. Nearly all samples contained marine litter items (95 %; n = 38), with only two transects from Port Lockroy, and two from Piñero Island free from marine debris (5 %). Concentrations ranged from 0 to 0.391 items m⁻³ (0–0.079 items m⁻²) per transect with an average of 0.086 ± 0.082 items m⁻³ (0.017 ± 0.016 items m⁻²) (Table S2). Particularly, considering all Livingston Island (LV) 2023 sampling sites, the average concentration was 0.116 ± 0.033 items m⁻³ (0.023 ± 0.015 items m⁻²) (Table S5). Most of the debris found in the study was located within LV South Bay Interior (0.193 ± 0.037 items m⁻³; 0.039 ± 0.021 items m⁻²), although the highest litter abundance observed in a single transect was at Penguin Island (0.391 items m⁻³; 0.032 ± 0.040 items m⁻²). In contrast, the sites with the lowest observed concentrations were Port Lockroy and Piñero Island (0.019 ± 0.033 items m⁻³; 0.004 ± 0.007 items m⁻²) (Table 1; Fig. 2; Table S5). In general, fibres were the most abundant type of litter, accounting for 91.30 % (n = 430), with an average of 0.078 ± 0.078 fibres m⁻³ (0.016 ± 0.016 fibres m⁻²). Fragments represented 8.70 % (n = 41), averaging 0.008 ± 0.015 fragments m⁻³ (0.002 ± 0.003 fragments m⁻²).

Table 1

Data on the abundance of marine litter items per unit area and volume, and on the variables used to investigate the main factors influencing litter distribution, extracted from the Council of Managers of National Antarctic Programs (COMNAP, 2024) and the International Association of Antarctica Tour Operators (IAATO, 2024).

Beach	Items m ⁻²	Items m ⁻³	Nearest Antarctic Facility	Latitude	Station distance (m)	Station max capacity (n° people)	Tourism load (Total visits)	n° Stations 10 km area	n° Stations 100 km area	Historical Sites distance (m)
Penguin Island	0.032 ± 0.040	0.161 ± 0.199	Comandante Ferraz	62.096	26592.93	66	1460	0	14	8878.24
Livingston Island	0.023 ± 0.015	0.116 ± 0.033	BAE Livingston	62.648	6723.60	50	22	2	16	64152.45
Deception Island	0.016 ± 0.010	0.080 ± 0.048	BAE Gabriel de Castilla	62.983	2910.37	36	22632	2	10	8332.70
Cierva Cove	0.010 ± 0.007	0.050 ± 0.033	Primavera	64.155	2356.07	18	14591	1	1	47755.28
Rongé Island	0.006 ± 0.003	0.029 ± 0.014	Gabriel Gonzalez Videla	64.673	21556.47	15	1371	0	5	19920.25
Anvers Island	0.022 ± 0.010	0.108 ± 0.049	Palmer	64.76	10122.80	46	5115	1	6	1550.50
Port Lockroy	0.004 ± 0.007	0.019 ± 0.033	Yelcho	64.817	998.56	28	28752	1	6	9503.75
Yalour	0.011 ± 0.016	0.057 ± 0.049	Vernadsky	65.22	3881.88	24	8998	1	5	9852.02
Piñero Island	0.004 ± 0.007	0.019 ± 0.033	Dirck Gerritsz Laboratory	67.569	11911.30	10	0	0	3	31441.51
Avian Island	0.019 ± 0.014	0.096 ± 0.070	Carvajal	67.7604	6301.05	46	0	1	3	3075.01

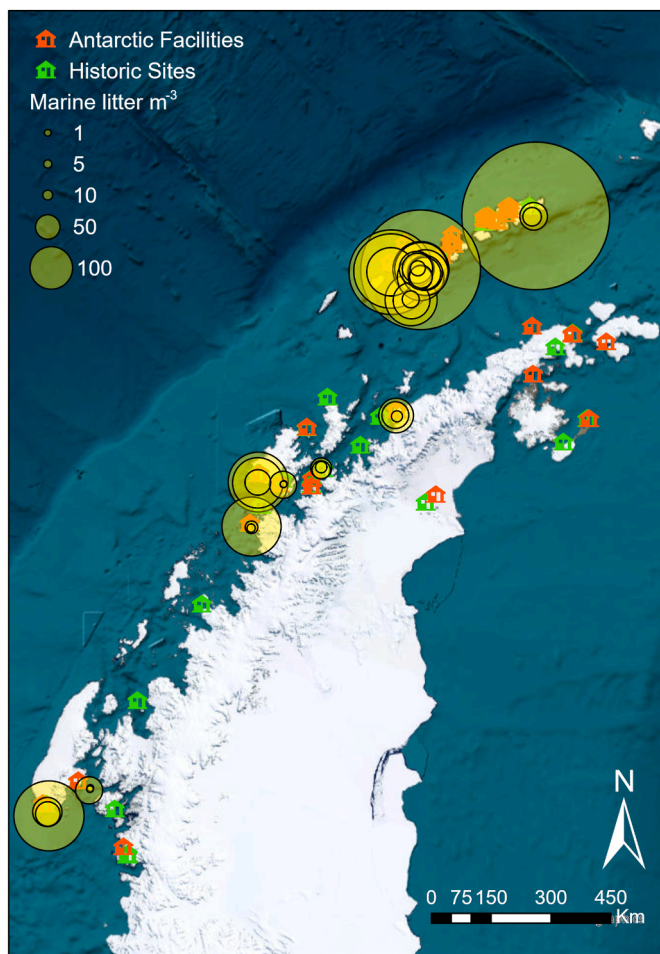


Fig. 2. Distribution of marine litter abundances across sampled transects along the Western Antarctic Peninsula campaign (2023). The size of the yellow circles represents the relative abundance of marine litter (item m^{-3}). Orange houses denote the locations of Antarctic facilities, and green houses denote the locations of Historic Antarctic stations (COMNAP, 2024). Map constructed with ArcGIS software (v 10.8).

All samples were successfully characterized by size and colour. Most fibres were micro-litter (67.92 %), while the remaining were meso-litter (32.08 %). In general, the 0.5–0.99 mm size range was the most predominant (18.37 %; $n = 79$), followed by 1–1.49 mm (10 %; $n = 43$) and 5–5.49 mm (7.44 %; $n = 32$) (Fig. 3). Fragments were predominantly micro-litter (88.24 %), with a smaller proportion of meso-litter (11.76 %). The most common size ranges among fragments were 0.25–0.49 mm (43.92 %; $n = 18$) and 0.5–0.99 mm (31.71 %; $n = 13$) (Fig. 3). Fibres colours were principally transparent (45.02 %; $n = 199$) and black (33.71 %; $n = 149$). Fragments, instead, were mainly black (26.83 %; $n = 11$) and weathered (21.95 %; $n = 9$) (Fig. 4).

A total of 442 items were analysed by FTIR techniques. We were able to analyse 93.63 % of the items found due to the limitations imposed by technical constraints. FTIR revealed most items were plastics polymers (92.97 %; $n = 411$) whereas the rest were cellulosic fibres (7.03 %; $n = 31$). In general plastic fibres ($n = 372$), were mostly composed of polyester (PET); 79.03 %; $n = 294$), followed by nylon (16.94 %; $n = 63$), acrylonitrile (3.76 %; $n = 14$), and polyetherurethane (0.27 %; $n = 1$). As for microplastic fragments ($n = 39$), polyurethane (20.51 %; $n = 8$) was the main polymer, followed by nylon (15.38 %; $n = 6$), ethylene vinyl acetate (PEVA; 15.38 %; $n = 6$), polyether urethane (12.82 %; $n = 5$), Tygon polymer (12.82 %; $n = 5$), polypropylene-polyethylene (7.69 %; $n = 3$), poly methyl methacrylate (5.13 %; $n = 2$), urethane alkyd (5.13 %; $n = 2$), acrylic acid (2.56 %; $n = 1$), and polypropylene (2.56 %;

$n = 1$) (Fig. 5; Table S6). Livingston was the main site presenting PET, particularly at the interior of South Bay ($n = 70$). Nylon was principally found in Avian Island ($n = 24$), Deception Island ($n = 17$) and LV, specifically in the exterior of South Bay ($n = 8$). For cellulose, the main site was Byers ($n = 17$), and for polyacrylonitrile Byers ($n = 3$), Penguin Island ($n = 3$), and LV stations, mainly in the interior of False Bay ($n = 3$). The rest of the polymers were more evenly distributed.

3.2. Abundance and characteristics of marine litter on Livingston Island

In the 2022 campaign a total of 427 items were retrieved from all samples analysed, collected across a surface area of $5.56 \cdot 10^{-3} \text{ km}^2$ and 1650 m^3 of filtered seawater. All samples collected presented marine litter items. Concentrations ranged from 0.021 to $0.466 \text{ items m}^{-3}$ ($0.005\text{--}0.117 \text{ items m}^{-2}$) per transect with an average of $0.259 \pm 0.164 \text{ items m}^{-3}$ ($0.065 \pm 0.041 \text{ items m}^{-2}$) (Table S2). Most of the debris was found in the exterior of False Bay ($0.418 \pm 0.026 \text{ items m}^{-3}$; $0.105 \pm 0.007 \text{ items m}^{-2}$) whereas the less contaminated sampling site was the interior of False Bay ($0.110 \pm 0.079 \text{ items m}^{-3}$; $0.028 \pm 0.020 \text{ items m}^{-2}$; Table S5). In general, fibres were the most abundant debris representing 90.16 % ($n = 385$) with an average of $0.234 \pm 0.153 \text{ fibres m}^{-3}$ ($0.059 \pm 0.038 \text{ fibres m}^{-2}$) followed by fragments which represented 9.84 % ($n = 42$) of the found items, with an average of $0.024 \pm 0.024 \text{ fragments m}^{-3}$ ($0.006 \pm 0.006 \text{ fragments m}^{-2}$).

We successfully characterized all samples by size and colour. Fibres were predominantly micro-litter (69.32 %; $n = 296$), while the remaining were meso-litter (30.68 %; $n = 131$). The most common size range was 0.5–0.99 mm (18.96 %; $n = 73$), followed by 1–1.49 mm (12.21 %; $n = 47$) and 5–5.49 mm (11.69 %; $n = 45$) (Fig. 3). All fragments were micro-litter, with the 0.25–0.49 mm size range being the most frequent one (61.90 %; $n = 26$), followed by the 0.5–0.99 mm (26.19 %; $n = 11$) class range (Fig. 3). Fibres colours were principally black (44.42 %; $n = 171$) and transparent (39.22 %; $n = 151$), whereas fragments were mainly composed by blue (59.52 %; $n = 25$), followed by black (16.67 %; $n = 7$) and green colours (11.90 %; $n = 5$) (Fig. 4).

A total of 402 (94.15 %) items were analysed by FTIR techniques. FTIR revealed most items were plastic polymers (95.64 %; $n = 385$) whereas the rest were cellulosic fibres (4.36 %; $n = 17$). Plastic fibres ($n = 350$), were mostly composed of PET (57.43 %; $n = 201$), followed by nylon (32 %; $n = 115$), polyethylene (21 %; $n = 15$), acrylonitrile (2.57 %; $n = 9$), butyl rubber (2.57 %; $n = 9$), ethylene vinyl acetate (PEVA; 0.86 %; $n = 3$), fibreglass (0.29 %; $n = 1$), and polypropylene (0.29 %; $n = 1$). As for microplastic fragments ($n = 35$), nylon (65.71 %; $n = 23$) was the main polymer, followed by polyurethane (14.29 %; $n = 5$), polypropylene, polyethylene and alkyd resin (5.71 %; $n = 2$), and PET (2.86 %; $n = 1$) (Fig. 6; Table S7). Both South Bay sites were the principal sites presenting PET (Interior $n = 80$; Exterior $n = 83$). In False Bay interior nylon stood out ($n = 80$). In the case of cellulose, it was principally found in South Bay exterior ($n = 12$). The rest of polymers were more evenly distributed.

3.3. Distribution of litter along the Western Antarctic Peninsula

Marine litter abundance exhibited homogeneity across the WAP sampling sites, as the Kruskal-Wallis rank-sum test indicated no significant differences (Chi-squared = 22.139, p -value = 0.053). The GLM Latitude and Distance model (R^2 : 0.786; AIC: -37.22) showed a significant negative correlation between item abundance and both latitude (p -value = 0.013) and tourism (p -value = 0.026). The intercept was also significant (p -value = 0.011). The Number of Stations model (R^2 : 0.933; AIC: -48.79) revealed a significant positive correlation between the abundance of items and the nearest station capacity (p -value = 0.004). The remaining explanatory variables in both models were not significantly correlated (p -value > 0.05) (Table S8). Additionally, when comparing the South Shetland sampling sites to those at lower latitudes, the Wilcoxon rank-sum test revealed significant differences ($W = 110$; p -

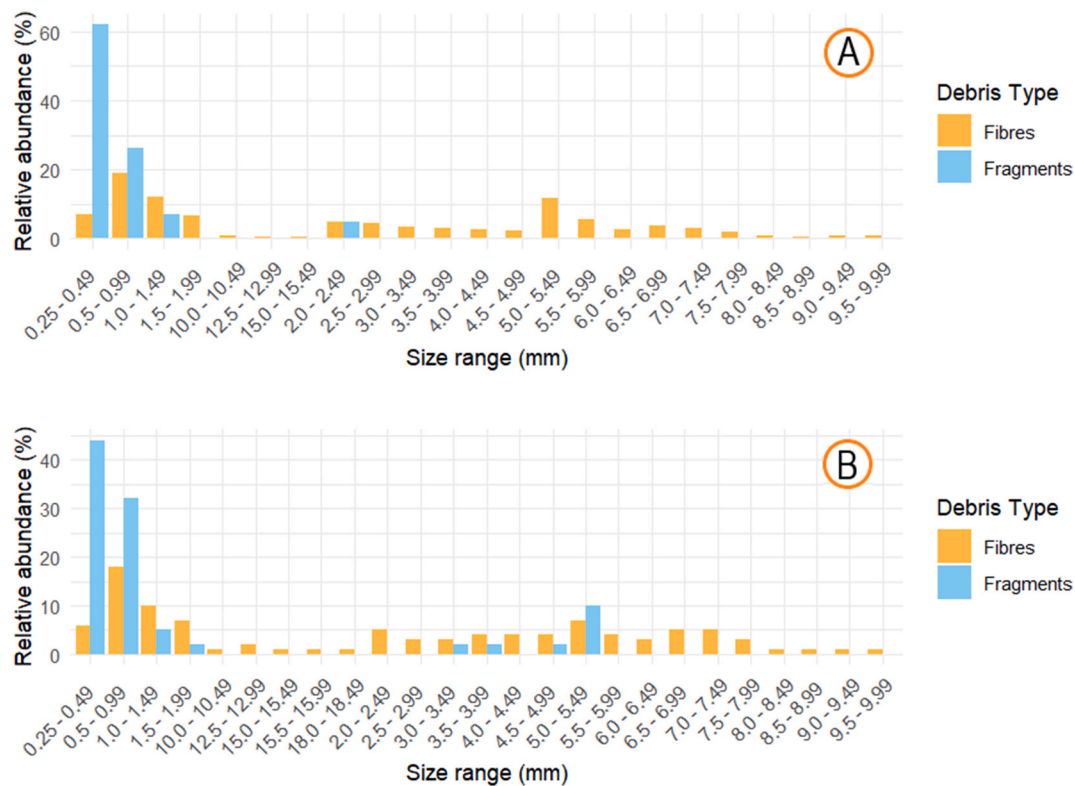


Fig. 3. A) Histogram of surface water marine litter along the Western Antarctic Peninsula (CHALLENGE-2, 2023) categorized into fibres ($n = 430$) and fragments ($n = 41$), by maximum size. B) Histogram of surface water marine litter of Livingston Island (CHALLENGE-1, 2022) categorized into fibres ($n = 385$) and fragments ($n = 42$), by maximum size. Data is represented as relative abundance (%) for each size group.

value = 0.006).

3.4. Temporal litter dynamics on Livingston Island

The temporal patterns of marine litter densities on LV revealed a significant decrease in litter abundance across campaigns (p -value = 0.002; Table S9). Our results also indicate that this decrease is homogeneous, as no significant differences among sampling sites were observed (p -value > 0.05; Table S7). Further analyses of the litter characteristics (polymer types, size ranges, and colours) showed no differences between years (p -value > 0.05; Table S10).

3.5. Quality assessment and control

A total of 74 items were found in the blanks during the 2022 campaign, of which 19 (25.68 %) were excluded from the samples due to matching either in visual identification or polymer composition (Table S3). All the items identified were fibres, predominantly black (70.48 %) and mainly composed of cellulose (76.19 %) (Table S4). During the 2023 campaign, 200 items were found in the blanks, and 43 (21.5 %) were excluded from the samples for the same reasons (Table S3). Most of the items were fibres (77.5 %), although fragments were also present (22.5 %). The majority were black in colour (78 %). In terms of polymer composition, control items were primarily cellulose (51.5 %), followed by PET (31.5 %) (Table S4). It is worth noting that the fibres were mostly cellulosic, likely textile microfibres, whereas the fragments comprised a broader range of polymers. These included black polyethylene fragments, likely originating from the manta trawl cod-end, and red and black paint fragments made of acrylonitrile, probably derived from the research vessel. All these items were conservatively excluded from the final counts.

4. Discussion

Our study provides novel insights into meso- and micro-litter waste in the Southern Ocean at two scales: broad-scale data collected along the Western Antarctic Peninsula (WAP) and focused temporal analysis on Livingston Island (LV; South Shetland Islands). This represents one of the widest surface water debris surveys conducted in the Antarctic environment, from 62° S to 67° S. However, there remains a strong need for additional data. In this context, we present new findings to enhance the understanding of the occurrence and distribution of marine litter on the surface layer of the water column across the WAP. Our results show a significant association between litter abundance and the intensity of local human activities, with latitude and nearby station personnel density emerging as significant factors influencing debris distribution. We identify the South Shetland Islands as an Antarctic hotspot for marine meso- and micro-litter waste and highlight the importance of long-term monitoring programmes to better assess temporal trends and the impacts of anthropogenic pressures in this remote region.

4.1. Marine litter along the Western Antarctic Peninsula

Along the WAP, marine litter was observed at every sampling site, though not consistently across all transects. The abundance of meso- and micro-litter ranged from 0 to 0.391 items m^{-3} per transect, with an overall mean of 0.086 ± 0.082 items m^{-3} . These findings align with the range of 0–0.56 items m^{-3} reported in a recent review of microplastic abundance in Antarctic surface waters; however, the same study reports a lower average abundance of 0.01 items m^{-3} (Gurumoorathi and Luis, 2023). Similarly, research around the Antarctic Peninsula reports lower average abundances: 0.013 ± 0.005 microplastics m^{-3} (Jones-Williams et al., 2020) and 0.008 microplastics m^{-3} (Lacerda et al., 2019), while an Antarctic circumnavigation survey found no microplastics (Kuklinski et al., 2019). These studies focused on microplastic abundances,

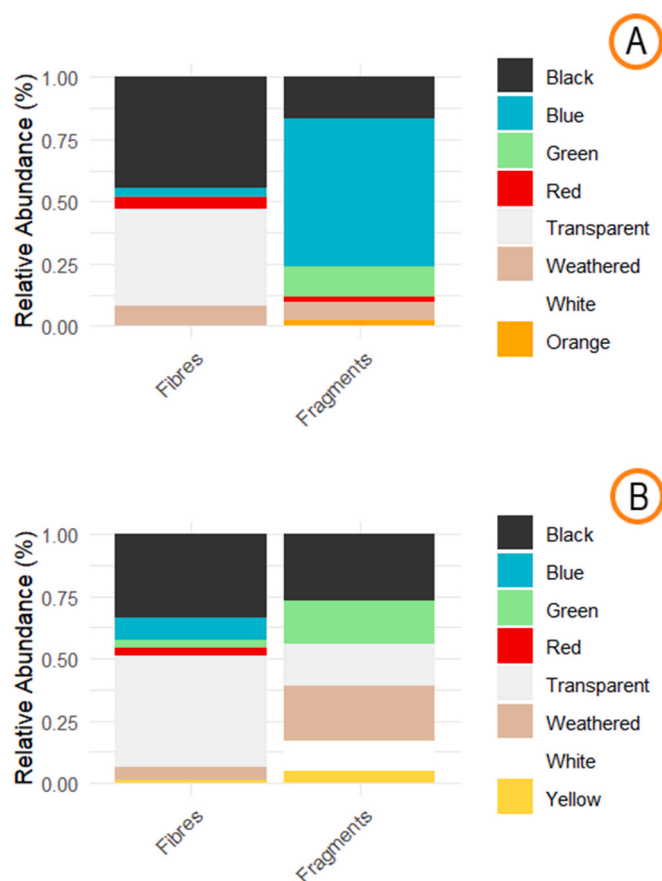


Fig. 4. A) Histogram showing the relative colour distribution of surface water marine litter along the Western Antarctic Peninsula (CHALLENGE-2, 2023) for fibres ($n = 430$) and fragments ($n = 41$). B) Histogram showing the relative colour distribution of surface water marine litter of Livingston Island (CHALLENGE-1, 2022) for fibres ($n = 385$) and fragments ($n = 42$). Data is represented as relative abundance (%) for each colour group.

excluding cellulosic items and mesoplastics, which could result in slightly lower waste abundances. In contrast, our study may have overestimated the average marine litter abundance along the WAP due to an uneven spatial distribution of sampling sites, with a notable concentration in the South Shetland Islands. This region has shown consistently higher litter abundances and, because it is overrepresented in our dataset, largely due to logistical constraints limiting sampling farther south, this likely biases the overall mean upward. Indeed, the highest litter concentration among WAP sites were all in the South Shetlands: South Bay interior (0.193 ± 0.037 items m^{-3}) and Byers Peninsula (0.174 ± 0.052 items m^{-3}) at Livingston Island, and Penguin Island (0.161 ± 0.199 items m^{-3}). These values align with previous reports from the Ross Sea (0.17 ± 0.34 items m^{-3}) (Cincinelli et al., 2017), the Ross Sea along Dumont d'Urville Sea, Davis Sea, and Prydz Bay (0.1 ± 0.14) (Zhang et al., 2022), and the same study area in LV (0.274 ± 0.196 items m^{-3}) (Monrás-Riera et al., 2023). These studies, conducted in coastal Antarctic areas, identified proximity to scientific stations as a major micro-litter source. Conversely, the sites with the lowest litter abundances in our study were Port Lockroy and Piñero Island (0.019 ± 0.033 items m^{-3}). Both locations are among the most remote and offshore sampling sites, with litter detected in only one of three transects. As mentioned before, similar abundances or sites without debris have been reported in studies around the Antarctic Peninsula, where most sampling sites were located offshore (Lacerda et al., 2019; Kuklinski et al., 2019; Jones-Williams et al., 2020), and also in the Wedell Sea (0.01 ± 0.01 microplastics m^{-3}), a scarce human activity region (Leistenschneider et al., 2021). As previous studies point out, our results also suggest that debris tends to accumulate nearshore, in areas characterised by weaker oceanic influence like fjords and outstanding anthropogenic activity (Jones-Williams et al., 2020; Leistenschneider et al., 2021; Onink et al., 2021; Zhang et al., 2022; Buckingham et al., 2022; Monrás-Riera et al., 2023; Garza et al., 2023; Antacili et al., 2024).

No significant differences were observed among sampling sites along the WAP, reflecting the considerable variability in globally observed marine litter abundance (Suaria et al., 2020a). Consequently, our results did not reveal any consistent spatial pattern. However, the analysis of explanatory variables related to potential meso- and micro-litter sources suggested that certain factors may partially explain the variability in

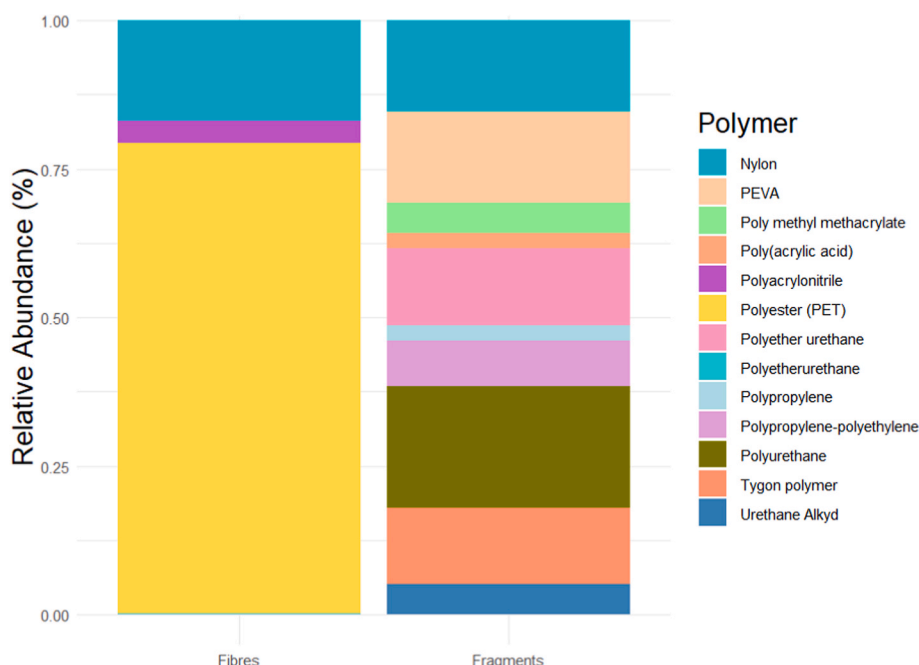


Fig. 5. Relative abundance of polymers on surface water along the Western Antarctic Peninsula identified by FTIR. Fibres ($n = 372$) and fragments ($n = 39$).

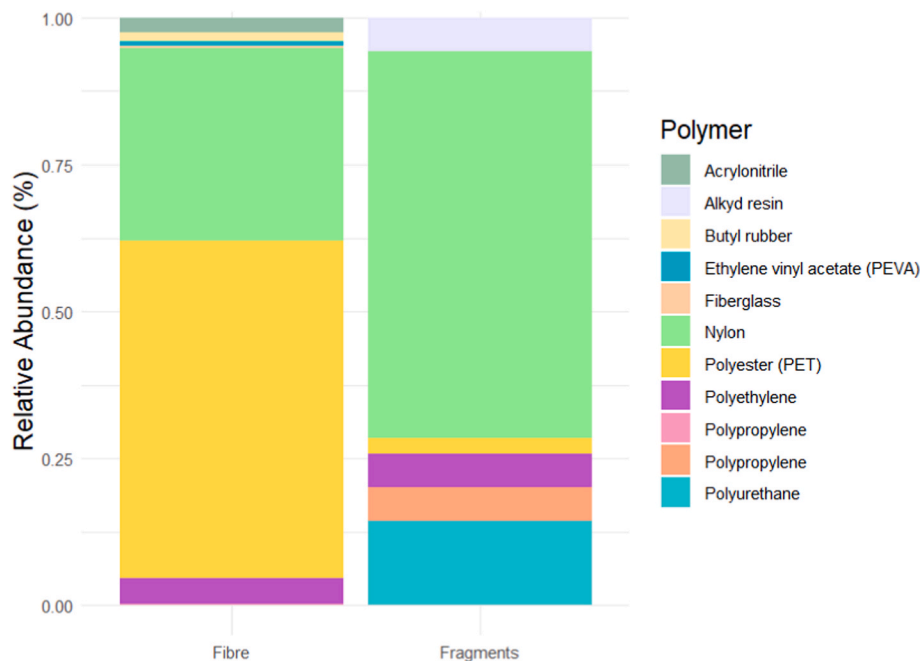


Fig. 6. Relative abundance of surface water plastics in Livingston Island (CHALLENGE-1, 2022) identified by FTIR, for fibres (n = 230) and fragments (n = 35).

item abundance observed in this study. For the Latitude and Distance model, latitude emerged as the most significant variable, showing a negative correlation with litter abundance, suggesting that more litter is likely to be found at lower latitudes. This probably reflects the higher concentration of broad-scale marine and terrestrial Antarctic human activities at lower latitudes, which are significant sources of waste. Additionally, lower latitudes may be more prone to receiving litter from distant sources, also contributing to higher concentrations of marine debris (Waller et al., 2017; Allen et al., 2019; Caruso et al., 2022). A significant negative correlation was also observed between tourism load and litter abundance, suggesting that tourism may not be a primary contributor to pollution in the studied area, perhaps because tourist operators are currently following stricter environmental practices. Regarding the Number of Stations model, the only significant variable was the nearest station's maximum personnel capacity, which showed a positive correlation, highlighting the influence of high human densities on land-based waste generation and underscoring Antarctic facilities as a major source of marine litter.

Generally, we hypothesised that litter levels would be higher near research stations and in areas with greater human presence, including tourist activity. While our results support elevated pollution near stations and sites with higher human density, the expected increase linked to tourism was not observed, maybe because tourist visits are brief, highly regulated, and conducted with strong environmental awareness, unlike the continuous presence and activities at research stations. Thus, our results underscore the importance of proper waste management by all parties involved and the need for stringent guidelines and environmental regulations to minimise their impact on the Antarctic environment. This further emphasises the pivotal role of the Antarctic Treaty and the Protocol on Environmental Protection. However, as demonstrated in the Mediterranean and Baltic Seas, effective measures require not only legal frameworks but also structured planning and coordination to prevent further environmental harm. In Antarctica, where the Antarctic Treaty System shows regulatory and infrastructural limitations, stronger international cooperation, targeted remediation strategies, and the application of problem-solving tools to overcome logistical and financial barriers are needed (Hodgson-Johnston et al., 2017; Battisti et al., 2020; Frantzi et al., 2021; De-la-Torre & Santillán, 2025).

Furthermore, litter abundance was significantly higher at sites in the

South Shetland Islands compared to those at higher latitude sites, suggesting that this region may serve not only as a reservoir but also as a hotspot for Southern Ocean marine debris. In contrast, more remote and inaccessible higher-latitude sites were more frequently debris-free. Therefore, our results support our hypothesis: areas with intense land-based and broad-scale human activities, such as the South Shetland Islands, exhibited elevated levels of litter. Thus, the nearshore waters surrounding the South Shetland Islands appear particularly vulnerable to litter contamination (Anfuso et al., 2020; Monrás-Riera et al., 2025).

4.2. Temporal litter abundance dynamics in Livingston Island

Over two years, our study revealed a significant decrease in meso- and micro-litter along the southern coastline of Livingston, with litter abundances declining from 0.235 ± 0.152 items m^{-3} to 0.116 ± 0.033 items m^{-3} . This trend is particularly relevant considering a previous study conducted between 2018 and 2019 in the same area reported 0.274 ± 0.196 items m^{-3} , similar to the litter abundances we observed in 2022 (Monrás-Riera et al., 2023). Marine debris was observed at all sampling sites and transects during both campaigns, although no significant differences in litter abundance were detected between sites across the years. Furthermore, no significant changes were observed in litter characteristics. Based on our results, we hypothesize that this reduction may reflect sampling variability influenced by environmental factors and seasonal dynamics, including hydrodynamic conditions. In 2022, notably higher abundances were observed in the outer area of False Bay (0.418 ± 0.026 items m^{-3}), while in 2023, most litter was found in the inner part of South Bay (0.193 ± 0.037 items m^{-3}), at the sampling site in near the Spanish and Bulgarian research stations. Thus, the lower litter abundance observed in 2023 may be related to the sampling time, which took place from January to early February, whereas in 2022 it occurred from February to early March. Earlier in the Antarctic campaign, inputs of marine litter from human activities are likely to be lower and more localised, and the influence of debris associated with deglaciation and oceanic currents may also be limited. As the season progresses, meso- and micro-litter in surface waters may become more widespread across the southern waters of LV (Isobe et al., 2017; Lacerda et al., 2019; Kelly et al., 2020; Mountford and Morales Maqueda, 2021). Moreover, as the litter presented similar

characteristics across both years and previous studies in the same area, this may suggest that the sources of pollution have remained consistent, most likely linked to local Antarctic activities (Monrás-Riera et al., 2023). Overall, further long-term studies are essential to enhance the understanding of the temporal dynamics of marine litter in the South Shetland Islands and the broader Southern Ocean, as this remains a significant knowledge gap.

4.3. Meso- and micro-litter characterisation

In general, the totality of our results showed a predominance of fibres (>90 %) over fragments (<10 %), following global and Southern Ocean trends (Suaria et al., 2020a; Zhang et al., 2022; Monrás-Riera et al., 2023; Antacli et al., 2024). Of those anthropogenic particles, we observed a predominance of the small size range, mainly 0.5–1.49 mm for fibres and principally 0.25–0.49 mm for fragments, which is in agreement with current Antarctic reports (Suaria et al., 2020b; Leitschneider et al., 2021; Zhang et al., 2022; Monrás-Riera et al., 2023). However, we also observed a considerable amount of fibres ranging from 5 to 5.49 mm and even larger ones along the WAP. Thus, our results could also point to fresh debris, which could result in increased debris in the future due to continuous fragmentation and accumulation, as observed in the Davis Sea (Zhang et al., 2022).

We observed a high diversity of colours among the marine litter, with transparent and black being the most predominant, consistent with previous Antarctic studies on surface water microplastics (Lacerda et al., 2019; Jones-Williams et al., 2020; Monrás-Riera et al., 2023; Antacli et al., 2024). Although little information can be obtained by colours itself, the majority of the colours appeared fresh rather than weathered, with weathered items accounting for only around the 7 % of debris found across both campaigns. This suggests that most of the anthropogenic particles had probably spent little time in the water, indicating nearby waste sources.

We found an outstanding majority of microplastics over cellulosic particles in contrast with similar global studies and in the South Shetland Islands (Monrás-Riera et al., 2023; Antacli et al., 2024; Suaria et al., 2020a). Those primarily consisted of PET and nylon for fibres, and nylon and polyurethane for fragments, which is in line with global and Antarctic surface water trends (Suaria et al., 2020a; Gurumoorthi and Luis, 2023). These polymers are among the most common debris types in the oceans, particularly PET fibres, which are widely used in the textile industry and frequently discharged through wastewater and laundry processes (Napper and Thompson, 2016; Napper et al., 2023). Nylon is similarly associated with the textile industry and is also a key material in maritime gear (Li et al., 2016). In this study, such debris was predominantly observed at LV, specifically at the site located in front of the island's research stations, during both sampling years. This finding is significant, as previous studies have highlighted the role of wastewater treatment stations as a major point source of marine debris, especially synthetic fibres from clothes washing (Browne et al., 2011; Napper and Thompson, 2016; Waller et al., 2017; Kalnina et al., 2022; Sun et al., 2019). Recent evidence further suggests that atmospheric deposition of fibres, generated during textile wear, is likely the primary contributor of fibres to the environment (De Falco et al., 2020; Napper et al., 2023). Furthermore, similar fibres to those found in our study have been identified in previous studies near other Antarctic research stations (Cincinelli et al., 2017; Zhang et al., 2022; Bergami et al., 2023). However, it is also important to acknowledge the role of long-range transport mechanisms, such as atmospheric fallout and oceanic currents, in contributing to Antarctic marine litter (Waller et al., 2017; Caruso et al., 2022; Allen et al., 2019). Overall, the predominance of black and transparent, mainly made of polyester and nylon, in our samples strongly points to local human activities as the primary source, including those involving vessels, such as fisheries, military, tourism, and research. This pattern has been consistently observed in Antarctic marine debris surveys since their inception and is corroborated by the

findings of this study (Convey et al., 2002; Almela and Gonzalez, 2020; Anfuso et al., 2020; Rota et al., 2022; Caruso et al., 2022; Monrás-Riera et al., 2023; Vesman et al., 2024).

5. Conclusions

This study presents one of the most extensive assessments of meso- and micro-litter in the surface waters of the Southern Ocean, spanning from 62°S to 67°S, with a detailed focus on Livingston Island. Marine litter was found at all sampling sites, indicating its widespread distribution even in remote Antarctic waters. While concentrations were low at high-latitude sites with limited human activity, significantly higher levels were recorded in nearshore areas such as the South Shetland Islands, where land-based and maritime activities converge. Sheltered environments like fjords and coastal zones appeared to act as accumulation areas, influenced by reduced oceanic flushing and local human presence. The South Shetland Islands emerged as a potential Antarctic hotspot for marine litter, likely due to the proximity of multiple Antarctic stations and frequent vessel traffic. Litter abundance showed strong associations with human-related variables, particularly latitude and the personnel capacity of nearby facilities. The predominance of synthetic fibres, mainly black and transparent polyester and nylon, suggests local sources, including operations related to science, tourism and fisheries. These findings highlight the need for sustained and expanded monitoring to detect long-term trends, capture interannual variability, and avoid seasonal biases. Improved waste management strategies and international collaboration are critical to reducing the input of litter into these fragile ecosystems. Such efforts are essential to support conservation goals and strengthen environmental governance under the Antarctic Treaty.

CRedit authorship contribution statement

Pere Monrás-Riera: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luis Francisco Ruiz-Orejón:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Carlos Angulo-Preckler:** Writing – review & editing, Supervision, Conceptualization. **Rafael Sardá:** Writing – review & editing, Supervision, Project administration. **Conxita Avila:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization.

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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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envres.2025.122560>.

Data availability

Data will be made available on request.

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