microplastics

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Omnipresence of Microplastics in Coastal Antarctic Sediments: Evidence or Assumption?

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Abstract

With the global increase in microplastic pollution, even environments considered pristine have shown signs of being affected by these contaminants. In this context, it becomes essential to conduct studies that identify and quantify the presence of microplastics in remote regions such as Antarctica. This continent is particularly relevant due to its low anthropogenic influence and its essential role in regulating planetary ecosystems and biodiversity. In this study, 49 Antarctic samples were analyzed using pretreatment techniques with NaCl and $ZnCl_2$ saline solutions, followed by fluorescence microscopy using Nile Red dye to estimate the microplastic abundance index. Both solutions showed good performance in the separation and identification of particles. Approximately 37% of the samples showed contamination by potential microplastics (PMPs), with a higher concentration of particles retained on paper filters and fibers observed in the supernatants. The results indicate that the presence of MPs in Antarctica is irregular and not ubiquitous, differing from other studies that suggest a wider distribution. It is speculated that the observed contamination results from oceanic transport from other regions of the planet and from sources associated with human activities on the Antarctic continent (e.g., tourism and research).

Keywords: fluorescence microscopy; plastic pollution; polar region; contamination

1. Introduction

Antarctica is considered a pristine environment, largely isolated from most anthropogenic disturbances. Several studies indicate that the increase in human activities, such as tourism and scientific research, can introduce various contaminants [1–4]. One of the contamination indicators that has been increasingly discussed in recent studies is the presence of microplastics (MPs) [5,6].

The impact of MPs in Antarctica differs from other regions due to the continent's geographic isolation and oceanographic and cryospheric barriers, which constrain the transport and deposition of particles (e.g., ocean currents and sea ice dynamics). Thus, the introduction of MPs into the Antarctic environment may be associated with some known sources, including the use of synthetic clothing by researchers and tourists. In this context, scientific activities—such as expeditions, the operation and maintenance of research stations, and seasonal field campaigns—require the continuous transport and use of materials and equipment, which can inadvertently contribute to the release and

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dispersion of contaminants, including microplastics, into this environment [7,8]. In many cases, these contaminants can be preserved for long periods due to the extreme cold and the presence of ice, which can slow down their degradation [9–11]. The impacts of MPs in Antarctica can vary from environmental pollution to stress in birds and other animals that ingest them, and they may even be transferred along the food chain [12,13].

The identification and quantification of MPs show high variability, both in the results obtained and in the methodologies applied. Among the main factors contributing to this inconsistency, there is the wide diversity of measurement units used to detect the presence of MPs in soils and marine environments, such as g/km, particles/m^2, items/km^2, particles/L, and others. This methodological heterogeneity hinders direct comparison between studies conducted in different regions of the world and constitutes one of the greatest challenges for consolidating scientific knowledge on MPs [14–18]. Due to the lack of standardization and the multiple measurement approaches, some authors describe MPs as ubiquitous contaminants, suggesting that they are globally distributed—a perception reinforced by the detection of these materials in various areas of Antarctica [11,19–21]. The literature indicates that MPs have been detected mainly in specific Antarctic locations, particularly ice-free coastal areas associated with research stations, logistics, and tourism [8,22,23]. In contrast, much of the Antarctic interior and remote regions show no detectable MPs or only very low and spatially inconsistent concentrations, indicating a heterogeneous continental distribution [24,25]. In this context, the improvement and refinement of existing analytical techniques become indispensable to increase precision, reliability, and scientific acceptance in the detection of MPs across different environmental matrices [26,27].

To address the challenges associated with the quantification and identification of MPs, fluorescence microscopy (FM) is commonly used as a complementary technique to spectroscopic approaches and is well established within the scientific community. This potential stems from the use of the Nile Red dye, whose affinity for plastic materials enables selective staining and preferential visualization of particles with a high likelihood of being MPs [28,29]. The technique involves using saline solutions—with NaCl and $ZnCl_2$, among others, the most commonly used—to promote density-based separation of MPs [30,31]. However, the diversity of polymers and the lack of standard procedures still pose significant challenges, especially in the determination of the most suitable saline solution for each type of sample [32–34]. Furthermore, this technique presents limitations due to interference from other materials with similar chemical composition which may also be stained by Nile Red, leading some authors to classify the detected particles as PMPs rather than confirmed MPs [35–37].

It is conjectured that different saline solutions, such as NaCl and $ZnCl_2$, when used in combination with FM are capable of identifying MPs in sediment samples from Antarctica, especially when associated with appropriate pretreatment techniques. This approach would allow the validation of MP occurrence in an environment considered pristine, even if distributed heterogeneously due to localized human activities (e.g., near scientific stations and tourism) and environmental transport processes. This study aims to apply FM to optimize the identification and characterization of microplastics through the comparison of two saline solutions, seeking to enhance the efficiency and precision of the process and to enable a more reliable initial screening of particles with plastic potential.

2. Materials and Methods

2.1. Sampling Area

The sampling was conducted on the Antarctic continent during the austral summer (December 2023), covering areas of the Maritime and Peninsular regions, as shown in Figure 1. In the Maritime region, samples were collected in the South Shetland Islands,

specifically on Keller Peninsula (425,809 m E, 3,116,560 m S), where the Comandante Ferraz Antarctic Station is also located (427,329 m E, 3,115,898 m S). These areas are located between Bransfield Strait and the Drake Passage, the region that separates the southern tip of South America from the Antarctic Peninsula. This geographic location is considered strategic, as it lies within a zone of convergence of oceanic and atmospheric currents. In the Peninsular region, sampling was conducted on James Ross Island (459,077 m E, 2,911,765 m S) and Vega Island (472,569 m E, 2,914,941 m S), an area that extends into the Antarctic continent. Consequently, the maritime regions are more directly exposed to influences from the Atlantic and Pacific Oceans, whereas the Peninsular regions are somewhat protected by the continent and are also characterized by sea ice formation during most of the year.

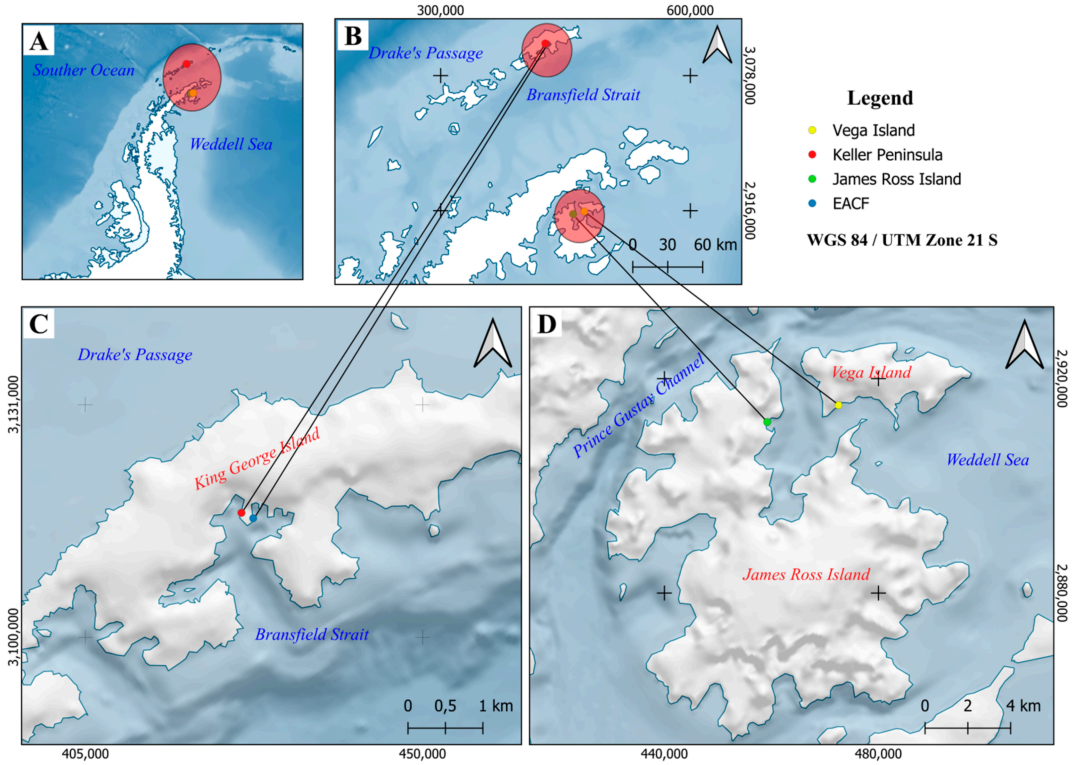

Figure 1. Location of the study area. (**A**) Location of the study area in the Maritime and Peninsular regions of Antarctica (**B**). Regional detail showing the sampling areas. (**C**). Maritime region: South Shetland Islands. (**D**). Peninsular region: James Ross Island and Vega Island.

2.2. Sample Processing and Extraction of Microplastics

The samples were collected within an area delimited by a 0.25 m^2 polygon, maintaining approximately 3.0 m between sampling points and a depth of 2 cm, meaning approximately 300 g of material was collected per sample location. At the laboratory, this material was subsampled to 60 g for every analysis, as shown in Figure 2. The sampling points were located along the upper high-tide line, and the collected material was stored in paper bags and aluminum containers. Subsequently, the samples were transported from Antarctica to Brazil in a Brazilian Navy vessel as part of the 42nd Antarctic Operation (OPERANTAR XLII). In the laboratory, the opening and processing of the samples were carried out under a laminar flow hood previously cleaned with 70% alcohol and exposed to UV light for 15 min, ensuring clean conditions and minimizing contamination.

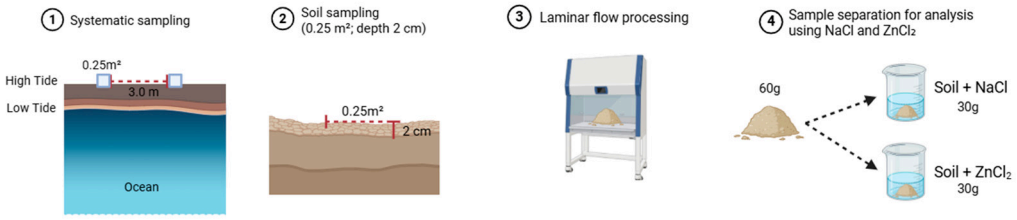

Figure 2. Sediment sampling design and density-based separation.

The density separation methodology was executed and adapted according to the Crawford and Quinn protocol [30]. NaCl (1.2 g/cm^3) and $ZnCl_2$ (1.5–1.7 g/cm^3) solutions were prepared. In some cases, hydrochloric acid (HCl) was used to facilitate the dissolution of $ZnCl_2$, assisting in the solubilization of the solution under specific environmental conditions particularly due to low ambient temperatures in southern Brazil during certain periods of the year. Additionally, it helped reduce solution turbidity, improving analytical performance. Drops of HCl were added until the point of solubilization was reached. The 60 g samples were divided into two subsamples of approximately 30 g each, with one portion processed using $ZnCl_2$ and the other using NaCl, in order to compare the performance of the two saline solutions. The samples from the four collection areas were submitted to the same density separation procedure with both saline solutions, and the measurement units were evaluated per sample prepared for each saline solution and then standardized for analysis according to the sampling area (m^2). After the sediment had been agitated, the solution was left to rest until complete stabilization of the supernatant. Later, the vacuum filtration was performed using qualitative paper filters acquired from J.Prolab, with an average pore size of 14 µm and a thickness of 0.2 mm. Paper filters were used to retain the particles present in the supernatant and separate the liquid fraction. Physical and chemical analyses were not performed at this stage, as the primary objective was to evaluate the methodology. Furthermore, the samples were not subjected to drying, as they did not present significant moisture upon receipt and were in suitable condition for direct use.

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

Before beginning the process and applying the methodology, a blank test was carried out [10,34,38]. These tests were performed in triplicate using only Milli-Q water, without the addition of soil or any other material [39–41], in order to verify that no contamination or interference occurred at any stage of the process from density separation to Nile Red staining. Additionally, each saline solution (NaCl and $ZnCl_2$) was prepared using Milli-Q water and subjected to the same filtration and staining procedures applied to the sediment samples. The solutions were subsequently stained with Nile Red and analyzed under fluorescence microscopy to validate the methodology, with all observations performed in triplicate. It was observed that none of the filters showed the presence of plastic particles, either in fibrous or granular form. Therefore, the authors developed protocols and techniques to standardize methods ranging from the cleaning of equipment with Milli-Q water and/or 70% alcohol, followed by proper drying, to the preparation of the laboratory environment where analyses of sediment samples were to be conducted—measures essential for avoiding interference in the experiments. All samples were handled under laminar flow conditions with UV light and controlled air circulation. Nitrile gloves were used throughout, and all equipment was cleaned with an HCl solution followed by Milli-Q water then wrapped in aluminum foil or paper towels and dried in an oven. At no stage was there any contact with plastic materials, and the entire team maintained rigorous contamination control procedures [32,42]. Additionally, it was crucial to control the movement of people in the

laboratory, ensure the use of appropriate clothing, and guarantee that researchers wore cotton lab coats, thereby maintaining proper conditions before starting any experimental activity [43–45]. These contamination control and mitigation procedures were conducted in accordance with established protocols, following the recommendations of Crawford and Quinn protocol [30], as in the density separation step.

2.4. Fluorescence Microscopy

Before the microscopy stage, the Nile Red dye was prepared for the fluorescence process. The dye was diluted at a ratio of 10 µL in 9 mL of acetone and stored in a closed container wrapped in aluminum foil to prevent light exposure and preserve its characteristics. A glass syringe fitted with a Millipore syringe filter (PTFE, 0.22 µm) was used to filter the solution and apply the dye efficiently, both to the supernatant (2 to 3 drops) and to the paper filter (2 to 6 drops), hence facilitating the identification of the MPs present [46–48]. After ensuring that all materials were thoroughly cleaned and organized, the supernatant was placed in a Büchner funnel, and the filters were arranged in steel and aluminum trays for FM (Figure 3).

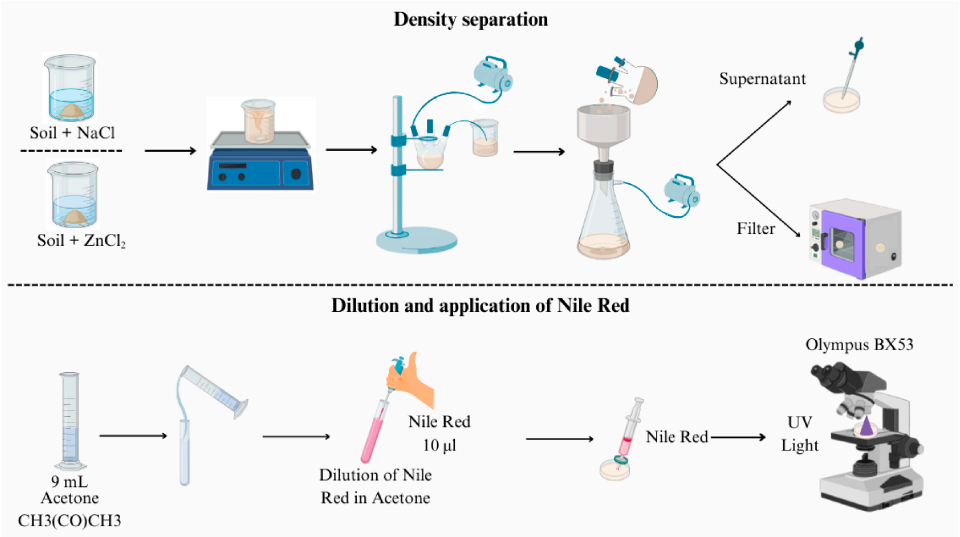

Figure 3. Illustrative scheme of the experimental procedure used for the extraction and identification of PMPs using Nile Red.

In order to certify accurate documentation, a camera attached to a digital eyepiece for Biofocus microscopes was used. Additionally, to avoid contamination, safety measures such as wearing a cotton lab coat and nitrile gloves were adopted, in accordance with established protocols. The dye was applied to the paper filters to check for the presence of MPs that did not pass through the filter pores. Microscopic analysis was implemented using an Olympus BX53 microscope (EVIDENT CORPORATION, Tokyo, Japan) with a UV light filter, emitting wavelengths in the range of 300–500 nm (10×/0.30 Ph 1 magnification). The Future Winjoe camera software was used to capture images of the MPs and to add scales and annotations. The ImageJ software was employed, allowing for scale calibration (mm or µm) to indicate the approximate size of the MPs. After the preparation and execution of the MP extraction process, the FM identification stage was conducted by organizing the data into two tables, separating the collected samples according to their location in Antarctica: Maritime (Figure 1C) and Peninsular (Figure 1D).

2.5. Identification and Quantification of PMPs

After density separation of PMPs using saline solutions and subsequent fluorescence application, the PMPs were qualitatively identified according to their shape and classified as

fragments or fibers in each sample. The particles were then photographed, and the images were calibrated to scale. The identified PMPs were recorded, counted, and organized in spreadsheets enabling the analysis of relative abundance among the different regions. Quantification considered the sampling location, the type of solution used, and the medium in which the PMPs were found (filter and supernatant), ultimately resulting in the creation of abundance graphs.

Generative AI was used to create the graphical abstract.

3. Results

3.1. Characterization of PMPs

FM enabled the identification and quantification of PMPs, as well as image recording and scale calibration of the particles present (Figure 4). The data were organized into tables for clearer presentation (Tables 1 and 2). The plastics appeared in different forms, both as granules and as fibers. In the supernatants, where the paper filter acted as a sink, the presence of fibers became more evident. The fibers exhibited an irregular, elongated, thin, and flexible shape which made microscope lens adjustment more challenging and their identification more complex compared to granules. The granules, on the other hand, with their well-defined structure and denser topology, were more easily identified, especially when stained with Nile Red [49,50].

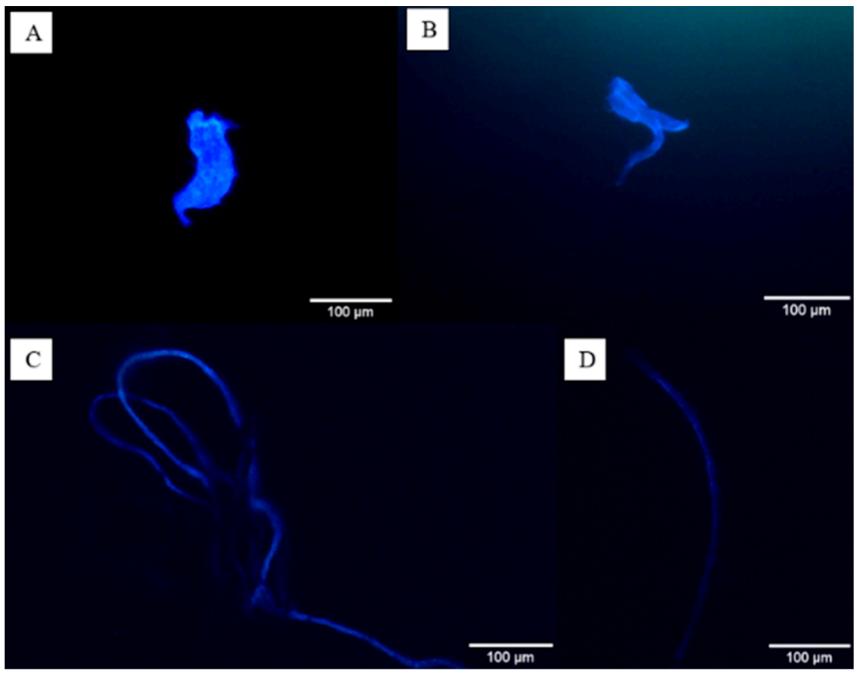

Figure 4. Samples of PMPs analyzed under FM. (**A**). Vega Island—Filter 06; (**B**). Keller Peninsula—Filter 15; (**C**). Vega Island—Supernatant 1; (**D**). Comandante Ferraz Station—EACF Supernatant 02.

The filters were examined using the microscope, and the UV filter provided the best performance, as reported in the literature [9,51]. The visualization of microplastics occurred when the Nile Red dye interacted with both the supernatant and with the paper filter. After locating the PMPs, image recording and abundance analysis were carried out for each identified sample.

Table 1. Analysis of the samples collected in two peninsular regions of Antarctica, James Ross Island and Vega Island, as identified by FM. Table values are expressed in particles per m^2.

Sample Local	Solution	Paper Filter	Supernatant		Paper Filter (Particles/m^2)	Supernatant (Particles/m^2)	
			Granule	Filter		Granule	Filter
Vega_01	NaCl	2	1	1	8	4	4
Vega_02	NaCl	0	0	0	0	0	0
Vega_03	NaCl	2	1	1	8	4	4
Vega_04	NaCl	1	0	0	4	0	0
Vega_05	NaCl	0	0	0	0	0	0
Vega_06	NaCl	2	0	0	8	0	0
Vega_07	$ZnCl_2$	0	0	0	0	0	0
Vega_08	$ZnCl_2$	0	0	1	0	0	4
Vega_09	$ZnCl_2$	0	0	0	0	0	0
Vega_10	$ZnCl_2$	1	0	0	4	0	0
Vega_11	$ZnCl_2$	0	0	0	0	0	0
Total		8	2	3	32	8	12
Sample Local	**Solution**	**Paper Filter**	**Supernatant**		**Paper Filter (Particles/m^2)**	**Supernatant (Particles/m^2)**	
			Granule	**Filter**		**Granule**	**Filter**
James_Ross_01	NaCl	0	0	0	0	0	0
James_Ross_02	NaCl	0	0	0	0	0	0
James_Ross_03	NaCl	1	0	0	4	0	0
James_Ross_04	NaCl	0	0	0	0	0	0
James_Ross_05	NaCl	1	0	0	4	0	0
James_Ross_06	NaCl	0	0	0	0	0	0
James_Ross_07	NaCl	0	0	0	0	0	0
James_Ross_08	NaCl	1	0	1	4	0	4
James_Ross_09	$ZnCl_2$	0	0	0	0	0	0
James_Ross_10	$ZnCl_2$	0	0	0	0	0	0
James_Ross_11	$ZnCl_2$	0	0	0	0	0	0
James_Ross_12	$ZnCl_2$	0	0	0	0	0	0
James_Ross_13	$ZnCl_2$	0	0	0	0	0	0
James_Ross_14	$ZnCl_2$	1	0	0	4	0	0
James_Ross_15	$ZnCl_2$	1	0	0	4	0	0
Total		5	0	1	20	0	4

Table 2. Analysis of the samples collected in two maritime regions, at EACF and Keller Peninsula, identified by FM.

Sample Local	Solution	Paper Filter	Supernatant		Paper Filter (Particles/m^2)	Supernatant (Particles/m^2)	
			Granule	Filter		Granule	Filter
EACF_01	NaCl	0	0	0	0	0	0
EACF_02	NaCl	0	0	1	0	0	4
EACF_03	NaCl	0	0	0	0	0	0
EACF_04	NaCl	0	0	0	0	0	0
EACF_05	$ZnCl_2$	1	0	1	4	0	4
EACF_06	$ZnCl_2$	0	0	0	0	0	0
EACF_07	$ZnCl_2$	0	0	0	0	0	0
EACF_08	$ZnCl_2$	0	0	0	0	0	0
EACF_09	$ZnCl_2$	0	0	0	0	0	0
Total		1	0	2	4	0	8

Table 2. *Cont.*

Sample Local	Solution	Paper Filter	Supernatant		Paper Filter (Particles/m^2)	Supernatant (Particles/m^2)	
			Granule	Filter		Granule	Filter
Keller_Peninsula_01	NaCl	0	0	0	0	0	0
Keller_Peninsula_02	NaCl	1	1	0	4	4	0
Keller_Peninsula_03	NaCl	0	0	0	0	0	0
Keller_Peninsula_04	NaCl	0	0	0	0	0	0
Keller_Peninsula_05	NaCl	0	0	0	0	0	0
Keller_Peninsula_06	NaCl	0	0	0	0	0	0
Keller_Peninsula_07	NaCl	2	0	0	8	0	0
Keller_Peninsula_08	NaCl	2	0	0	8	0	0
Keller_Peninsula_09	$ZnCl_2$	0	0	0	0	0	0
Keller_Peninsula_10	$ZnCl_2$	1	0	0	4	0	0
Keller_Peninsula_11	$ZnCl_2$	0	0	0	0	0	0
Keller_Peninsula_12	$ZnCl_2$	1	0	0	4	0	0
Keller_Peninsula_13	$ZnCl_2$	0	0	0	0	0	0
Keller_Peninsula_14	$ZnCl_2$	0	0	0	0	0	0
Total		7	1	0	28	4	0

3.2. Abundance of PMPs

The preliminary analysis of PMP abundance in the peninsular regions of Vega Island and James Ross Island considered the different sampling points and the extent of the sampled area (Table 1). The samples were evenly divided, receiving equal amounts of NaCl and $ZnCl_2$ solutions. It is important to note that NaCl is limited to the extraction of low-density polymers (<1.2 g cm^{-3}), whereas $ZnCl_2$ enables the recovery of denser polymers, such as PET and PVC, due to its higher density [52].

This approach was adopted because the sampling sites were geographically close, allowing both methodologies to be applied without compromising the representativeness or integrity of the results. For each 30 g aliquot, after density separation using NaCl and $ZnCl_2$ solutions, abundance quantification was performed, and the results were expressed as particles per sample. To further assess the method's ability to detect microplastics, selected samples were intentionally spiked with equal amounts of reference particles produced from plastic sheets (PE, PET, PP, and PVC). These samples were subjected to the full analytical procedure, including density separation using saline solutions and Nile Red staining. A complete recovery of the spiked particles was observed on the paper filters. Based on previous studies and the literature, particles were classified as granules or fibers according to their visual morphology under microscopy [53].

On Vega Island, 54% of the samples showed the presence of PMPs, while on James Ross Island this percentage was lower, corresponding to 33% (Table 1). The preliminary analysis of PMP abundance in the maritime regions of Antarctica (Table 2) indicated that in the vicinity of the Comandante Ferraz Antarctic Station (EACF), 22% of the samples contained PMPs, whereas on Keller Peninsula this value was 36%. Accordingly, the PMPs identified by FM in the peninsular regions of Antarctica correspond to the samples collected on Vega Island and James Ross Island (Table 1), while those observed in the maritime regions are associated with samples from the surroundings of EACF and Keller Peninsula (Table 2). It was observed, through extrapolation to particles per square meter, that both the peninsular region, represented by Keller Peninsula, and the maritime region, represented by Vega Island, exhibited significant levels of potential microplastics, with some samples reaching approximately 8 particles per m^2. To obtain these values, appropriate proportional adjustments were applied to the samples collected from the supernatant. Specifically, a

mass of 30 g of supernatant was considered representative of a sampling area of 0.25 m^2, allowing for the extrapolation of results to particles per square meter in a consistent and standardized manner. The graphs unveil the abundance of PMPs in each solution, considering the different regions individually (Figure 5). The comparison between the saline solutions used allowed for the separate evaluation of the performance of each methodology.

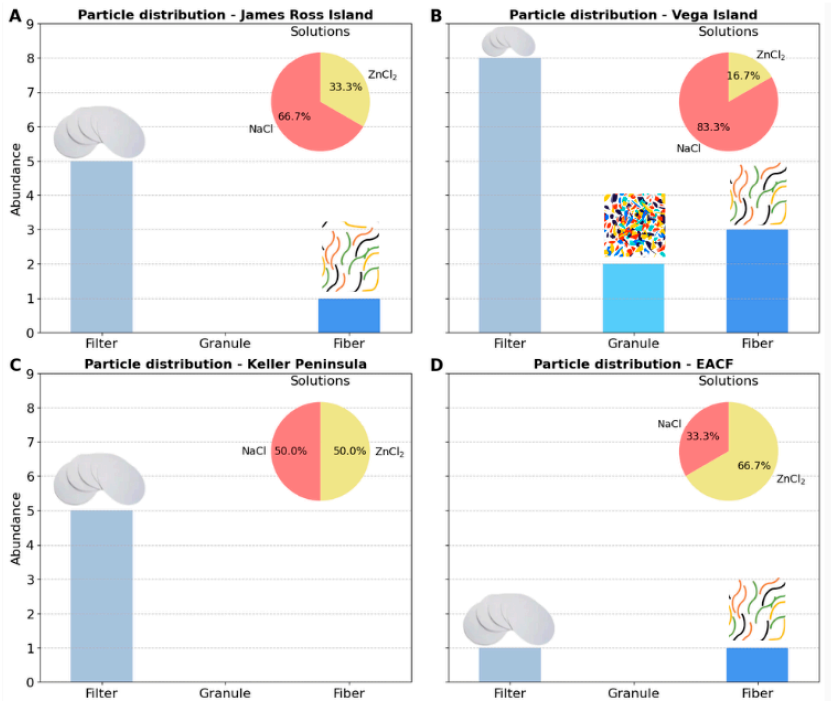

Figure 5. Distribution of MPs by region. (**A**,**B**) Peninsular regions. (**C**,**D**) Maritime regions.

The results indicated consistent performance for both saline solutions. In the peninsular regions, it was observed that the NaCl solution showed better performance in the recovery of PMPs. On the other hand, in the maritime regions, the $ZnCl_2$ solution demonstrated greater efficiency in the distribution of the extracted PMPs (Figure 5). The quantity of PMPs in the EACF and James Ross Island regions remained similar, as evidenced by the linear trend observed in the cumulative concentration curve. On average, the paper filter retained the highest proportion of PMPs. In contrast, a more expressive variation was observed in Keller Peninsula and Vega Island, with particular emphasis on points Vega_01 and Vega_03, where four PMPs per sample were identified. Overall, 83% of the samples showed PMP retention on the paper filter. Based on the data obtained at each sampling site in Antarctica, it was possible to perform a general analysis (Figure 6) of PMP abundance and the respective solutions across all studied islands.

The presence of PMPs was observed in both solutions in general, with 70% identified in the NaCl solution and 30% in the $ZnCl_2$ solution. It was also found that Vega Island was the only location to present PMPs both on paper filter and in the supernatant, differing from the other sampled regions. Following that, James Ross Island and Comandante Ferraz Station stood out, whereas Keller Peninsula showed PMPs only on the paper filter. Therefore, approximately 37% of the 49 samples collected showed the presence of microplastics mainly in areas influenced by anthropogenic activities.

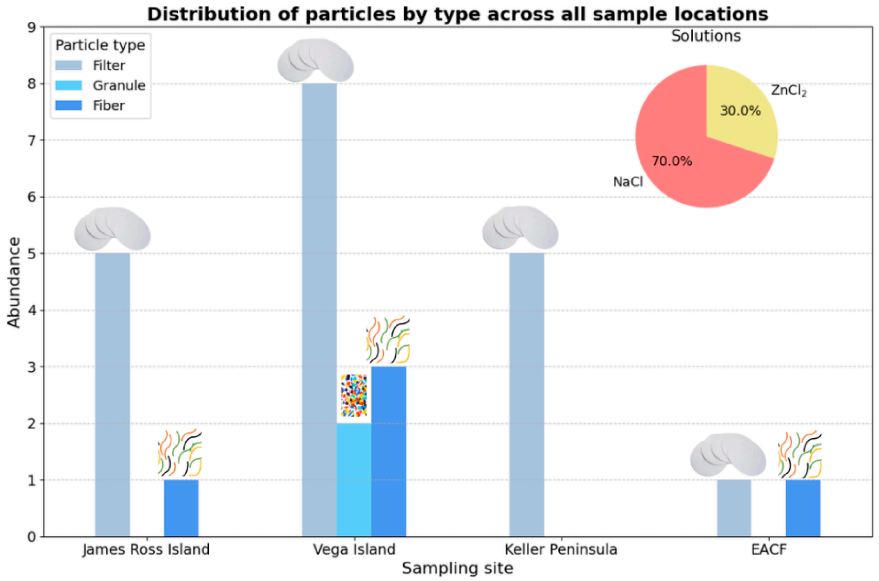

Figure 6. Distribution of MPs across all sampled locations.

4. Discussion

This study demonstrated that the presence of PMPs is occurring even in environments considered pristine, such as Antarctica. The sediments from the four Antarctic locations analyzed revealed the presence of PMPs, with particular emphasis on Vega Island, which showed a possible diversity of PMPs. This variability was indicated by both NaCl and $ZnCl_2$ solutions and the use of the paper filter and supernatant (Tables 1 and 2), suggesting the presence of distinct PMPs. This also includes particles possibly smaller than the micro scale, such as nanoplastics (NPs), given that the processing steps may interfere with and fragment the detected MPs. Additionally, the morphology of the PMPs varied, with both granules and fibers being found (Figure 4) and identified through the application of pre-processing techniques based on the existing literature [54–56], including the use of dyes such as Nile Red [57] to support MF. Fibers were most evident in the supernatants, possibly due to the vacuum filtration process [58–60]. The pressure applied to draw the liquid through the paper filter may force the passage of fibers—because they are flexible structures—through the filter pores, causing them to be carried along with the filtered liquid. The saline solutions NaCl and $ZnCl_2$ were employed in order to evaluate the efficiency of PMP extraction methodologies in Antarctic sediments, assessing whether different sediment types would exhibit distinct behaviors depending on the method applied.

As expected, the paper filter showed a higher quantity of PMPs per samples: there were 13 in the peninsular regions (Table 1) and 8 in the maritime regions (Table 2). In comparison, the supernatant contained six PMPs in the peninsular regions (Table 1) and three in the maritime regions (Table 2), predominantly in the form of granules or fibers. Notably, through extrapolation to particles per m^2, both Keller Peninsula and Vega Island exhibited significant levels of PMPs, with some samples reaching approximately 8 particles/m^2, reinforcing the relevance of contamination in both peninsular and maritime environments. This difference may be related to the unique environmental conditions of Antarctica, such as intense ultraviolet radiation, the presence and intensity of human activities, and interactions with local fauna and microbiota [8,61]. These factors can promote the fragmentation of plastics and alter their physicochemical characteristics, resulting in the formation of PMPs with different sizes, shapes, and densities. Moreover, such processes may influence the spatial distribution of PMPs: while some fragments may percolate over the ice-covered surface, others may become buried or trapped by seasonal freeze–thaw cycles. Consequently,

certain regions with high potential for PMP accumulation may not exhibit clear evidence of their presence, particularly depending on the separation method used, which may favor the recovery of specific polymer types according to their physicochemical properties [62]. The methodology used for microplastic quantification through particle counting proved to be one of the most accessible. This is partly due to the extremely small size of these particles, whose mass and density are very low, making precise measurements by other methods difficult [9,63,64].

The results revealed that, in the Antarctic maritime regions, 22% of the samples collected near the EACF and 36% of those from Keller Peninsula showed the presence of PMPs. In the peninsular areas, PMPs were identified in 33% of the samples from James Ross Island and in 54% of those from Vega Island. The preliminary abundance analysis suggests that the peninsular areas, especially Vega Island, may be more susceptible to PMP pollution possibly due to factors such as ocean currents, human activities, or long-term accumulation. The difference in PMP presence between the peninsular and maritime regions highlights the need for further investigations to understand the sources and mechanisms of dispersion of these pollutants and the need to develop effective mitigation strategies and environmental conservation measures [65,66].

The distance between the sampled locations, both at the EACF and on Vega Island, did not prevent these regions from exhibiting a remarkable similarity in the presence and composition of microplastics. This pattern suggests that, even in distinct Antarctic areas, common sources or processes of dispersion and accumulation of PMPs may occur, resulting in similar pollution characteristics. This outcome diverged from the initial hypothesis that PMPs would appear in similar proportions among sampling points within the maritime region and within the peninsular region. Theoretically, the peninsular and maritime zones are distinct, since in the peninsular region the Weddell Sea remains frozen for most of the year, which may restrict the arrival of PMPs via ocean currents. Conversely, in the maritime areas, where the sea does not freeze, there is direct contact with other oceanic regions mainly because of the influence of the Drake Passage—a potential pathway for PMP transport [67–70]. Most of the PMPs were retained by the paper filter, indicating that those passing through likely had dimensions smaller than the pore size. In the case of fibers, their passage may be related to both their length and diameter as well as to the pressure applied by the saline solution, which may force them through the filter [71,72]. The evidence presented indicates that the occurrence of PMPs in Antarctica was neither uniform nor standardized, contrasting with studies suggesting their presumed ubiquity in the environment [14,73,74]. In addition to factors related to ocean currents, geographic position likely also contributes to the observed results. In this context, Vega Island, located further north than James Ross Island, may play a key role in explaining the higher abundance of MPs detected [75–77].

It is important to highlight that some hypotheses were considered to explain the divergence in the results. One possibility was contamination of the samples during the methodological process. However, tests were performed to verify the reliability of the methodology, which followed rigorous protocols and was supported by existing literature [31]. Another potential source of interference could have occurred during sample collection in Antarctica. Nevertheless, precautions were taken to minimize any biases. Some challenges emerged throughout the process, such as camera focusing issues due to the irregular shape of certain PMPs particularly in fibers. Even so, the generated images were able to visually represent PMPs in the form of granules or fibers, highlighting the irregular topology of the particles identified. Therefore, if plastics are used as reference materials for testing, it is essential to conduct additional experiments, especially those

involving degradation processes, considering that Antarctica's environmental conditions may influence the weathering of plastics [70,78].

Limitations

Samples must be analyzed with caution to avoid contamination that could interfere with identification using Nile Red dye, as it is lipophilic and may react with materials of similar characteristics, thereby compromising the exclusive detection of PMPs. In addition, the use of complementary equipment and higher-resolution cameras is essential to ensure better image quality and to enable the observation of details that assist in determining the origin of the materials. Qualitative analysis also represents a limitation, as it depends on visual inspection and the analyst's perception. Thus, the use of appropriate solutions and Nile Red dye is crucial to minimize biases and ensure greater reliability in MP identification [27,79–81]. Polymer confirmation was not performed (e.g., μFTIR or Raman spectroscopy), and therefore the detected particles should be interpreted as potential microplastics [82–85]. No organic matter digestion step was applied, as the samples consisted of beach shoreline sediments collected at high tide. This decision was based on the potential drawbacks of additional chemical treatment, which may increase the risk of contamination or lead to alterations in the physicochemical properties of polymeric particles. Furthermore, such treatments can significantly influence the integrity of microplastics present in the samples. Therefore, avoiding chemical digestion was considered appropriate, particularly given the importance of carefully selecting and validating digestion techniques to ensure accurate recovery and characterization of microplastics [58,86–88].

5. Conclusions and Perspectives

This study demonstrated that the initial analyses conducted in the maritime and peninsular regions of Antarctica indicate the presence of PMPs both in the form of granules and fibers, possibly as a result of anthropogenic interference. In addition, it was observed that the PMPs are distributed in a uniform manner and that factors such as coastal ice dynamics and tidal movement may promote leaching or percolation of PMPs due to freeze–thaw cycles, which may have reduced the expected evidence of plastics in the maritime regions. In this context, the PMPs may have been concealed within the sediment matrix. However, even with the detection of PMPs in remote regions, it is not possible to categorically affirm the so-called omnipresence of these contaminants in all seacoast locations of Antarctica, since there are still locations with no evidence of their occurrence. This study showed that despite the presence of PMPs in Antarctica, there are still locations free from significant contamination, without localized or widespread indications. The recorded evidence was restricted to a few sampling points which are considerably distant from each other, and the factors explaining this distribution have been discussed in the study. Thus, considering plastics as omnipresent in Antarctica may be a somewhat premature statement, given that some samples showed no detectable presence of PMPs. Future studies will incorporate radiometric techniques (such as μFTIR and Raman) and provide greater clarity regarding blank control procedures. Nevertheless, all analyses were conducted with strict care, using materials free of plastic components, equipment cleaning protocols based on the literature, and procedures carried out without any laboratory contamination.

It is undeniable that the continuous growth in plastic production and consumption has driven the increasing presence of MPs on a global scale. What stands out, however, is that this advance has not yet impacted some regions as severely. In this context, proposals have been discussed by UNESCO, through the SDGs, as well as by other organizations, with the aim of mitigating the exponential consumption of plastics. Even so, further studies are needed to validate the methodologies already applied, adapting them when necessary,

in order to refine analyses, reduce experimental errors, and consolidate standardized techniques. This would allow for the establishment of criteria for measuring MP contamination and, consequently, defining levels of severity across different areas of Antarctica.

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Abbreviations

The following abbreviations are used in this manuscript:

EACF	Comandante Ferraz Antarctic Station
MP	Microplastic
FM	Fluorescence Microscopy
PMP	Potential Microplastic

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