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Latitudinal patterns of microplastic contamination in remote areas

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ABSTRACT

Microplastics (MPs) have been detected in a wide array of remote terrestrial areas. Analysing the occurrence of MPs in remote areas is paramount to understand their transport and deposition patterns. Despite the growing body of publications on this topic, studies are often spatially restricted. This limits assessments of global patterns in MPs distribution. Glaciers are landscape features without substantial MPs local inputs, which allows the evaluation of transport and deposition mechanisms. To fill this gap, we gathered 57 samples of supraglacial debris from 9 glaciers, ranging in latitude from 46°S to 78°N. MPs contamination was studied in terms of concentration, shape, size, and polymeric composition, observing significant variations with latitude for all considered parameters. The same held true when considering all anthropogenic particles (APs), including natural polymers. No single polymer was so common to be detected on all glaciers, suggesting atmospheric transport as the main driver of MPs contamination, possibly showing consistent global patterns. Presence of human modified environments in the areas surrounding the glaciers affected MPs size and composition. Detecting latitudinal trends is fundamental for constraining the atmospheric limb of the global plastic cycle and modelling MPs deposition. Since MPs can release toxic additives and pigments into the environment, studies on their distribution can help assess contamination loads and hazards at a global scale.

1. Introduction

Microplastics (MPs, plastic items in the size range of 1–5000 μm (Brahney et al., 2021) have been reported in a wide array of different environments (Brahney et al., 2020; Cabrera et al., 2022; Kanhai et al., 2017; Peeken et al., 2018). The presence of MPs in the environment is due either to the release of primary MPs (e.g., microbeads), or to the degradation of larger plastic items (i.e., secondary origin). Due to the nature of polymers, plastic items are meant to last and, once in the environment, fragment into increasingly smaller particles rather than decompose. This has led to the hypothesis that their concentrations and absolute numbers in the environment will increase with time (Lebreton and Andrady, 2019). MPs may reach remote areas transported by wind and subside by wet or dry deposition (Allen et al., 2019; Evangeliou et al., 2020; Zhang et al., 2021). Atmospheric transport, especially if long-range, is affected by the buoyancy and persistence of the polymers that constitute the transported MPs, but also by the seasonal movements of air masses and other atmospheric processes that may affect source-sink dynamics of MPs pollution (Zhang et al., 2021). Various sources of MPs have been modelled for terrestrial remote areas, among which sea spray and roads, depending on their proximity to the studied sites (Brahney et al., 2021). This suggests that MPs are often deposited and entrained again, resulting in ubiquitous distribution in both marine (Leistenschneider et al., 2024; Waller et al., 2017) and terrestrial remote

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areas (Brahney et al., 2020; González-Pleiter et al., 2020; Zhang et al., 2016). MPs dry deposition rates are positively correlated with elevation (Brahney et al., 2020), suggesting that MPs presence and concentration in alpine environments is relevant information to understand patterns of transport and accumulation. In addition, it is known that glaciers may act as sinks of airborne contaminants (Peeken et al., 2018; Zhang et al., 2021) also by wet deposition, as snow is considered an efficient contaminant scavenger (Blanco-Alegre et al., 2024; Lei and Wania, 2004). Thus, glaciers, ice caps, and seasonal snowpack may all become contaminant reservoirs on different time scales (Blais et al., 1998; Daly and Wania, 2005; Wania and Mackay, 1993; Wania and Westgate, 2008), depending on their lifespan. MPs could undergo the same fate and be stored in glaciers until the ice melts. Therefore, the ablation areas of glaciers could represent historical registers for MPs deposition. In addition, studying MPs contamination of glacial areas – regions with any, or few, substantial local inputs – allows us to evaluate mechanisms of transport and deposition. Determining the contribution of different sources and transport media can help in assessing the potential hazards due to MPs occurrence, such as the release of toxic additives (Liu et al., 2020). Previous regional-scale studies have evaluated MPs contamination on glaciers in alpine (Ambrosini et al., 2019; Zhang et al., 2021) and polar regions (González-Pleiter et al., 2021; Rosso et al., 2024). As of our knowledge, however, no study so far investigated trends of MPs contamination in remote areas over large latitudinal ranges. Compared to regional studies, the detection of trends at a larger scale is necessary to constrain and model the limbs of the global plastic cycle. In addition, due to the complex topography of mountain ranges – and the generated air fluxes – the accuracy of global circulation models in these areas is low (Brahney et al., 2021), and on-site data collection becomes irreplaceable.

To fill this gap, we compiled a dataset of 57 samples of supraglacial debris from 9 glaciers from three continents, including equatorial, temperate and subpolar regions. Sampled sites ranged in latitude between 46° S and 78° N (Table 1 and Fig. 1). The first aim of the study was to determine the patterns of MPs contamination across glaciated areas that vary in geographical location, climatic parameters, glacier extent, and closeness to densely populated urban areas (Fig. 1). The second aim was to assess whether these characteristics influence the concentration, shape, size or composition of MPs detected in those remote areas. We expected higher concentrations, bigger and heavier particles on glaciers closer to urban areas, and glaciers close to one another to be more similar in concentration, shape, and composition.

2. Methods

2.1. Sampling

Samples were collected on the ablation zones of seven glaciers (Fig. 1), namely: Longyearbreen and Midtre Lovénbreen (Svalbard), Steindalsbreen (Northern Norway), Prè de Bar (Italian Alps), Lewis (Kenya), Iver (Central Chile), and Exploradores (Chilean Patagonia). We added to the dataset previously published data on MP contamination on Forni and Cedec glaciers (Italy), for a total of nine glacier comprised in the analysis. Here, respectively 15 and 8 samples were collected with similar methods (Crosta et al., 2022). Data collected in the same study on the Ebenferner Glacier (Crosta et al., 2022) were excluded from the dataset, as this glacier hosts significant infrastructure on the ice, which strongly influences MPs contamination pattern and could thus introduce a bias. Coordinates, regions, sampling dates, and number of samples – including samples from the previous publication – are available in Table 1, while the geographical position of the glaciers and the surrounding densely populated areas are available in Fig. 1.

Sampling of original data occurred during local summers 2019 and 2020. At each chosen glacier, we collected 5 samples of supraglacial debris, except for Steindalsbreen where only 4 samples were gathered. For the Iver and Exploradores glaciers only 3 and 4 samples respectively were available for the analysis, out of the 5 collected samples, because of potential accidental contamination of the remaining samples during transport. Supraglacial sediment accumulations were chosen for sampling if they were not interested by water flow and predominantly made of fine sediment.

At each sampling point, sediment was collected in glass jars or tin cans using a metal spoon, previously washed with acetone to remove potential contamination. For the same reason, sampling was carried out wearing a cotton surgical gown. According to published geological surveys of the studied sites, many glaciers are dominated by one rock type (e.g. the Forni, Pré de Bar and Lewis glaciers), while others show higher variation in the surrounding rock formations (e.g. the Midtre Lovenbreen). Details about the rock formations surrounding each glacier are given in Table 1. Studies have shown that the formations exposed in the different catchments strongly influence debris composition on the glaciers (e.g. Kirkbride et al., 2023). Therefore, the surrounding rock formations can be considered a proxy for the mineralogy of the supraglacial debris. Organic matter (OM) content was estimated by weight loss on ignition (at 550 °C for 3 h) on three samples per glacier. Samples

Table 1

General information about sampling sites and collected samples. Sampling dates are expressed as month/year (mm/YYYY). ESDAC: European Soil Data Centre; GdC: Geoportal of Chile, ISPRA: Italian Institute for Environmental Protection and Research; NGU: Geological Survey of Norway; NPI: Noerwgian Polar Institute.

Glacier	Latitude	Longitude	Avg. altitude	Region	Avg. HMc	Rock type	% OM ± SD	Date	Samples
Longyearbreen	78°10′53.76″ N	15°30′53.17″ E	573	Arctic	0.026911	Shale, siltstone and sandstone (NPI)	7.58[b]	07/2019	5
Midtre Lovénbreen	78°53 25.30″ N	12°2′53.52″ E	345	Arctic	0.016016	Phyllite, schist with quartzite bands, sandstone, chert, carbonate (NPI)	3.09 ± 1.03	07/2019	5
Steindalsbreen	69°23′40.16″ N	19°52′45.14″ E	1459	Arctic	0.149066	Gabbro (NGU)	11.91 ± 1.44	08/2019	4
Prè de Bar	45°54′21.99″ N	7°2′47.71″ E	3105	Alps	0.421966	Granite (ISPRA)	1.66 ± 1.36	07/2020	5
Cedec[a]	46°26′56.98″ N	10°35′47.78″ E	3281	Alps	0.344860	Paragneiss, micaschist (ISPRA)	1.96 ± 1.70	09/2019	8
Forni[a]	46°23′35.74″ N	10°35′24.63″ E	3144	Alps	0.353185	Paragneiss, micaschist (ISPRA)	1.55 ± 1.27	07/2019	15
Lewis	0°9′21.39″ S	37°18′53.98″ E	4779	Kenya	0.387116	Kenyte (ESDAC)	9.59 ± 3.20	03/2020	5
Iver	33°15′17.17″ S	70°13′40.08 W	4835	Andes	0.179476	pyroclastics rocks, andesite, dacite (GdC)	3.00 ± 1.35	01/2019	5
Exploradores	46°30′44.532″ S	73°10′14.05″ W	1688	Patagonia	0.081843	Granite, granodiorite, tonalite (GdC)	0.74 ± 0.56	02/2019	5

[a] Data from Crosta et al. (2022).

[b] Data from Rozwalak et al. (2022).no SD available.

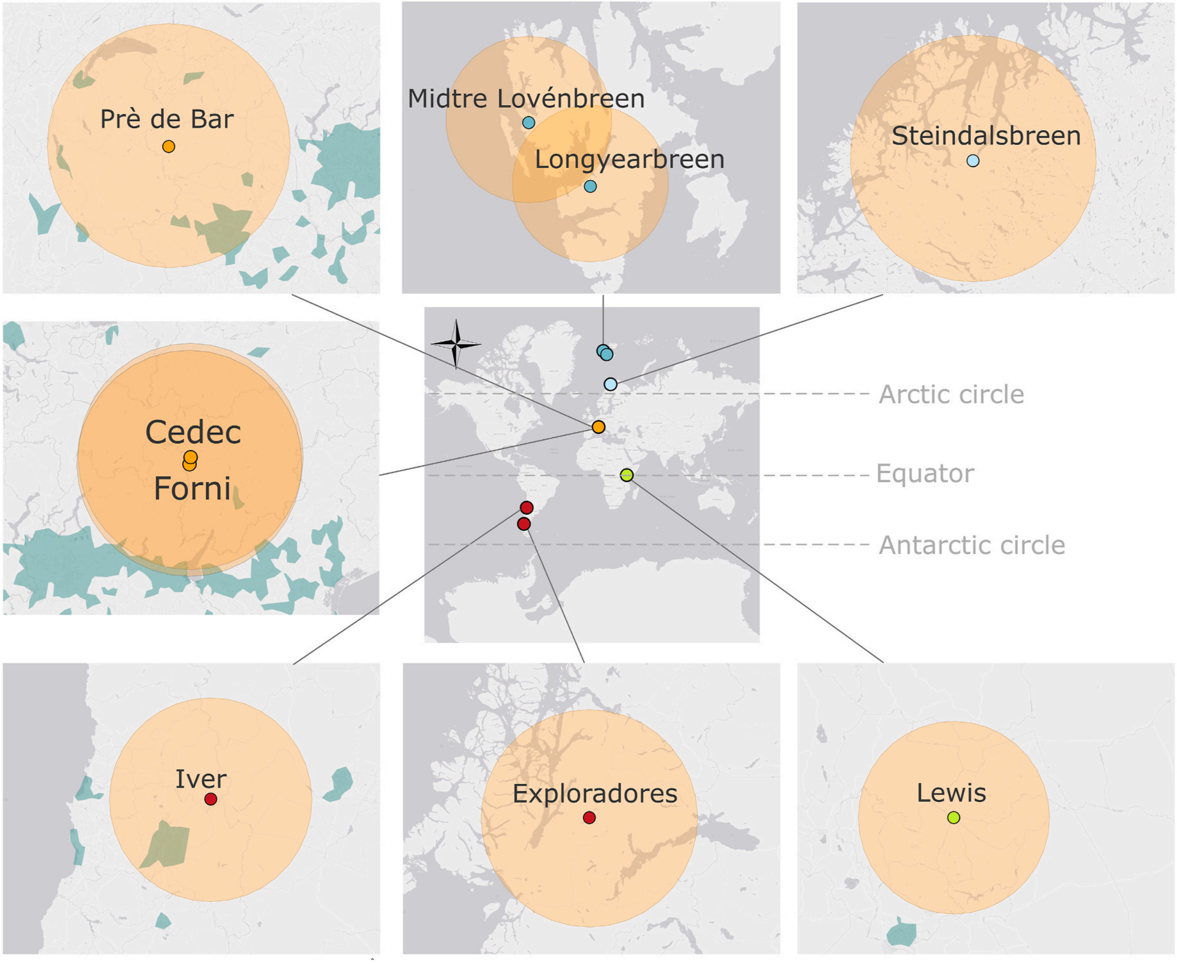

Fig. 1. Geographical distribution of the study sites. Green polygons represent urban areas from MODIS satellite data. The orange circles represent a radius of 100 km from each study site (yellow dots). Dot colors in the central thumbnail world map highlight the different geographical areas. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

from the Longyearbreen had no fine sieved material left for this analysis, and the values refer to available literature (Rozwalak et al., 2022). Percent OM content varied between 1.55 ± 1.27 SD for the Forni Glacier to 11.92 ± 1.45 SD for the Steindalsbreen. Measures for each glacier are available in Table 1.

2.2. *Isolation and identification of MPs*

Samples were desiccated at 60 °C for 48 h and stored inside glass jars. To prevent contamination during MPs extraction, solutions were filtered on cellulose filters (StonyLab, pore size 1 μm; Ø = 47 mm). Glassware was washed with ultrapure filtered water and covered with tinfoil. Sample preparation was performed following a protocol described in literature (Crosta et al., 2022; Parolini et al., 2021). Sample preparation included the sieving of samples down to 1 mm to ensure that all samples had similar granulometry in the following analyses.

Briefly, anthropogenic particles (APs) were isolated from the matrix using density separation (sodium chloride solution, density = 1.2 g/cm^3), followed by digestion of organic matter (hydrogen peroxide solution, 15 % final concentration). A blank control was prepared for each extraction batch. Samples were filtered and visually inspected under a stereomicroscope (Leica EZ4W). APs were hand-picked with stainless pins and laid on silver membrane filters. The main axis length of each item was measured through the ImageJ Fiji (Schindelin et al., 2012). Polymer characterization was carried out through μ-FTIR microscopy with a Nicolet iN10 MX Infrared Imaging Microscope (Thermo Scientific, Waltham, MA, USA). The cellulose based semi-synthetic polymers, such as cellophane and rayon fibres, were separated from natural cellulose based on characteristic spectral bands, as described by Cai et al., (2019). As cellophane and rayon have the same chemical composition, their only difference is that cellophane is filmed and rayon is spun in fibres, they were both labelled as cellophane. Further details about wavelength range and libraries are available in previous publications (Crosta et al., 2022; Parolini et al., 2021). Polymers were considered as identified if match percentages were higher than 70 %. Lower percentages were included if the spectra were classified by an expert polymer chemist.

2.3. *Statistical analyses*

Data were analysed with R ×64 4.1.2 (R Core Team, 2021). Spatial data were processed with QGIS stable version “Firenze” (QGIS Development Team, 2022).

MPs contamination patterns were investigated according to four main parameters: concentration (number of MPs per kilogram of dried debris), shape (proportion of fibres on the total number of MPs), particle size, and polymeric composition.

For each glacier, we created a centroid located approximately at the middle point of its main axis. A 100 km buffer was calculated from the centroid of each glacier. Average population density within the buffer was calculated from the raster density layer provided by NASA Socioeconomic Data and Applications Center (SEDAC), through the project

Gridded Population of the World (GPW), version 4, with a resolution of 30 arcseconds (Center For International Earth Science Information Network-CIESIN-Columbia University, 2018). From the same source we obtained the Global Human Modification of Terrestrial Systems metric (Kennedy et al., 2020, hereafter HMc), which was used as a second index for quantifying human influence within the 100 km buffer. HMc includes several stressors, like human settlements, agricultural land, transport, mining sites, and electrical infrastructure (Kennedy et al., 2019). As the HMc is only available for terrestrial ecosystems, the average in the buffer area used for the analysis was calculated based on the number of cells included in the buffer areas.

Differences in MPs concentration among the glaciers were tested with a one-way ANOVA. A binomial Generalized Linear Model (GLM), corrected for overdispersion, was run to test for differences in the proportion of fibres among the glaciers. Trends in the concentration of MP and the proportion of fibres were tested using latitude and its second and third-degree polynomials, HMc, mean population density, glacier surface and mean altitude as single predictors in separate linear mixed-effects models with the glacier as a random factor. To check for patterns in particle size distribution, the same predictors were used in mixed-effects models with sample and glacier as nested random effects. Then, a second set of mixed-effects models was used to test whether the third-grade polynomial and population density as predictors improved the model fitting. Altitude and glacier surface were excluded from these tests, as they were too collinear with latitude and among each other (GVIF $\geq$13.52). To test whether the latitudinal pattern of MPs concentration could be due to atmospheric transport, the same test was run on the whole dataset – including anthropogenic particles of natural polymers. Significance of mixed models was tested using likelihood-ratio tests.

The third-grade polynomial of latitude and population density were entered as predictors in a distance-based redundancy analysis (db-RDA) based on Bray-Curtis dissimilarity, between MPs polymeric composition in each sample. The predictors' significance was tested with 1000 permutations. To avoid increased similarity among samples due to similar absolute abundances – an effect of Bray-Curtis dissimilarity – a redundancy analysis (RDA) based on Hellinger distance – which accounts only for the relative abundances – was run with the same predictors. The associations between polymers and glaciers were tested with an indicator species analysis with 10000 permutations. P-values were then corrected with the false discovery rate (FDR) procedure.

Since the samples from Lewis Glacier showed very high MPs concentrations (see Results), the analyses were repeated with a reduced dataset (hereafter "restricted dataset") that excluded them. Details on the methods and results for this latter group of analyses are reported in the supplementary material.

3. Results

Overall, 238 anthropogenic particles (APs) were isolated from the samples collected on Longyearbreen (Svalbard, n = 35), Midtre Lovénbreen (n = 29), Steindalsbreen (Norway, n = 8), Pré de Bar (Italy, n = 32), Lewis (Kenya, n = 80),Iver (n = 21), and Exploradores (Chile, n = 33), . In these samples, 98 items (41.2 % of APs) were identified as MPs, while the remaining were natural polymers. Contamination in the blanks amounted to 1.50 ± 0.96 APs/blank ± standard error (SE), of which 0.17 ± 0.17 SE MPs/blank. Most identified MPs were fibres (70.4 %). The maximum length of a single item ranged between 0.091 mm and 2.932 mm, averaging 0.66 ± 0.062 SE mm. MP concentration per sample averaged 63 ± 13 SE MPs/kg of dried debris, ranging between 20 and 170 MP/kg. The lowest average concentration was found on the Steindalsbreen and the highest on the Lewis Glacier. The mean HMc in the buffer areas was 0.22, and ranged from 0.02 for the Midtre Lovénbreen to 0.42 for the Pré de Bar Glacier. Average population density in the buffers ranged from 0.07 inhabitants/km^2 (for Longyearbreen), to 265.10 inhabitants/km^2 around the Iver Glacier. The most widespread polymers among all samples were cellophane and polyethylene terephthalate (PET, Fig. 2). The following statistical analyses include data from two additional glaciers, which was published in a previous article (Crosta et al., 2022), for a total of 348 APs and 133 MPs particles. The Lewis Glacier showed significantly higher MPs concentrations than all other glaciers ($|t| \leq 3.614$, df = 8, $p \leq 0.019$). No significant differences were detected in the proportion of fibres among glaciers (F = 1.768, df = 8,34, p = 0.078), nor in their size (F = 1.479, df = 8,110, p = 0.173).

We detected a significant non-linear relationship between MPs concentrations in each sample and latitude, represented by a third-degree polynomial ($\chi^2 = 17.95$, df = 3, $p < 0.001$), with two relative maxima at the Equator and northernmost latitudes (Fig. 2). The non-linear relationship held true when considering all APs, including natural polymers ($\chi^2 = 11.926$, df = 3, p = 0.008), and the relationship between MPs concentration and the cubic function of latitude was only marginally non-significant for the restricted dataset ($\chi^2 = 7.552$, df = 3, p = 0.056). The same non-linear variation with latitude also significantly explained the proportion of fibres in each sample ($\chi^2 = 8.043$, df = 3, p = 0.045) and MPs particle size ($\chi^2 = 8.402$, df = 3, p = 0.038), and was only marginally non-significant when using the restricted dataset ($\chi^2 = 7.034$, df = 1, p = 0.071). However, the peak in size distribution is found at mid-latitude in the Northern Hemisphere. Detailed results of each model can be found in Table S1.

When adding population density as a predictor, the significance of latitude did not change, while population density was non-significant (see Supplementary material). Results of the same analysis were non-significant with the restricted dataset (see Supplementary material). The HMc, instead, was a significant predictor of MPs size ($\chi^2 = 4.170$, df = 1, p = 0.041), but not of the other parameters. The same result held true when considering the restricted dataset ($\chi^2 = 6.119$, df = 1, p = 0.013). The relationships between the average glacier altitude or surface area and MPs concentration and size were non-significant for both datasets (Supplementary material), while glacier area was negatively related to the proportion of fibres (z = −2.092, p = 0.036) and marginally so in the restricted dataset (t = −1.951, df = 1, p = 0.051). A distance-based redundancy analysis (db-RDA) on Bray-Curtis dissimilarity showed that MPs polymer composition in samples also changed non-linearly with the latitude (overall test for a third-degree polynomial variation with latitude: F = 2.196, df = 3,38, p = 0.001), while population density was not significant (F = 1.114, df = 1,38, p = 0.336). The first two db-RDA dimensions contributed to 12.9 % of the variance (Fig. 3). Similar results were obtained with the restricted dataset (latitude only: F = 1.941, df = 1,36 p = 0.043; latitude and population: F = 1.671, df = 2,35, p = 0.024), with the first two dimensions explaining 8.0 % of variance. Differently from population density, HMc was a significant factor in predicting MPs composition for both the complete (F = 3.190, df = 1,38, t = 0.001) and restricted dataset (F = HMc: F = 3.030, df = 1,33, p = 0.002). To account only for the relative abundances of the polymers, we repeated the analysis using an RDA on Hellinger distance with the same predictors. Again, the third-degree polynomial of latitude was the only significant predictor (F = 1.916, df = 3,38, p = 0.008), and the first two RDA dimensions explained 12.0 % of the variance (Fig. 3). However, the same analysis run for the restricted dataset yielded both latitude and population density as significant (latitude: F = 2.092, df = 3,33, p = 0.001, population: F = 2.577, df = 1,33, p = 0.004). HMc was a significant predictor in the RDAs on Hellinger distance both for the complete (F = 3.059, df = 1,38, p = 0.004) and restricted dataset (F = 2.899, df = 1,33, p = 0.002). An indicator species analysis was run to test whether any polymer was significantly associated with specific glaciers. After FDR correction, only cellophane resulted significantly associated with the glaciers Iver, Lewis, Midtre Lovénbreen, and Steindalsbreen (IndVal = 0.89, $p_{FDR} = 0.014$, values for the association to the group of four glaciers).

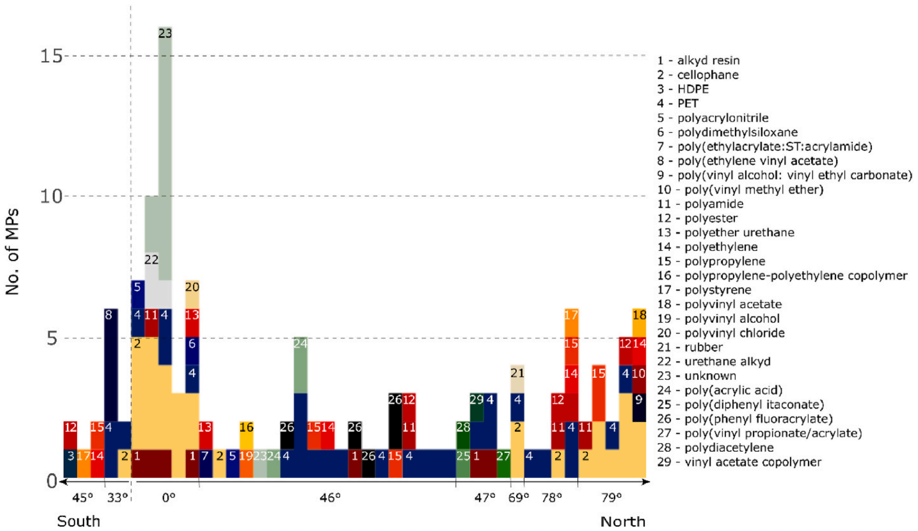

Fig. 2. Stacked bar plot of particles and their composition within each sample. Samples are ordered from South to North. Only samples where MPs have been detected are shown. The dashed vertical line represents the Equator. Polymers are identified by numbers as in the legend.

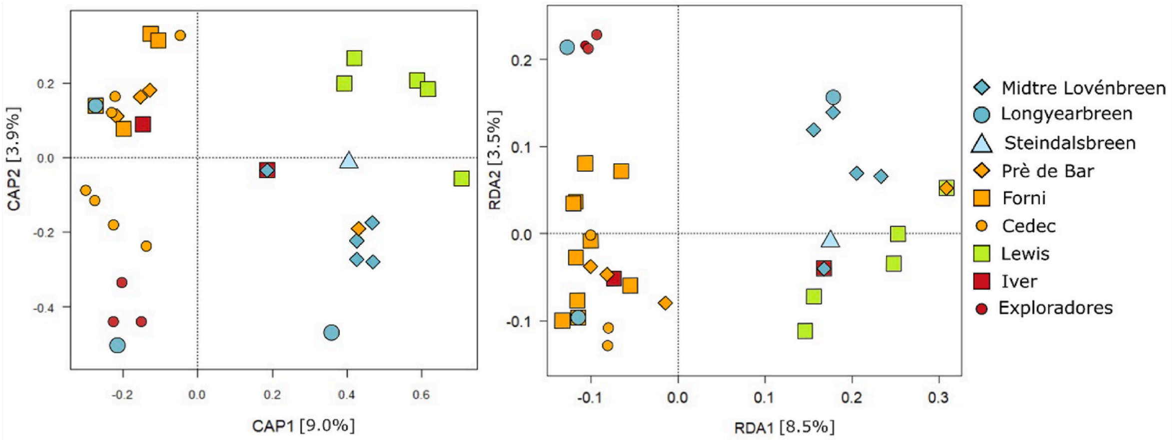

Fig. 3. Polymeric composition of MPs. Left-hand panel - dbRDA ordination plot based on Bray-Curtis' distance. CAP1, CAP2 represent the first two dimensions individuated by the dbRDA analysis, in squared brackets the amount of variance explained by each dimension. Right-hand panel - RDA ordination plot based on Hellinger distance. RDA1, RDA2 represent the first two dimensions individuated by the RDA analysis in squared brackets the amount of variance explained by each dimension. Symbol fill colors represent the geographical areas as in Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4. Discussion

MPs contamination is ubiquitous. Our results add to the available knowledge by disclosing patterns of MPs contamination in some of the most remote areas of the globe, including alpine and polar glaciers. We highlight that the concentrations in this study are still clearly inferior to those on glaciers with significant infrastructures (Crosta et al., 2022). MPs are present regardless of the distance from highly populated areas (our results) and the intensity of human presence – as shown by studies in other glacial areas (Cabrera et al., 2022; Zhang et al., 2019) and by the very low HMc values for some sampled glaciers in our study. While differing in the average HMc values in the buffer areas, all our study sites are visited by tourists and mountaineers, although without any substantial infrastructure (e.g. ski slopes). As the equipment used for outdoor activities is similar all over the world, the polymers released by them should be uniform across all sites. However, the absence of polymers common to all glaciers suggests that atmospheric deposition may be more relevant than human activity in the studied sites.

We found a striking non-linear latitudinal trend in the concentration of MPs on a large latitudinal scale. This trend followed a third-degree polynomial function with a maximum at the Equator, a minimum at mid-latitudes, and a new increase at the northernmost latitudes. The same pattern occurred in the proportion of fibres – with two relative maxima at the Equator and the northernmost latitudes – as well as in the polymeric composition of MPs, both when accounting for absolute and relative abundances of polymers. The trend for particle size was slightly different, with bigger particles detected in the Alps. The trends were marginally non-significant when repeating the analyses on the restricted dataset, suggesting that the trends are robust, and warranting further analysis with more latitudinal replicates. The consistency of the results suggests that latitude might be a driver of MPs deposition. Contrary to our expectations, neither population density within 100 km from the glacier, nor altitude or surface extent of the glaciers appeared to significantly affect MPs deposition and polymer composition. In fact, the highest concentrations could come unexpected, as they were observed in a large, long established national park (Mount Kenya National Park), and in polar areas (Svalbard Archipelago) with limited human population. However, a more comprehensive metric of human impact, such as the HMc, clearly outperformed population density and significantly predicted MPs size and polymeric composition.

Both MPs and other contaminants can show a latitudinal variation in distribution, which is a function of the intensity and closeness of sources and the potential for atmospheric transport of the emitted particles. MPs in the Atlantic Ocean show a latitudinal variation, although no proper trend in MPs concentration was found, suggesting the single location, rather than latitude itself, was the main driver of MP concentration (Kanhai et al., 2017). Therefore, as of our knowledge, this study is the first to detect a clear latitudinal pattern in MPs contamination. This pattern is partly consistent with the latitudinal distribution of dust and polluted dust (Mehta and Singh, 2018), which show lower concentrations in the Southern Hemisphere and a maximum close to the Equator. However, the increase in concentrations at the northernmost latitudes we found for MPs was not detected for dust (Mehta and Singh, 2018). Such difference may be due to the extremely different sources of dust and MPs. In addition, MPs wet deposition rates are positively correlated with dust deposition (Brahney et al., 2020), suggesting that at the northernmost latitudes, dry deposition could prevail.

The increase in concentrations with latitude in the Northern Hemisphere is known for some contaminants such as fluorene, phenanthrene and hexachlorobenzene (Gioia et al., 2006; Jaward et al., 2004). The sources of these organic pollutants probably correspond better to those of MPs than those of dust, which might cause the similar increase in concentration at northern latitudes. However, as both MPs and dust are particles suspended in the atmosphere, their potential for atmospheric transport can be considered more similar than those of MP and the other above-cited contaminants. Indeed, in some areas of the world the deposition rates of MPs and dust are positively correlated (Brahney et al., 2020).

Glacier altitude and surface are factors that may affect MPs deposition, however – when tested – these parameters were not significant. Glacier surface seems to have a slightly negative effect on the proportion of fibres, but the reason behind this is unclear.

Population density and HMc in a radius of 100 km can be both considered a proxy for the closeness of MPs sources (Allen et al., 2019) and for MPs emission intensity. However, population density alone was not a significant predictor of MPs concentration, shape, size and did not substantially improve the explained variance in the polymeric composition with respect to models with the polynomial of latitude as the only predictor (latitude only: $R^2_{adj} = 0.095$; latitude and population density: $R^2_{adj} = 0.100$). In turn, HMc significantly predicted MPs size and polymeric composition in most models (see Supplementary Materials). Given that this index includes human activities such as agriculture and mining, it is better suited to determine human impact in areas surrounding the studied sites and to evaluate possible MPs sources. The HMc and other human modification indices were significant predictors of MPs concentration also in other studies, based on environmental matrices (e.g. stormwaters, Reshadi et al., 2025) and organisms (e.g. estuarine bivalves, Vasques Ribeiro et al., 2025) also at a broader geographical scale (Jankauskas et al., 2024). This suggests that synthetic indices of anthropogenic habitat modification are robust predictors for MPs contamination across very different ecological compartments, and should be considered in the sampling design, analysis and modelling when studying MPs spatial distribution. The results of models including HMc suggest that short-range transport of MPs involves particles with different size and composition than long-range transport. However, we did not detect this discrepancy when considering particle shape, which should also play a role in the transport potential of MPs. Nonetheless, both particle size and proportion of fragments were highest in samples from the Alps, where HMc also peaks, suggesting that a clearer pattern regarding MPs shape could be detected with a broader choice of sampled points. We suggest that depending on the size of the urban areas, industrialization level, land use, and national and international regulations, different areas of the world could be sources for different polymers (Schwarz et al., 2023), contributing to the diversity in MPs contamination pattern. On the other hand, distance from densely populated areas and other human activities – most of which are included in the HMc – could also contribute to the diversity in MP composition in our samples, by selecting more buoyant low-density plastic items (such as fibres), favoured in long-range atmospheric transport. Indeed, results obtained for the Exploradores and Svalbard glaciers, which are surrounded by areas with low HMc and low population densities, confirm similar polymeric compositions of the detected MPs both when accounting for absolute abundances (db-RDA) and relative abundances (RDA). Low-density MPs, such as polyethylene, polypropylene, and polyester fibres prevail on all three glaciers (Fig. 2). These glaciers are in the so-called “high-latitude areas” following a working definition used for dust deposition, i.e. areas at latitudes higher than 40°S and 50°N respectively (Bullard et al., 2016; van Soest et al., 2022). The environmental conditions and low human activities in these areas could be a factor in determining this resemblance. Accordingly, polyester is found more often in samples from remote areas (Fox et al., 2024). Additionally, the RDA analysis on the restricted dataset using the absolute value of latitude is not significant, suggesting no correspondence between the polymeric composition of samples from mid-latitude glaciers of the Northern and Southern hemisphere. As shown by the plot of the db-RDA, the Exploradores and Iver glaciers also bear a resemblance to mid-latitude Alpine glaciers. Since Bray-Curtis’s distance accounts for the absolute abundances, this similarity might be due to the low absolute abundance of MPs in these two areas. Indeed, when accounting only for relative abundances (RDA), the Iver Glacier clustered with Alpine glaciers and the Lewis, while the Exploradores clustered with a sample from Longyearbreen. Reasons for the significant association of cellophane to the glaciers Iver, Lewis, Midtre Lovenbreen, and Steindalbreen are unclear, and might be due to local emission sources.

Other characteristics of the studied glaciers – such as altitude and glacier surface – do not seem to play a clear significant role in determining MP concentrations, shape occurrence, size or composition, strengthening the prominence of latitude in influencing MPs deposition.

Indeed, latitude significantly affects MPs concentration, shape, size, and polymeric composition, suggesting atmospheric transport as the main driver of MPs contamination. The Human Modification metric (HMc) is an important predictor of particles’ size and composition and should be considered when modelling MPs deposition. Consistent global patterns are fundamental to constrain the atmospheric limb of the global plastic cycle and to model MPs deposition. In turn, these aspects are necessary to assess hazards due to MPs themselves and additives, highlighting the importance of further studies with more sampled sites.

5. Conclusions

MPs contamination in supraglacial sediment is the product of deposition from the atmosphere or local sources. As no single polymer has been detected on all the sampled glaciers, it is reasonable to assume that leisure activities on the glaciers (e.g., tourism), which all imply the same gear and materials, are not the main contributor to MPs contamination in the studied sites. The detected latitudinal trends in MPs concentration, composition, size, and shape are robust, even when removing possible outliers. However, the mechanisms behind these trends are unclear. Robust trends have also been detected between particle size and composition and the Human Modification metric in the areas surrounding the studied sites. Further studies with a broader geographical range of sampling and focusing on MPs transport in the atmosphere are fundamental to improve our understanding of the matter.

CRediT authorship contribution statement

Arianna Crosta: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Beatrice De Felice:** Writing – review & editing, Investigation. **Viviana Minolfi:** Investigation. **Roberto S. Azzoni:** Writing – review & editing, Investigation. **Francesca Pittino:** Writing – review & editing, Investigation.

Andrea Franzetti: Writing – review & editing, Investigation, Funding acquisition. **Marco A. Ortenzi:** Writing – review & editing, Methodology. **Stefano Gazzotti:** Writing – review & editing, Methodology. **Valentina Gianotti:** Writing – review & editing, Resources, Methodology, Investigation. **Maddalena Roncoli:** Investigation. **Eleonora Conterosito:** Writing – review & editing, Resources, Methodology, Investigation. **G. Francesco Ficetola:** Writing – review & editing, Investigation, Funding acquisition. **Rahab N. Kinyanjui:** Writing – review & editing, Investigation, Funding acquisition. **Marco Parolini:** Writing – review & editing, Resources, Methodology, Investigation, Conceptualization. **Roberto Ambrosini:** Writing – review & editing, Investigation, Formal analysis, 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.

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Lewis: NACOSTI permit P/20/7339 (2020–2021) to RNK and NACOSTI permit NACOSTI/20/3981 to GFF; Longyearbreen and Midtre Lovénbreen: RiS permit ID 11115 (2018–2023) to RA; Exploradores: CONAF permit N. 019/2018.

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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.2025.121553.

Data availability

Datasets are available at the following permanent link: https://doi.org/10.13130/RD_UNIMI/PNVC2I, under the title "Replication Data for: Global patterns of microplastic contamination in remote areas".

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