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Research article

Geographical distribution of plastic items in the mountains of Lombardy region–Northern Italy

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ABSTRACT

Mountain environments are becoming receptacles for plastic pollution due to the increasing use and improper disposal of plastic products. However, data on plastic occurrence in mountain ecosystems remains scarce. This study fills this gap by providing an assessment of plastic waste distribution in high-altitude landscapes. We collected plastic items (both mesoplastics and macroplastics) along 28 transects in the Alps and Prealps of Lombardy – Northern Italy. Items were classified by weight, size, original use, and polymer composition. GPS coordinates of plastic item positions were recorded along 21 of these transects. Plastic items (979 overall) were found along all the transects. On average (± standard error), 34.96 ± 5.10 plastic items per transect were found, corresponding to 24.30 ± 37.29 g km^{-1}. Polypropylene (24.92 %), polyethylene (15.71 %), and polyvinyl chloride (10.83 %) were the most abundant polymers, while food packaging (31 %), mountain clothes (5 %), health care (5 %), and mountain equipment (4 %) were the most represented original uses. *In-situ* abandonment seems, therefore, the predominant source of plastic waste along mountain paths. Plastic distribution seems not related to the presence of mountain refuges (i.e., staffed mountain structures), altitude, geographical position, or frequentation of the transects (assessed using STRAVA tracks). However, the mean number of items decreased from the start to the end of the transects, with most items found in the first km. Straightforward policies, such as placing recycling bins at the start of mountain paths, promoting portable trash cans for backpackers, and conducting awareness campaigns against plastic abandonment, could effectively reduce plastic dispersion in mountain areas.

1. Introduction

Since their discovery, plastic materials have provided solutions to numerous challenges across various technological sectors. Plastic materials are obtained through the polymerization of small organic compounds (i.e., polymers), derived from petroleum or other natural substances, into long molecular chains (Melo and Watanabe, 2022). There are numerous types of plastic materials, including modified natural polymers, thermosetting plastics, thermoplastics, and biodegradable plastics that can be alternatives to traditional plastics and their uses (e.g., Andrady and Neal, 2009; Lamba et al., 2022; Moshood et al., 2022; van der Vegt, 2006). The most widely produced polymers are polyethylene (PE, both high and low density), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and polystyrene (PS) (Andrady and Neal, 2009; Plastics Europe 2023). Their use has become frequent and irreplaceable in many daily activities (e.g., Marhoon et al., 2024; Melo and Watanabe, 2022) and, in this respect, the success of plastics has been substantial (Napper and Thompson, 2023).

Despite their advantages and widespread use, the transport and improper disposal of plastics lead to their entry into the environment,

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where they are exposed to environmental factors that promote ageing, fragmentation, and degradation. (e.g., Andrady, 2017; Barnes et al., 2009; Barrett et al., 2024). According to their size, plastic pollutants are classified as macroplastics (>25 mm), mesoplastics (5–25 mm), microplastics (1 μm −5 mm), and nanoplastics (<1 μm) (e.g., Alimi et al., 2018; Hassan et al., 2023; Loganathan and Kizhakedathil, 2023; Lim et al., 2023).

Since the ‘70s, plastics have become widely recognized as pollutants and a significant environmental risk on a global scale as plastic contamination has been reported in both all marine and terrestrial environments, including remote areas (e.g., Allen et al., 2019; Ambrosini et al., 2019; Zhang et al., 2021). Plastics affect also living organisms (e.g., Akdogan and Guven, 2019; Caixeta et al., 2018; Silva et al., 2021), for instance, they can be ingested and thus enter the ecological food chains (e.g., Caruso et al., 2022; Khalid et al., 2021; Kumar et al., 2021; Lusher et al., 2013; Thompson et al., 2004; Wright et al., 2013). Furthermore, they have the potential to cause negative consequences in some ecosystems and release chemicals that are hazardous to the environment and human health (e.g., Blettler and Mitchell, 2021; Napper and Thompson, 2023; Ragusa et al., 2021; Schwabl et al., 2019; Williams and Rangel-Buitrago, 2022). Polycarbonates, for example, during chemical and physical degradation, can release bisphenol-A, which is a known endocrine disruptor (e.g., Ben-Jonathan et al., 1999; Freitas et al., 2017; Rochester, 2013). In addition, polymers are rarely used in their pure form, as sometimes they are mixed with additives to improve performance and appearance, and these additives can further contribute to the spread of toxic substances into the environment (e.g., Andrady and Neal, 2009; Cole et al., 2011; Lechthaler et al., 2020; Montagner et al., 2021; Zhang et al., 2024).

Due to their nature, plastic polymers persist in the environment potentially for a long time (e.g., Ali et al., 2024; Sahu et al., 2023; Wright et al., 2013). Thus, plastic pollution has raised additional concerns because it may cause future detrimental effects to the ecosystems and biodiversity through effects that are currently not fully understood and quantified (Caruso et al., 2022; Kumar et al., 2021).

Despite the recognition of plastic pollution as a global concern, there is still no binding international agreement on its use and disposal, but only agreements that consider the sharing of information, plans, measures, and best practices to combat and reduce plastic pollution (Ministry of the Environment of Japan, 2019; Kraemer, 2017). In addition, although strategies established by the United Nations exist for managing plastic waste, practical problems persist that undermine the ability of the international community to solve these problems and, in turn, to implement the Sustainable Development Goals (SDGs) (e.g., Andriamahefazafy et al., 2022; Arora et al., 2023; Cummings et al., 2017; Haas, 2023; He et al., 2024; Islam et al., 2024; Johansen and Vestvik, 2020; Lebreton and Andrady, 2019; Nash et al., 2020; The Global Goals, 2025; Walker, 2021). For these reasons, plastic pollution has been recognized as one of the great challenges of our time, mainly due to its high degree of pollution, persistence, and distribution in various environments (Islam et al., 2024; Nava et al., 2023).

Mountain regions are not exempt from plastic contamination (e.g., Allen et al., 2019; Ambrosini et al., 2019; González-Pleiter et al., 2020; Parolini et al., 2021a, 2021b). Large plastic items in the size range of mesoplastics (MePs) and macroplastics (MaPs) can enter the mountain environment by being directly dispersed into the mountain environments, both intentionally (e.g., by the deliberate abandonment of mountain equipment often made of plastics by expeditions; (e.g., Napper et al., 2020; Parolini et al., 2021a, 2021b) and accidently (e.g., the fall of plastic equipment during an ascent; Parolini et al., 2021a, 2021b). Indeed, studies in different mountain regions, such as Forni Glacier in the Italian Alps (Ambrosini et al., 2019), Mount Everest, Nepal (Napper et al., 2020), Himalayas (Talukdar et al., 2023), and Tibetan Plateau (Zhang et al., 2021), have shown that plastic pollution in high-altitude environments is often linked to anthropic activities, tourism, climbers' clothing and equipment, and inadequate waste management (Padha et al., 2022).

Furthermore, microplastics (MPs) and nanoplastics (NaPs) can derive from the breakdown of these larger plastic items or by transport from surrounding areas (e.g., Allen et al., 2019; Evangeliou et al., 2020; Thompson et al., 2004; Zangh et al., 2021). All these plastic items harm mountain ecosystems worldwide, which are of vital importance for many human populations (Gloersen et al., 2004), and fragile due to their extreme conditions and the often short and scarcely redundant ecological networks they host, which make them particularly vulnerable to contamination, including that from plastics (e.g., Crosta et al., 2022; Parolini et al., 2021a; Parolini et al., 2024). The United Nations considers plastic debris as one of the biggest challenges globally (Napper and Thompson, 2023). In addition, to raise awareness of the importance of protecting mountain ecosystems, the United Nations declared 2022 as the "International Year of Sustainable Development for Mountains" (United Nations General Assembly (UNGA), 2002). This effort has highlighted a crucial need for detailed information on mountain pollution, particularly concerning plastics. However, there is still a lack of information regarding the presence of plastics in mountains (Parolini et al., 2021b), and most research has focused on aquatic mountain environments, which also have hydrogeomorphological characteristics that can enhance the mechanical degradation and dispersion of plastic items (e.g., Liro et al., 2022; Liro et al., 2023; Zielonka and Liro, 2024). In contrast, very few studies have focused on terrestrial mountain environments.

1.1. *Aim: Plastic pollution in the Alps and Prealps*

In Italy, mountain areas suffer high anthropic pressure due to their relatively high population densities (Parolini et al., 2024), and tourist exploitation related to the recreational opportunities they provide to the close, highly populated lowlands (e.g., Ebner et al., 2022; Crosta et al., 2022; Feng et al., 2021; Jäger et al., 2020; Parolini et al., 2024). Not surprisingly, plastic polymers have been found in the Italian Alps in rather large amounts, also at high altitudes (Ambrosini et al., 2019; Parolini et al., 2024). To date, the few studies that have investigated plastic pollution in the Italian Alps have observed the presence of MPs in the snow (Azzoni et al., 2018) and of both MPs and MaPs on glaciers (e.g., Ambrosini et al., 2019; Parolini et al., 2021a, 2021b; Crosta et al., 2022). However, plastic pollution in terrestrial mountain ecosystems remains largely unexplored compared to marine, freshwater, and other terrestrial habitats, representing a significant knowledge gap (Parolini et al., 2021b). In this work, we investigate the distribution of plastic items in the size of MePs and MaPs (i.e., all plastic items >5 mm in size) in the Alps and Prealps of Lombardy (a first-level administrative division located in the north of Italy), across a wide range of altitudes and geographical locations (Fig. 1). We thus aim to fill a knowledge gap regarding plastic pollution in Italian mountain ecosystems. Understanding the distribution and sources of plastic waste in these environments can ultimately contribute to planning future strategies to manage and mitigate plastic pollution in mountain environments.

2. Methodology

2.1. *Study area and field methods*

This research was carried out in the Alps and Prealps of Lombardy, a 23,844 km^2-wide region in Northern Italy, where mountain ranges cover 40.5 % of the territory (Marazzi, 2005). This area is in the center of the Italian part of the Alpine chain, which is densely inhabited and close to urbanized areas, such as the cities of Sondrio (~21,000 inhabitants), Brescia (~197,000 inhabitants) and Bergamo (~121,000 inhabitants) in Lombardy, Verona (~257,000 inhabitants) and Vicenza (~112,000 inhabitants) in the close Veneto region.

Plastic items were collected along 28 transects (Fig. 1), averaging (± standard deviation) 5.71 ± 2.94 km. between July 8th, 2020, and

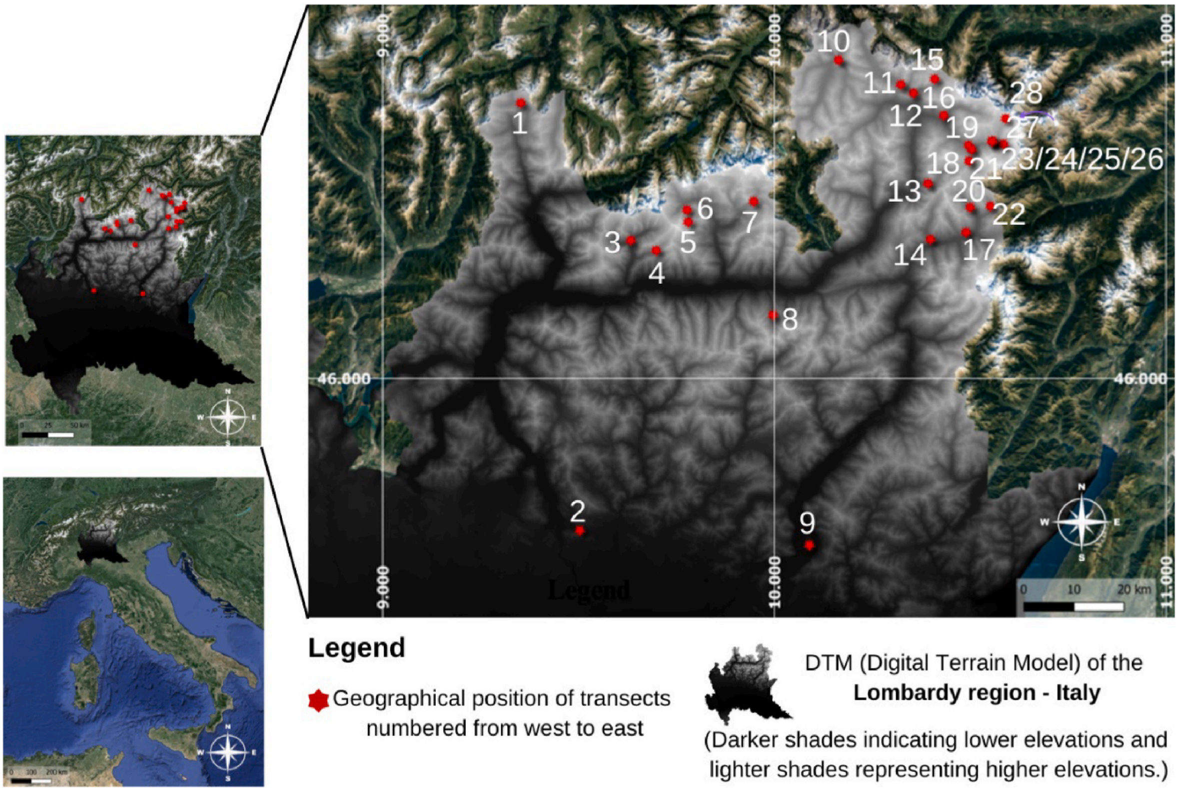


Fig. 1. Map of the geographical distribution of the transects. Panels show the position of Lombardy in Italy and the Alps and Prealps of Lombardy. Transects are numbered from west to east.

January 4th, 2024. They spanned between 45.70° N and 46.56° N and 9.35° E and 10.59° E (coordinates of the starting point of each transect) at an altitude between 501 and 3033 m above sea level (m a.s.l.; Fig. 1; Table S01). The transects followed existing mountain paths and were selected opportunistically based on path accessibility and the presence of operators in the area, allowing for covering a representative range of altitudes and geographic characteristics. The goal was to ensure sampling from different areas within the Alps and Prealps of Lombardy, including areas that may be more prone to plastic accumulation due to human activity and tourism. They were travelled by foot at an average speed of 2.14 ± 1.26 km h^{-1} (N = 25 transects). Full details of each transect characteristic are available in Table S01.

The 28 transects covered broad variations in altitude, level of human frequentation, and proximity to refuges. In a subset of 21 transects (ID 02, 03, 09–27; Fig. 1), the position of each item of anthropogenic origin, which was presumably made of plastics, was also determined with a GPS and marked. GPS data was not recorded for the remaining 7 transects due to technical issues during fieldwork. Sample collection was performed within a 2-m-wide strip on both sides of each transect. To ensure consistency, all transects were sampled under good weather conditions, avoiding rain, snow, and strong winds. All visible plastic fragments (>5 mm) were collected in cotton bags, then wrapped in aluminum foil marked with the identification code of the transect and transported to the laboratory for subsequent analysis.

According to the criteria established in the literature, macroplastics (MaPs) were defined as plastic items >25 mm in size, while mesoplastics (MePs) were those between 5 mm and 25 mm. To prevent cross-contamination, all collection tools were cleaned between transects, and the operators used nitrile gloves throughout the sampling and transport process.

2.2. Laboratory analysis and plastic identification

In the laboratory, all sampled items were washed with filtered ultrapure water and dried at room temperature, measured with a ruler (±1 mm), weighted using either of two laboratory scales (precisions of ±0.01 g and ±0.1 mg), and photographed. Each item was then classified according to its presumed use into six categories: food packaging, mountain equipment, mountain clothing, health care products, others (i.e., items with a presumed use different from the previous categories), and unknown (all materials for which we could not identify a possible use).

The categorization was based on identifiable features such as shape, material, labeling, and branding, when available, following Parolini et al. (2021b). For instance, when we found part of a plastic bag reporting the label, or the brand, or (part of) the list of ingredients of a snack, we classified this item as “food packaging”; Conversely, if the label, brand, or ingredients were those of a medicine, we classified the item as “health care”. A detailed list of item types included in the different categories is reported in Table S03.

After further washing with filtered ultrapure water, each item was analyzed with a Spectrum 100 - Fourier Transform Infrared (FTIR) spectrometer to obtain information regarding its chemical composition. In detail, the FTIR spectrometer was run in attenuated total reflection (ATR) mode with a resolution of 4.0 and 256 scans in a range of wave numbers between 4000 cm^{-1} and 400 cm^{-1}. The polymeric composition of each plastic item was finally identified by comparing the spectrum obtained with those present in the databases provided by the PerkinElmer library. Polymers were identified when the matching between the observed spectrum and that in the library was >0.8. When the matching was <0.8, items were classified in the “unknown” category. All spectra were also visually checked by the authors to confirm the matching.

FTIR was chosen due to its rapid, non-destructive nature and high accuracy in polymer identification. Compared to Raman spectroscopy, FTIR is less affected by fluorescence interference, and unlike pyrolysis-GC/MS, it does not require destructive sample preparation. The identified polymers were then further grouped into six polymer macro-categories: acrylates, polyesters, polyolefins, other types of polymers (e.g, rubber, polycarbonate, etc.), and non-plastic substances (aluminum, other metals, glass, wood, cotton, other cellulose fibers, wool) following Parolini et al. (2021b). Items made of natural polymers (i.e., cotton, wood, wool, and cellulose) were included in the "non-plastic substances" category in the analyses of polymer macro-categories, but they were excluded from the analyses based on the polymeric composition of plastic items.

2.3. Potential determinants of plastic items distribution

The geographical position of each transect was entered as the latitude and longitude of its starting points, while altitude was assessed as the mean between the highest and lowest altitude points of the transects.

To have an index of human frequentation, we extracted the number of visitors along each transect from crowdsourcing data obtained from the social sports network STRAVA (https://www.strava.com). This network allows users to track and monitor their outdoor physical activities through its digital platform, and these data provide information for evaluating the real human presence in natural environments (Pla et al., 2024). The STRAVA database was accessed between July 10th and July 17th, 2024 through the link https://www.strava.com/heatmap. This online tool allowed visualizing, selecting, and considering all tracks recorded by STRAVA users. All sports were selected, and the number of performances (i.e., the number of times a given path was travelled by the same or by different people) was noted. Finally, the human frequentation index was obtained by dividing the number of STRAVA tracks by the length of the transect. Thus, our human frequentation index represents the mean number of people who have travelled in a distance unit of that transect. We note that while the STRAVA dataset provides valuable insights into visitor distribution, it may not fully capture all human presence, as it primarily reflects activities recorded by STRAVA users.

We also obtained the positions of mountain refuges in Lombardy from ERSAF Lombardy through the link https://www.ersaf.lombardia.it and used them to define a dichotomous variable indicating whether a transect crossed a refuge or not. We hypothesized that the presence of refuges may increase human frequentation and therefore affect plastic distribution.

2.4. Statistical methods

The analyses of the polymeric composition were performed by considering the total mass of the plastic items made of each polymer, divided by the total length of the transects to account for their different lengths. The analyses where we considered polymer macro-categories or use categories were based on the total mass of plastics in each category per km of transect. The number of MePs and MaPs in each use category and transect was counted, and their amounts were compared between use categories with the Kruskal-Wallis test followed by Dunn post-hoc tests. These tests were chosen over ANOVA due to deviations from the normality assumptions of ANOVA models.

Multi-dimensional scaling (MDS) was used to represent the polymeric composition of both MePs and MaPs along different transects. These analyses were based on the Bray-Curtis dissimilarity index, as it accounts for differences in the absolute abundance of polymers (Legendre and Legendre, 2012). The same approach was used for polymer macro-categories and use categories. Variables potentially affecting the plastic items distribution (i.e., latitude, longitude, altitude of the transect, number of STRAVA tracks per km of the transect, and whether the transect crossed a refuge) were also plotted on MDS biplots. The MDS was chosen as a descriptive statistical method to explore the patterns of plastic distribution, rather than to perform formal hypothesis testing, because the sampling strategy was opportunistic rather than random or specifically designed for inferential analyses. Indeed, MDS allows for a visual interpretation of trends in the data without making strong statistical assumptions.

GPS data were used to analyze the number of plastic items found at different distances from the beginning of the transect. To account for the different lengths of transects, the length of each transect was normalized to unity, and the number of plastic items found in each 5 % section of the transect was counted. The number of items in each section was then related to the mean normalized distance of that section from the start of the transect in a negative binomial generalized linear mixed model (GLMM) where transect identity was entered as a random grouping factor.

Statistical analyses were performed using the R statistical software (version 4.0.2; R Core Team, Vienna, Austria) with the R packages vegan (version 2.5.7) and glmmTMB (version 1.1.2.3). The distribution of plastic items was mapped using QGIS software (version 3.34 LTR for Windows).

3. Results

On the 28 transects, we found 979 items of anthropogenic materials with a total weight of 3784.206 g. On average (± standard deviation), we found 34.96 ± 5.10 (range 2–93) items per transect, corresponding to 7.14 ± 4.87 items km^{-1} (range 0.14–16.9 items km^{-1}). The items were on average 8.56 ± 11.49 cm (range 0.6–152.5 cm) in length along the main axis, the mean weight was 3.87 ± 23.32 g (range 2.2 mg–379.00 g) and the average amount per km was 24.30 ± 37.29 g km^{-1} (range 0.80–162.69 g km^{-1}).

3.1. Use categories and spatial distribution

Food packaging (31 %) was the most frequent original use of anthropogenic items, followed by mountain clothes (5 %), health care products (5 %), and mountain equipment (4 %). Other and unknown uses represented 24 % and 31 % of items, respectively (Fig. 2).

The Kruskal-Wallis test showed significant differences in the average abundance of items per km of transect between categories ($\chi^2 = 70.21$, $df = 5$, $P < 0.001$) and Dunn post-hoc tests showed that food packaging, other and unknown plastics were significantly more abundant than mountain clothes, mountain equipment, and health care products ($|z| \geq 3.973$, $P \leq 0.001$; $|z| \leq 1.113$, $P \geq 0.393$ in all the other cases) (Fig. 3).

3.2. Polymer composition and sources

The most abundant polymers collected along each transect were polypropylene (24.92 %), polyethylene (15.71 %), and polyvinyl chloride (10.83 %) belonging to the polyolefin macro-category, and polyethylene terephthalate (9.97 %) belonging to the polyesters macro-category (Table 1, Fig. 4). According to a broader classification, these most abundant polymers were polyolefins (57.85 %) and polyesters (10.83 %) (Table S02), which are commonly found in food packaging (Behera et al., 2022), because they are exceptionally durable in the environment. All the other polymers represented <10 % in weight of plastics found (Table 1, Fig. 4). Further information on the most abundant polymers, their main uses, and environmental pathways and concerns are reported in Table 1.

3.3. Environmental influences on plastic distribution

MDS analyses showed a large overlap between transects crossing or not a refuge, suggesting that the presence of a refuge does not affect plastic item distribution and composition. However, some transects with a refuge seem associated with mountain clothes and polymers classified as "others" in the polymer macro-categories (Fig. 5a).

The abundance of the items with unknown use seems also positively

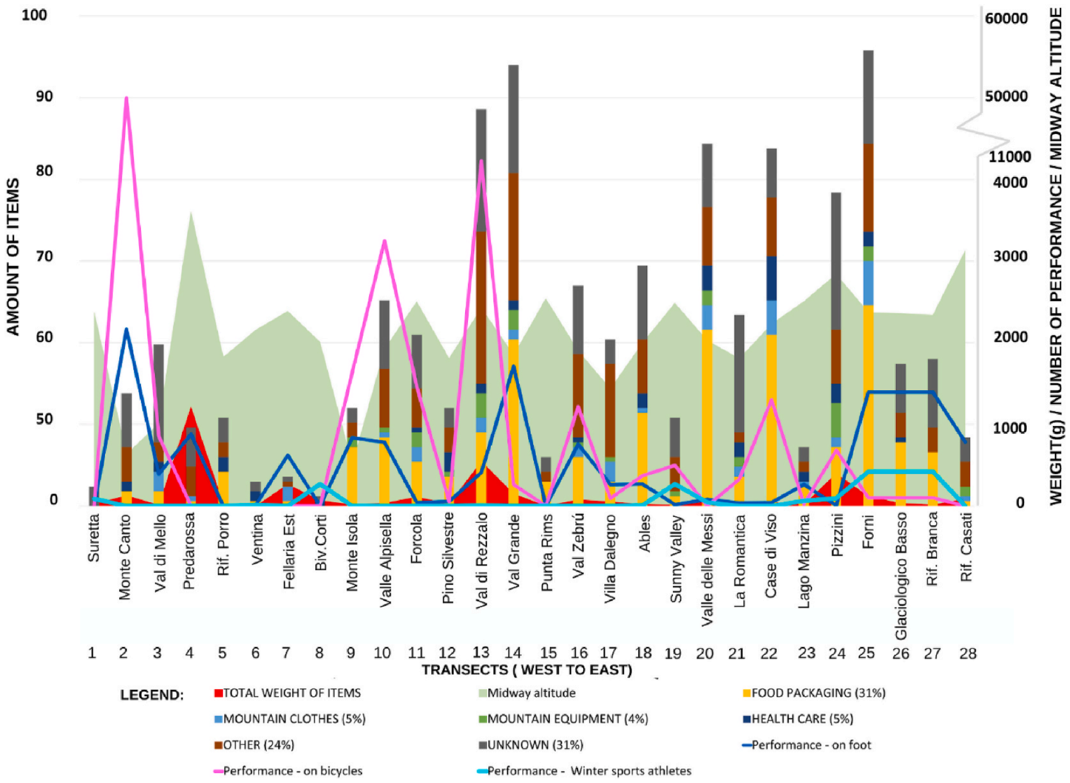


Fig. 2. Summary information on items found in each transect and transect features. The stacked bars represent the number of items in the different use categories on each transect. Percentages are reported in the graph legend. The red area represents the total weight (g) of items on each transect. The green area indicates the mean altitude (m a.s.l.) between the highest and lowest point of each transect (midway altitude). The blue, pink, and cyan lines represent the mean number of STRAVA tracks for athletes, respectively, on foot, bicycle, and winter sports on each transect per km of transect. Transects are reported from west to east and numbered according to Fig. 1.

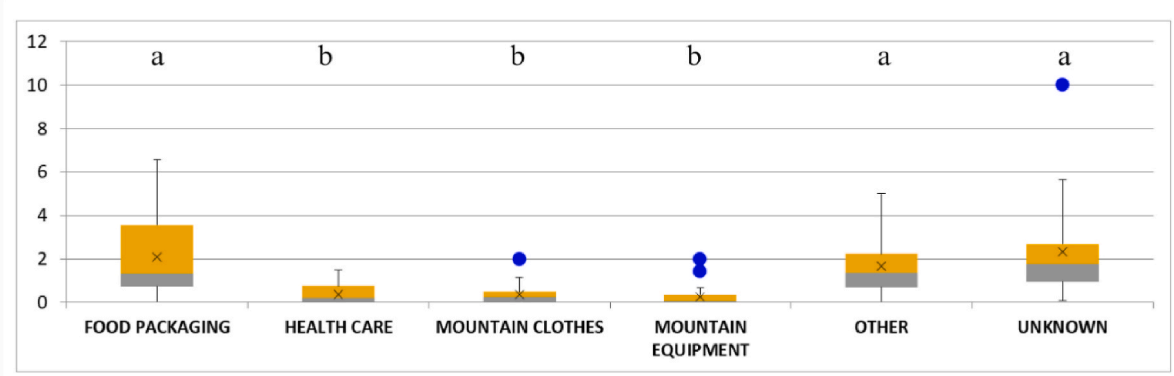


Fig. 3. Boxplot of the number of items per km of transect in the different use categories. The box represents the interquartile range; the change of colour represents the median, while the x symbols represent the mean value; blue dots represent outliers, while the whiskers extend to the lowest and the highest values except for outliers. Different letters indicate significant differences between categories at Dunn's post-hoc tests.

associated with transect altitude as shown by the proximity of the centroid of this category to the vector representing this variable (Fig. 5a). Altitude seems also important in shaping the composition of plastic items both in terms of use and polymer macro-category, as indicated by the length of the vector representing this variable (Fig. 5b and c). Longitude seems related to item use, as suggested by the length of the vector, although no use category seems strictly related to this variable (Fig. 5a). The other variables, including the number of tracks in the STRAVA database, seem to have relatively low importance for plastic items composition (Fig. 5).

STRAVA tracks were by hikers, bikers, and winter sports athletes only (Fig. 2).

3.4. Distribution patterns along transects

The analysis of the exact positions of plastic items showed that their frequency decreased with the relative distance from the start of the transects and was not affected by the presence of a refuge along it (Table 2, Fig. 6). Indeed, the largest number of items was found in the first km of the transect (Fig. S02).

Table 1
Most abundant polymers collected along transects, their main uses, environmental concerns, potential impacts in mountain environments, degradation and persistence, and management and policy considerations.

Polymer	%	Polymer Macro-category	Main Uses	Density	Environmental Concerns and Potential Impacts in Mountain Environments
Polypropylene (PP)	24.92	Polyolefin	- Commonly found in food containers (Health and Environment Alliance, 2020; Plastics the facts, 2019).	0.89–0.91	- Low density, facilitating its dispersion in the environment (Li et al., 2021); - Resistant to biodegradation (Carvalho and Rosa, 2016); - Undergoes photodegradation, with predominant chain splitting reactions under exposure to UV radiation, becoming brittle and fragmenting over time (Fechine et al., 2006); - Photooxidation under natural light accelerates the degradation of PP (De Souza et al.,); - Formation of MPs due to progressive fragmentation, reduction of mechanical resistance; - Possible release of chemical compounds into the environment.
Polyethylene (PE, LDPE, HDPE)	15.71	Polyolefin	- Bottles, bags, containers (HDPE: caps, detergent bottles, toys; LDPE: plastic films, bread bags, frozen food packaging) (Alabi et al., 2019; Health and Environment Alliance, 2020; Plastics-the facts, 2019).	0.91–0.97 (LDPE: 0.91–0.94; HDPE: 0.94–0.97)	- Highly resistant to biodegradation (Carvalho and Rosa, 2016) PE can lose only 0.2 % of weight in 10 years (Montazer et al., 2020) due to its hydrophobic chemical structure and high molecular weight. The lack of polar functional groups and the high structural stability make attacks by microorganisms very difficult. - Need for previous abiotic degradation (UV, heat, oxidation) for microorganisms to initiate polymer fragmentation (Nowak et al., 2012); - Differences in crystallinity between LDPE and HDPE influence their degradation behaviour (Kesti and Sharana, 2019).
Polyvinyl chloride (PVC)	10.83	Polyolefin	-Building materials, health care, sport equipment, home, packaging components, products for consumers, and others (Edo et al., 2024; Plastics-the facts, 2019); -Medical devices packaging, health care (Ugoeze et al., 2021; Plastics-the facts, 2019),	1.3–1.5	- Contributes to chemical pollution and health risks (e.g., Alabi et al., 2019; Kudzin et al., 2024; Proshad et al., 2018); - Highly resistant to biodegradation (Carvalho and Rosa, 2016; Edo et al., 2024); - Bioaccumulation of Contaminants due to the slow release of toxic additives; - Its high density favours its accumulation in the soil; - PVC causes modifications to the microenvironment (Edo et al., 2024.
Polyethylene terephthalate (PET)	9.97	Polyester	-Beverage bottles, food packaging, textiles, and various applications (Health and Environment Alliance, 2020; Plastics-the facts, 2019).	1.3–1.4	- Resistant to biodegradation and persistent in the environment (Taniguchi et al., 2019; Webb et al., 2013; Joseph et al., 2024); - Its high density reduces aerial dispersion and favors its sedimentation in water bodies. Crystalline PET is more resistant to degradation. PET microplastics can accumulate in soils and waterways, affecting local ecosystems; - Improper disposal continues to challenge plastic waste management, because it is recyclable but durable (Macedo et al., 2020; Pudack et al., 2020).
Other polymers	23,51	Various	-Mixed industrial and consumer products, including cables, bicycle parts, wire parts, and electronics (Parolini et al., 2021a).	–	- Accumulation in isolated mountain regions; - Potential release of chemicals used as additives or coatings; - Fragmentation over time can lead to MPs and NPs formation, affecting soil, water, and local biodiversity; - Difficult waste management: these polymers may not be easily recyclable or degradable, leading to long-term accumulation.
Unknown	15.06	Unknown	- Unidentified plastic items; -Possibly complex blends or chemically altered materials (Parolini et al., 2021a).	–	- Possible long-term persistence in the environment due to unknown degradation rates and chemical composition; - Potential interactions with local biota, including ingestion by animals; - Unknown transport and accumulation patterns in mountain ecosystems, potentially affecting soil and water quality.

4. Discussion

4.1. Sources of plastic pollution

This large-scale geographical investigation revealed that plastic items are widespread throughout the Alps and Prealps of Lombardy. The fact that 31 % of items originated from food packaging suggests that local human activities are the most relevant sources of plastic items in mountain environments. The use of plastic for food packaging is particularly high due to its versatility, durability, and low cost, but it

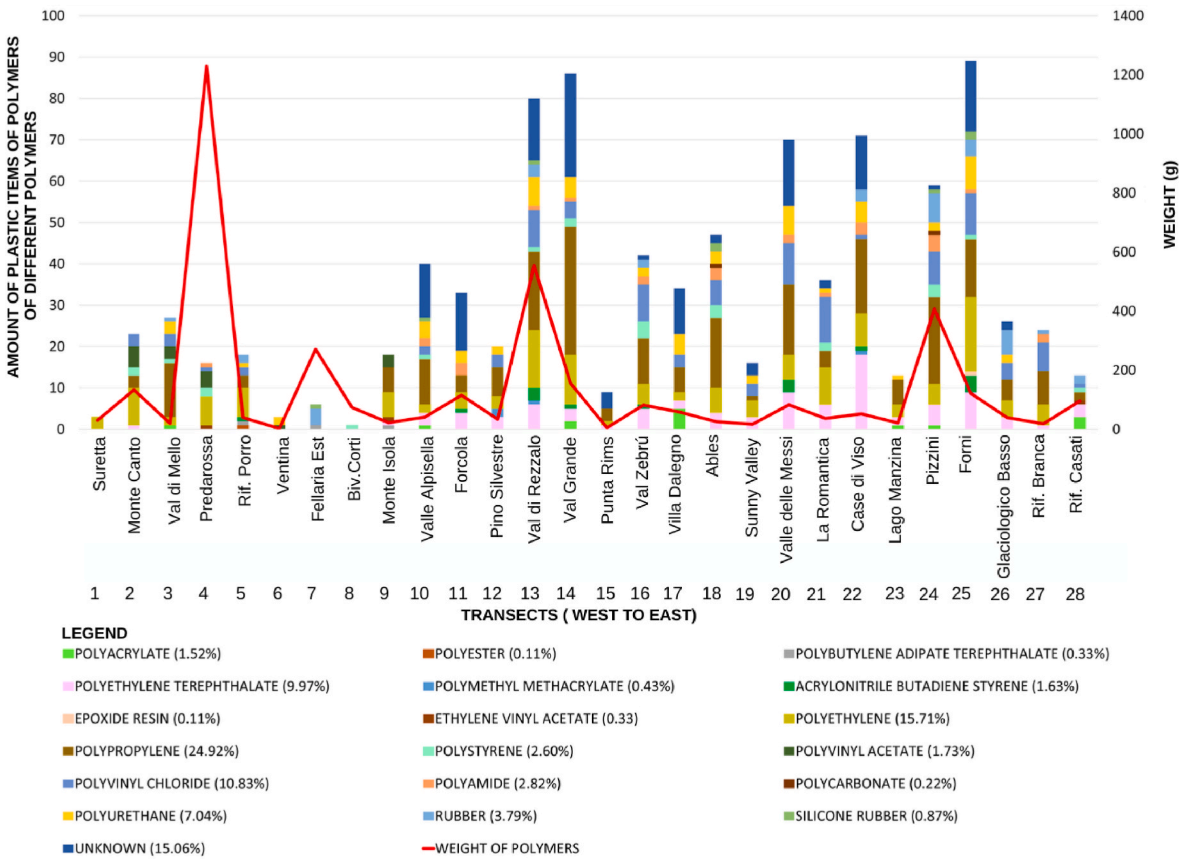


Fig. 4. Total amount of plastic items of different polymers collected along each transect and their total weight. The stacked bars represent the number of plastic items of different polymers along each transect. The red line indicates the total weight of plastic items collected along each transect. The polymer macro-categories are reported in alphabetical order, as well as the polymers in each category. Transects are reported from west to east and numbered according to Fig. 1.

also represents one of the main challenges for waste management and environmental sustainability (Kan and Miller, 2022). Indeed, 88.4 % of items classified as food packaging were made of plastic, and single-use packaging, particularly snack wrappers and beverage containers, are the most common waste items. This pattern is strongly linked to hiking and outdoor activities, where convenience drives the consumption of packaged foods. The widespread presence of plastics with this origin along mountain paths highlights the urgency of developing alternative solutions for food packaging, such as biodegradable or reusable materials, to reduce their environmental impact (e.g., Guillard et al., 2018; Moshood et al., 2022; Zielonka and Liro, 2024). Although less abundant than food packaging, the number of items deriving from healthcare products (5 %) suggests that despite plastics being widely used in the medical field due to their weight, cost, hygienic and versatile properties (McKeen, 2014), their use and disposal must also be carefully addressed to prevent their dispersal into the mountain ecosystems.

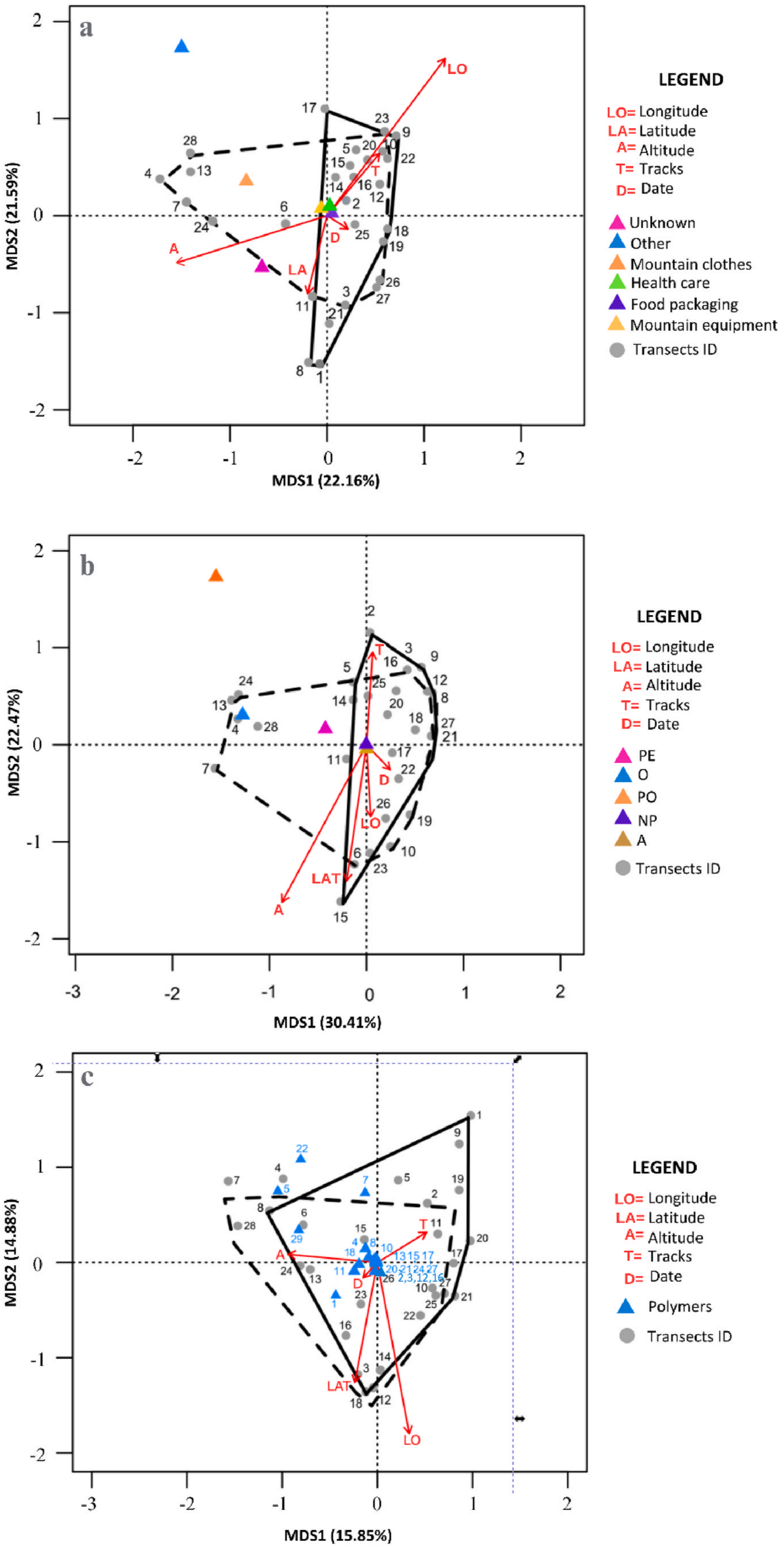
The abundance of items derived from mountain clothes (5 %) and mountain equipment (4 %) also highlights the importance of plastic materials in outdoor products. Indeed, the use of plastics in this sector is often related to the search for durable and lightweight materials, but their improper disposal still contributes to environmental pollution, especially in natural areas. Indeed, these fibers are highly persistent and can be transported, accumulating even in remote mountain regions. Similar trends have been observed in studies assessing microplastic pollution in high-altitude environments (Ambrosini et al., 2019). Plastic fibers from clothing, particularly synthetic textiles, can also be released into the environment during activity, and their spread into the environment can be locally relevant as their association with some transects suggests. For instance, transect Forni (ID 25) presented the greatest number of plastic items from mountain clothes, and Pizzini (ID 24) had the greatest number of plastic items from mountain equipment (Fig. 2). These transects were along paths in the Stelvio National Park that are highly frequented by hikers and alpinists all year round. However, human frequentation is also high along other transects that are less impacted by mountain clothes and equipment. So, their high abundance along these transects may be due to chance factors.

Overall, these results suggest that policies aimed at developing sustainable solutions to reduce the use and improper disposal of plastics in the mountain should focus on the most common categories of plastic waste, such as food packaging and health care products, because their proper disposal may be effective in lowering the amount of plastic items in the mountain. In contrast, replacing plastic with sustainable materials in mountain clothing and equipment may be more challenging, potentially requiring the redesign of industries and the promotion of environmentally conscious methodologies in the creative process of developing these materials (Sawant et al., 2024). However, a sensibilization of hikers and alpinists toward avoiding the abandonment of plastic equipment may contribute to reducing plastic pollution.

4.2. *Most abundant polymers*

The most abundant polymers identified were polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) (Table 1, Fig, 4).

These data are consistent with the distribution and use of plastics in Europe. Indeed, PP and PE account for 49.0 % of the European plastic demand in 2018 (Plastics the facts, 2019) and are extensively used for food packaging. In addition, PET is commonly found in various applications (Plastics the facts, 2019) due to its excellent properties and possibility of recycling, including the production of technical clothing



(caption on next page)

Fig. 5. Multidimensional scaling of the mass of items per km of transect classified into a) use macro-categories, b) polymer macro-categories, and c) polymers. The amount of variance explained by each axis is shown in brackets. Grey dots represent the transects (numbered from west to east, as in Fig. 1). The solid polygon includes the transects crossing no refuge, and the dashed polygon represents the transects with refuges. Red lines represent the potential determinants of plastic item distribution. Triangles represent a) use macro-categories, b) polymer macro-categories, c) polymers indicated by blue numbers as follows: polypropylene (1), polyethylene terephthalate (2), polyvinyl chloride (3), polyamide (4), rubber (5), polyethylene (7), silicone rubber (8), polyacrylate (10), polyurethane (11), polystyrene (12), polycarbonate (13), acrylonitrile butadiene styrene (15), ethylene vinyl acetate (16), epoxide resin (17), polymethyl methacrylate (20), unknown (21), polyvinyl acetate (22), polyester (24) and polybutylene adipate terephthalate (29).

Table 2
Fixed effects of a negative binomial generalized linear model of the number of plastic items at 5 % intervals of the total extent of a transect and according to the presence or absence of a refuge along the transects.

Effect	Coef.	SE	z	P
Intercept	1.409	0.114	12.305	<0.001
Distance	−0.752	0.180	−4.184	<0.001
Refuge	−0.168	0.199	−0.844	0.399

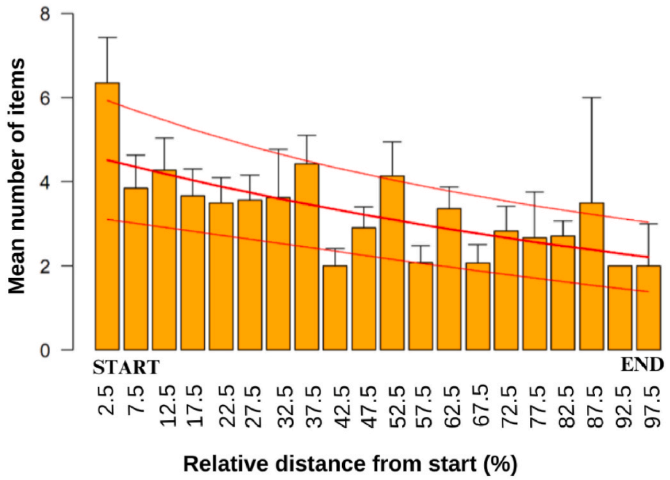


Fig. 6. Mean number of plastic items found at different relative distances from the beginning of a transect. Distance from the start is expressed as a proportion of the total length of the transect and reported in classes of 5 % width. The red curves represent the interpolated function (thick line) and its 95 % confidence limits (thinner lines).

(Majumdar et al., 2020) and equipment. Although PET is one of the most recyclable polymers, its durability (Macedo et al., 2020; Pudack et al., 2020) and improper disposal continue to challenge plastic waste management.

The prevalent sources and composition of MaPs and MePs we found were also consistent with findings from other studies, like on glaciers in the Alps (Parolini et al., 2021a), and similar to what has already been observed for MPs in the same mountain range. Indeed, PE was the prevalent polymer found in the snow on the Swiss and Bavarian Alps (Bergmann et al., 2019) and on the Italian Western Alps (Parolini et al., 2021a), and PE, PET and PP were the most abundant polymers on three Alpine glaciers (Ambrosini et al., 2019; Crosta et al., 2022). The similar polymeric composition of MaPs and MPs on mountains and glaciers in the Italian Alps further supports the hypothesis already proposed in previous studies that the degradation and breakage of large plastic items represent a relevant source of MPs in these environments (Parolini et al., 2021a). Atmospheric transport may thus not be the main source of MPs in high-altitude environments, and local sources may be more relevant than previously hypothesized.

We could not identify a rather large amount (15.06 %) of the total plastic items. This can be due either to the complexity of the plastic analyzed (e.g., blends between two or more materials) or to the degradation or chemical alteration of the native polymer, which prevents the unequivocal recognition of the polymer (Parolini et al., 2021a). Similarly, a rather high percentage of plastic items were classified in the “other” (24 %) and “unknown” (31 %) categories. This can be due to the exposure of the items to environmental conditions, such as UV radiation, temperature variations, and mechanical action, that may have hindered the identification of the original use of the items found. In addition, the classification employed was rather coarse and focused on categories relevant to the specific uses of plastics in the mountain environment. For instance, items such as cables, wires, and electronic components, albeit identifiable, were grouped into the “other” category. These factors may have contributed to the increased number of items in the “unknown” and “other” categories in the analyses.

All these plastic items can potentially undergo degradation and fragmentation, leading to their long-term persistence in the environment (e.g., Dimassi et al., 2022; Pilapitiya and Ratnayake, 2024).

Overall, these results suggest that waste management policies should primarily focus on the most common polymers, such as polypropylene and polyethylene, to reduce environmental plastic dispersion. It may also be useful to promote more effective waste management and recycling solutions, especially for more difficult-to-treat materials like PVC (Lu et al., 2023) and PET. Moreover, these data highlight the importance of developing more targeted recycling policies, alternative plastic materials that are more easily recyclable or biodegradable, and the urgency of reducing the use of single-use plastics, especially in sectors that produce food packaging and everyday consumer products, to reduce the environmental impact of persistent plastics.

4.3. Spatial and environmental patterns of plastic distribution

The distribution of plastic items in the Alps and Prealps of Lombardy seems uniform and not related to any geographical pattern. Indeed, the MDS analysis showed weak effects of the transect’s geographical position. In contrast, altitude appears to influence the overall composition of plastic waste, both in terms of use and polymer macro-category (Fig. 5b and c). Interestingly, the abundance of plastic with unknown use seems to increase with altitude, which may be related to the more rapid degradation of plastics at higher altitudes, which may have hindered our identification of their original use.

Refuges in mountain areas have been suggested as potential sources of plastic waste, but our data do not indicate a direct relation between their presence and increased plastic pollution. However, refuges also represent points where waste can be conferred. The waste management strategies of refuge staff may thus balance the increased amount of waste produced by a presumably larger number of tourists on paths leading to refuges.

Surprisingly, the human frequentation index derived from the analysis of STRAVA data seems not strongly related to either the quantity or the composition of plastic items. This may be because STRAVA is primarily used by individuals tracking their training, rather than by tourists who visit the mountains to enjoy nature. For example, among our transects, the highest number of STRAVA tracks (n = 48,243) was in Monte Canto (ID 2), located near the city of Bergamo, while the lowest was for Rif. Porro (ID 5) and Punta Rims (ID 15), both with zero tracks. The Rif. Porro transect follows an easy path to a refuge near a popular tourist area in Val Malenco, frequented by families in summer and backcountry skiers in winter. In contrast, the Punta Rims transect is an easy trail departing from the road that reaches Stelvio Pass, an area of historical significance from World War I, mostly visited by hikers in the summer. Thus, STRAVA tracks, despite being considered an important digital tool and source of information for human frequentation of natural environments (e.g., Langenbach et al., 2023; Pla et al., 2024; Savre and Eveillard-Buchoux, 2024), may not represent the actual tourist frequentation of paths in the Alps and Prealps of Lombardy. Thus, the original use of plastic items we found suggests that plastic pollution in the mountain environments of Lombardy is related to human activities, but the lack of association with STRAVA data and refuge presence suggests that it is not necessarily related to the number of people in the area. Possibly plastic distribution is related to a general lack of awareness regarding the impact of plastic waste released into mountain environments both between tourists and local people (Padha et al., 2022; Velasco et al., 2020) (Fig. 2).

Interestingly, we observed that the number of plastic items decreases along the transects, with a high amount found in the first km (Fig. S02). Such a pattern can be explained if we assume that people start their trekking with plastic items with them and can lose them inadvertently with constant probability along the whole path. Indeed, our transects usually start from a car park, where tourists or local people also begin their trekking. Alternatively, we can hypothesize that hikers and bikers tend to discard waste near the starting points of transects, where they are more likely to consume food and beverage items.

In both cases, a possible management strategy to reduce the number of plastic items could be to provide the possibility to dispose of plastic waste at the beginning of mountain itineraries, for instance by placing rubbish bins for plastics at parking sites.

4.4. *Awareness and pollution in mountain environments*

It is necessary to develop awareness regarding pollution in mountain environments, also with innovative communication strategies and media (Barbagallo et al., 2024; Diolaiuti et al., 2021), and to create precautionary strategies to limit the distribution of plastic items in these fragile ecosystems.

The United Nations Sustainable Development Goals (SDGs) explicitly mention mountains among the ecosystems to be conserved, restored, and sustainably used in Target 15.4 of SDG 15 (The Global Goals, 2025; Ivasciuc and Ispas, 2023). By 2030, achieving the conservation of mountain ecosystems is essential for sustainable development (The Global Goals, 2025). However, the lack of agreement on comprehensive measures to address plastic pollution in mountain environments remains. The indicators set by the UN to monitor the implementation of the SDG mentioned only plastic pollution in marine environments (indicator 14.1. - 1.b Marine plastic debris) (United Nations, 2024; The Global Goals, 2025; Walker, 2021; Directive EU, 2019). Indeed, the United Nations, through the existing international agreement with a Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), monitors marine plastic debris (Watson-Wright et al., 2024). Given this, we emphasize the importance of monitoring, recording, mapping, and quantifying plastic pollution also in mountains and terrestrial habitats to effectively manage plastic waste and minimize pollution at the source (Cottom et al., 2024). After all, despite being often considered a pristine environment, waste is accumulating in the mountains, and a substantial proportion is made of plastic items (Bergmann et al., 2019; Napper et al., 2020) that may not only remain in the environment where they were deposited but can also break down into MPs and NPs and be transported to other environments. Thus, the environmental damage caused by plastics in mountain ecosystems can be multifaceted. In addition, plastic waste contributes to visual pollution and aesthetic degradation, and it is even depicted by contemporary artists to chronicle the plastic crisis (Chertkovskaya et al., 2020). These combined factors make plastic cleanup in mountain environments particularly challenging (Semernya et al., 2017). Environmental management plays a critical role as a preventive tool against environmental degradation (Moreno and Litholdo, 2000) and is also essential for ensuring the sustainability of mountain ecosystems.

4.5. *Policy recommendations and sustainable management*

Addressing plastic pollution in such areas requires integrated strategies, including public awareness-raising tools, improved waste management, and the promotion of alternative materials (e.g., Nobusawa, 2023; Prata et al., 2019; Senese et al., 2023). Reducing plastic pollution in mountain environments requires a combination of policy interventions, infrastructure improvements, and behavioural changes. While waste disposal measures are essential, a more effective strategy involves reducing plastic consumption at the source. Policies such as banning single-use plastics in mountain refuges, promoting reusable alternatives, and encouraging manufacturers to develop sustainable materials for outdoor gear could significantly lower plastic waste generation.

Additionally, raising awareness among visitors about responsible waste management is crucial. Campaigns focusing on environmental education, combined with stricter regulations for waste disposal in protected areas, could help minimize plastic pollution. Establishing incentive-based initiatives, such as reward programs for carrying out trash or deposit-return systems, may obtain promising results.

These actions align with the United Nations SDGs, particularly SDG 12 (Responsible Consumption and Production) and SDG 15 (Life on Land). By implementing targeted policies to reduce plastic waste, ecosystems, including mountain ones, can be better preserved, contributing to broader global sustainability efforts.

5. Final considerations

5.1. *Urgency of action and policy recommendations*

This study provides one of the first large-scale assessments of plastic pollution in the Alps, offering key insights for future monitoring efforts and practical mitigation measures. Our findings reveal that plastic contamination is widespread along mountain paths in Lombardy, with food packaging, healthcare products, and outdoor equipment as the main sources. The prevalence of PP, PE, PVC, and PET highlights the need for targeted waste management and recycling policies. In Lombardy, the total path network spans ~19,893.7 km (data obtained from the inventory of paths of Lombardy – REL, Lombardy hiking network; http://www.geoportale.regione.lombardia.it/). We can thus estimate that the total amount of plastic items along mountain paths in Lombardy is 479.92 ± 140.29 s.e. kg. All this plastic waste in mountain environments seems strongly linked to human activity, but not necessarily to visitor frequency, as indicated by the limited correlation with STRAVA data. This suggests that behavioural factors, lack of awareness, and inadequate disposal infrastructure play a critical role in pollution patterns.

While some plastic loss is accidental (e.g., due to wear on mountaineering equipment), much of the pollution, particularly from food packaging and healthcare products, is avoidable. Addressing this issue requires an integrated approach that combin*es* research, policy interventions, stakeholder involvement, and increased public awareness.

5.2. *Measures to reduce plastic pollution in the mountain ecosystems*

To effectively reduce plastic pollution, we propose the following measures that we think can be immediately translated into action.

1. Encourage manufacturers to develop biodegradable alternatives for food packaging and outdoor equipment, to prevent pollution at the source;
2. Install waste collection points at key entry points of mountain paths and in the car parks to facilitate proper disposal;
3. Promote awareness campaigns highlighting the impact of plastic pollution and encouraging responsible consumption habits;

4. Develop regulations to minimize the use of single-use plastics by mountain tourists and encourage sustainable practices, including responsible waste management and the adoption of eco-friendly alternatives;
5. Promote the use of portable waste solutions such as reusable trash containers for hikers to carry and properly dispose of waste.

Plastic pollution threatens the integrity of mountain ecosystems, which are crucial for biodiversity and water resources. Protecting these environments aligns with global sustainability efforts, particularly SDG 12 - Responsible Consumption and Production and SDG 15 - Life on Land. Strengthening international collaborations, such as those promoted by the Mountain Partnership and UNESCO-designated mountain biosphere reserves, could enhance the effectiveness of conservation policies and facilitate the exchange of best practices in sustainable mountain management.

CRediT authorship contribution statement

Taise Litholdo: Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation. **Beatrice De Felice:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Stefano Gazzotti:** Writing – review & editing, Methodology, Investigation. **Arianna Crosta:** Writing – review & editing, Investigation. **Viviana Minolfi:** Writing – review & editing. **Antonella Senese:** Writing – review & editing, Investigation, Data curation, Conceptualization. **Riccardo Scotti:** Writing – review & editing, Investigation. **Marco Aldo Ortenzi:** Writing – review & editing, Resources. **Gustavo Henrique Ribeiro da Silva:** Writing – review & editing, Supervision, Resources. **Marco Parolini:** Writing – review & editing, Resources, Investigation, Conceptualization. **Roberto Ambrosini:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, 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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.125758.

Data availability

Data will be made available on request.

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