



Macroplastics contamination on glaciers from Italian Central-Western Alps

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ABSTRACT

Plastics are synthetic organic polymers playing an irreplaceable role in our everyday life. However, their massive use, improper management and end-life disposal cause plastic accumulation in the environment. Plastic contamination is ubiquitous in aquatic and terrestrial ecosystems, including mountain remote areas. The present work aimed at investigating the presence of macroplastics on five glaciers of the Italian Central-Western Alps, namely Cedec and Forni glaciers (Ortles-Cevedale group) and Indren, Lys and Verra glaciers (Monte Rosa group). In late spring-summer of 2020, macroplastics were collected along normal access paths leading to some peaks of these mountain groups. In laboratory, macroplastics were sorted according to their weight, size, color, origin, usage section and polymeric composition. Macroplastics were found along all the paths, with a mean (\pm standard error) abundance of 18.9 ± 5.1 items per transect and an abundance per linear km ranging between 2.4 and 26.4 items/km. No significant differences of macroplastic abundance occurred between the mountain groups. Polyolefin, such as polyethylene, polystyrene and polypropylene, were the most frequent polymers contaminating glaciers, accounting for the 31% of the fingerprint, followed by polyethylene terephthalate (12%) and polyurethane (8%). The origin of most macroplastics was attributable to food packaging and items deriving from the wear of mountaineering equipment and/or clothing, which reached glacier paths through deliberate or involuntary abandonment. Virtuous behaviors aimed at limiting the abandonment of plastic waste or at collecting the items encountered on the paths should be encouraged to reduce the amount of macroplastics in remote areas.

1. Introduction

Plastic contamination has been identified as one of the predominant environmental challenges that we have to face. Plastics are essential assets to meet our daily needs, but their imprudent and massive use, exacerbated by the throw-away habits of our society and their inappropriate end-life disposal, have led to the accumulation of plastics in natural ecosystems. In addition, the same features making plastics so versatile and used in a variety of applications, mainly their durability and persistence, represent the main cause of accumulation in the environment. A recent study has estimated that about 6,300 metric tons of plastic waste is generated annually worldwide, but only 9% of the total amount is recycled, 12% is incinerated and the remaining 79% is accumulated in the environment (Geyer et al., 2017). A large number of monitoring surveys have highlighted the environmental presence of a heterogeneous array of plastics with different shapes, sizes, colors, and polymer types (e.g., Veerasingam et al. 2016, Piehl et al. 2018,

Vidyasakar et al. 2018, Maharana et al. 2020). Plastic bags, bottles, packaging straps and fishing lines have been identified as the most common plastic waste floating in marine ecosystems globally (Blettler et al., 2018) and cigarette butts, food wrappers, drinks bottles and straws/stirrers are the predominant items on coastal beaches (www.coastalcleanupdata.org, accessed March 28th, 2021), while food wrappers, bottles and lids, bags and cigarette butts resulted as the main contributors to freshwater plastic contamination (Winton et al., 2020). Although the presence of plastic waste on agricultural and urban soils represents normality for our daily life, reports on macroplastics in terrestrial ecosystems are still limited (e.g., Huang et al. 2020, Gui et al. 2021). The monitoring of macroplastics in the environment results of particular concern not only because of their aesthetic and biological impacts, but also for the consequences of their degradation. In fact, the breakage of large-sized plastic items has been identified as the predominant source of microplastics (MPs), small-sized items < 1 mm or < 5 mm (Eerkes-Medrano et al., 2015) that have been recognized as

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ubiquitous contaminants in aquatic and terrestrial ecosystems worldwide (e.g., Boyle and Örmeci 2020, Li et al. 2020, Pirsahab et al. 2020). For instance, over 5 trillion of MPs have been estimated to float on the surface of the oceans (Eriksen et al., 2014), with a total amount that is reasonably destined to increase as a consequence of macroplastics weathering (Cózar et al., 2014), while terrestrial contamination has been estimated as more than 20-fold larger than in aquatic environments (Zhang and Liu, 2018; Li et al., 2020). All these studies have demonstrated that both macro- and microplastics contaminate both aquatic and terrestrial ecosystems of any part of the globe. In addition, recent monitoring surveys have highlighted that also the so-called remote areas suffer plastic contamination. A wide range of plastic items, mainly MPs, have been found in deep sea, Southern Oceans, Arctic and Antarctica (Hamid et al., 2018; González-Pleiter et al., 2020). Similarly, the presence of MPs has been detected also in high-mountain ecosystems, such as in sub-alpine lake sediments (Imhof et al., 2013), pelagic water and shoreline debris from high-mountain lakes (Free et al., 2014; Zhang et al., 2016; Velasco et al., 2020), soils from Alpine valleys (Scheurer and Bigalke, 2018) and French Pyrenees (Allen et al., 2019), fresh and residual snow from Italian, Bavarian and Swiss Alps (Bergmann et al., 2019; Parolini et al., 2021; Pastorino et al., 2021), as well as supraglacial sediments from an Alpine glacier (Ambrosini et al., 2019). These studies suggested that MPs can reach these remote areas through atmospheric transport (Allen et al., 2019). However, weathering processes of macroplastics, including mechanical (erosion, abrasion), chemical (photo-oxidation, hydrolysis) and biological (degradation by microorganisms) modifications (Andrady, 2017), might represent an additional source of MP contamination in mountain ecosystems. For instance, a recent study has suggested that MPs found in snow collected along the normal access path to the Mt. Everest can originate from windblown atmospheric transport and release of climbing clothes, but also from the breakage of macroplastic waste left behind from previous expeditions, including old tents, fixed ropes, used oxygen bottles and human waste (Bishop and Naumann, 1996; Napper et al., 2020). Despite these findings, the information on the presence of macroplastics in high-mountain, glacier ecosystems is still very scant.

Thus, the aim of the present study was to quali-quantitatively investigate the presence of macroplastics on five glaciers from the Italian Alps, namely Cedec and Forni glaciers (Ortles-Cevedale group) and Indren, Lys and Verra glaciers (Monte Rosa group). Macroplastics were collected along the normal access paths leading to peaks towering above the five glaciers mentioned above, categorized according to their usage

section and grouped per polymer type to shed light on their possible origin. Considering that thousands of mountaineers visit these glaciers every year, we expect to find macroplastics on the paths we visited because of their unintentional or deliberate abandonment.

2. Materials and methods

2.1. Study areas

This study was performed on five glaciers included in Ortles-Cevedale and Monte Rosa groups (Italian Central-Western Alps). On the Ortles-Cevedale group, transects were travelled on two glaciers (coordinates; area in km², Smiraglia and Diolaiuti, 2015), i.e., Cedec (46° 27' 00" N, 10° 36' 22" E; 2.07 km²) and Forni (46° 23' 32" N, 10° 35' 28" E; 11.34 km²). On the Monte Rosa group, transects were travelled on three glaciers, i.e., Indren (45° 53' 51" N, 7° 51' 33" E; 0.92 km²), Lys (45° 54' 31" N, 7° 49' 58" E; 9.58 km²) and Verra Grande (45° 55' 34" N, 7° 45' 33" E; 6.62 km²) glaciers (Smiraglia and Diolaiuti, 2015).

In late spring-summer 2020, macroplastics were collected along normal access paths leading to peaks of these mountain groups (Fig. 1). In detail, four transects were travelled in the Ortles-Cevedale group, along the normal paths to Cima di Solda - Suldenspizze (T1), Tre Cannoni - Eiskofel (T2), and Monte Cedevale (T3), as well as the path conducting from the front of Forni Glacier up to the automatic weather station (AWS-Forni) (T4). Three transects were travelled on the Monte Rosa group; T5 crossed the Indren Glacier up to the Gnifetti hut, while T6 and T7 were along the normal paths leading to the summit of Punta Gnifetti - Signalkuppe and to Breithorn West. Features of travelled transects are reported in Table 1. Moreover, the departure point of transects has different accessibility, as those traveled in the Monte Rosa groups can be reached by a cableway. All the transects are commonly visited by thousands of ski mountaineering and hikers in spring and summer, while the initial quarter of T7 was travelled alongside ski slopes. Overall, the average length (\pm standard deviation) of the transects was 2.59 ± 1.57 km and they were traveled in 92 ± 60 min, depending on the length and the difference in height of each transect. Macroplastics were collected on the paths (considering as a buffer zone about 2 m on each side of the path) only uphill. Macroplastics found downhill were collected but not included in the sample. All the macroplastics sampled in each transect were wrapped in a tinfoil previously marked with the identification code of the transect and then transported to the laboratory for categorization.

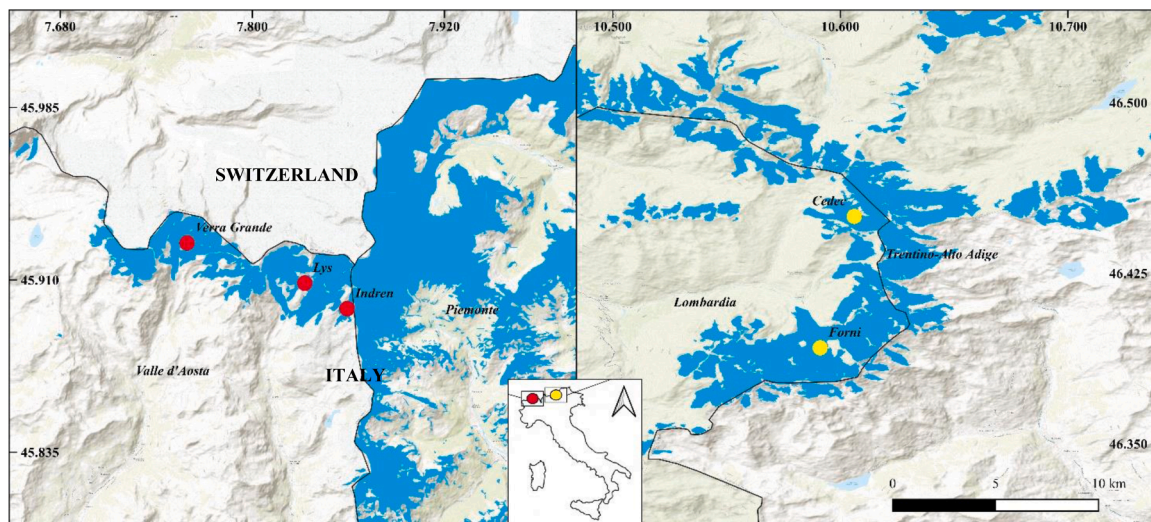


Fig. 1. Map of the study areas and geographical position of glaciers on Ortles-Cevedale (Cedec and Forni Glaciers, yellow dots in right panel) and Monte Rosa (Verra Grande, Lys and Indren Glaciers, red dots in left panel) groups where transects were travelled to collect macroplastics (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

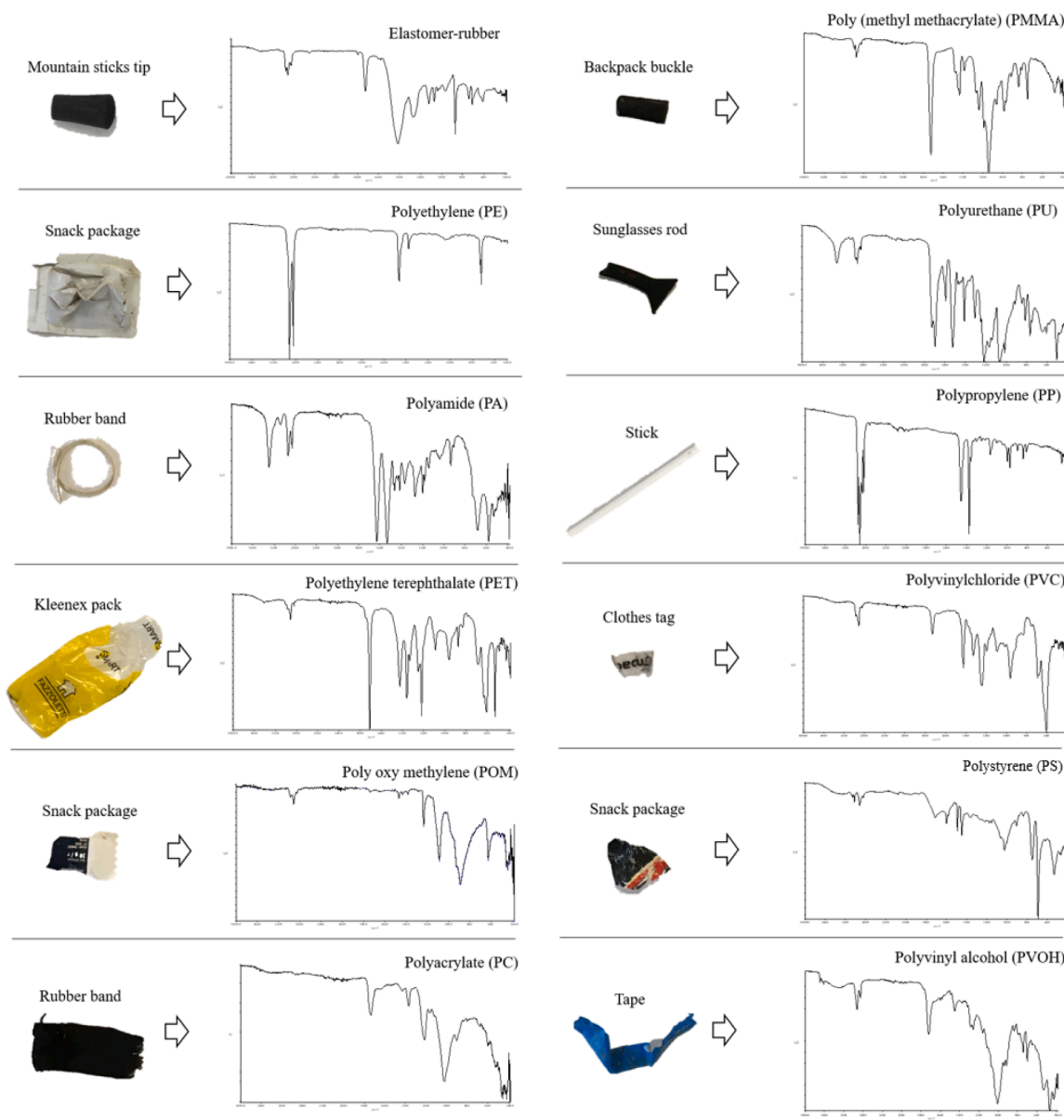
Table 1

Features of each transect travelled on Ortles-Cevedale (T1-T4) and Monte Rosa (T5-T7) groups.

Transect	Point of departure	Point of arrival	Length (km)	Time (min)	Starting altitude(m.a.s.l.)	Arrival altitude(m.a.s.l.)	Difference in height (m)
T1	Casati hut	Cima di Solda - Suldenspitze	1.7	30	3,256	3,387	131
T2	Casati hut	Tre cannoni - Eiskofel	2.5	45	3,256	3,275	19
T3	Casati hut	Monte Cevedale	1.66	80	3,256	3,765	500
T4	Front of Forni Glacier	Automatic weather station	0.87	65	2,496	2,523	27
T5	Punta Indren	Gnifetti hut	1.8	80	3,278	3,654	378
T6	Gnifetti hut	Punta Gnifetti - Signalkuppe	4.8	140	3,654	4,556	902
T7	Plateau Rosa	Western Breithorn	4.77	203	3,457	4,175	718

Macroplastics were grouped according to their presumed usage section, namely food packaging, mountain equipment, mountain clothes, health care and other (i.e., items not attributable to the previous sections). When items could not be related to any of the previous categories they were referred to as unknown. Then, each item was categorized

according to its specific use (e.g., food packaging items were specifically referred to e.g., snack or candy wrappers, lollipop sticks, water bottle cap and so forth). The size of each macroplastic was measured using a caliper (± 0.1 cm), and the total weight (± 0.1 g) of the macroplastics collected in each transect was recorded. Lastly, a picture of all the

**Fig. 2.** An example of macroplastics and the corresponding spectra obtained by FTIR analysis for each polymer we identified.

macroplastics from each transect was taken (see Supporting Information) and, after washing with ultrapure water and air-drying, the polymeric composition of each item was determined using Spectrum 100 spectrophotometer (Perkin Elmer) in attenuated total reflection (ATR) mode with a resolution of 4.0 and 256 scans, in a range of wavenumber between 4,000 cm^{-1} and 400 cm^{-1} . A single-bounce diamond crystal was used with an incidence angle of 45°. Polymeric composition of each macroplastic was identified by comparing the spectrum of each single item with that of the corresponding polymer in the Perkin Elmer library. In Fig. 2 are reported an example of macroplastics and the corresponding spectra for each polymer we identified.

2.2. Statistical analysis

Given the small sample size ($n = 7$ transects), differences in the macroplastics abundance, in terms of the total number of items and number of items per linear km, size and weight between glaciers from Monte Rosa and Ortles-Cevedale groups were tested by means of a permutation procedure whereby all the 35 possible combinations of data into the two groups were systematically enumerated and the Student's t -value of the difference between mean values was calculated for any combination of the data. Significance was then assessed as the rank of the absolute value of the t -statistic calculated on the observed data over the distribution of values obtained from the procedure (Manly, 1997). This test provides the highest possible statistical power for small sample sizes and is insensitive to deviation of data from normality assumptions. In addition, we also run non-parametric Kruskal-Wallis test to check for differences in macroplastics abundance between mountain groups, returning similar results. We also tested if the mass of plastic items made by different polymers or differed by mountain groups using redundancy analysis (RDA). Before performing RDA, total mass of plastic items of each polymer was Hellinger-transformed to avoid the so-called "double-zero" problem in multivariate analyses and reduce the importance of polymer abundance over occurrence (Borcard et al. 2011). Similarly, we used RDA based on Hellinge distance to test if the mass of plastic items in different presumed usage sections differed in the two mountain groups. P -value < 0.05 was set as significance threshold. Statistical analyses were run using the R statistical software (version 4.0.2; R Core Team, Vienna, Austria).

3. Results and discussion

Macroplastics were collected along all the travelled transects from both the study areas, with an overall mean abundance (\pm standard error, SE) of 18.9 ± 5.1 items. Specifically, in the Monte Rosa group, the mean abundance of macroplastics (\pm SE) was 28.7 ± 8.0 items (range 17–44 items), while in the Ortles-Cevedale group it accounted for 11.5 ± 4.0 items (range 6–23 items). However, the difference in the abundance of macroplastics between the two mountain groups was marginally non-significant (unpaired t -test: $t = 2.091$, $df = 5$, $P_{\text{perm}} = 0.086$; Kruskal-Wallis test: $\chi^2_1 = 3.125$; $P = 0.077$). The mean (\pm SE) abundance of macroplastics per linear km (i.e., macroplastics/km) the Monte Rosa and Ortles-Cevedale groups was 11.1 ± 6.7 (range 3.5–24.4) and 9.7 ± 5.6 (range 2.4–26.4) macroplastics/km, respectively, with no significant difference between the two mountain groups (unpaired t -test: $t = 0.154$, $df = 5$, $P_{\text{perm}} = 0.829$; Kruskal-Wallis test: $\chi^2_1 = 0.000$; $P = 1.000$). Accordingly, the mean weight (\pm SE) of macroplastics collected on glaciers was 13.7 ± 3.9 g (range 0.79–29 g) and did not significantly differ between the mountain groups (unpaired t -test: $t = 0.875$, $df = 5$, $P_{\text{perm}} = 0.371$; Kruskal-Wallis test: $\chi^2_1 = 0.500$; $P = 0.479$), while the mean size (\pm SE) was 9.2 ± 1.5 cm (range 0.6–100.1 cm) and it did not significantly differ between Monte Rosa and Ortles-Cevedale groups (unpaired t -test: $t = 0.103$, $df = 130$, $P_{\text{perm}} = 0.272$; Kruskal-Wallis test: $\chi^2_1 = 0.125$; $P = 0.723$). The lack of significant differences in macroplastic amount between the mountain groups might depend on the high inflow of people characterizing both the areas, which are visited all year

long by thousands of mountaineers, as well as on the limited sample size. The limited sample size in the current study, however, is a result of the challenging access to glaciers due to COVID-19 travel limitations.

Grouping macroplastics per usage segment, in spite of a 19% of items that could not be classified to any category, food packaging (27%) and items from mountain equipment (22%) or technical clothes (8%) were the most abundant macroplastic found in all the transects, with the exception of T7 (Fig. 3). Indeed, along the T4 transect, a low amount of food packaging was found, while 40% of items were ascribable to other usage, mainly tape cuts and cable ties, which are common equipment used during scientific surveys conducted on Forni Glacier (R.S. Azzoni, personal information; Ambrosini et al., 2019). Overall, collected food packaging waste was various and included snack (or energy bars) and candy wrappers (16% of the total amount of macroplastics), bands of plastic cups (5%), water bottle caps (3%), lollipop sticks (2%) and a fruit juice brick (1%) (Fig. 4). Items from boot sole (15%) and backpack buckle (3%) were the main items related to mountain equipment, while threads (8%), clothes tag (3%) and a button (1%) were attributable to technical clothes used in mountaineering activities. Tape and insulating tape (7%), watch strap and sunglasses rod (1% each) were also attributable to mountaineering activities. Interestingly, health care related items were also found (4%), whereby besides Kleenex packs and an earplug, a facemask was also found on T6, showing the impact of Covid-19 global pandemic also in remote ecosystems.

Despite the differences in the fingerprints among transects due to the sporadic presence of some polymers, polyethylene (PE) was the most represented polymer in all transects except T4 (Fig. 5). Overall, according to usage segment, polyolefin polymers, namely polyethylene (PE; 14%), polystyrene (PS; 12%) and polypropylene (PP; 5%), contributed for 31% of the fingerprint, followed by polyethylene terephthalate (PET; 12%) and polyurethane (PU; 8%). The contribution of polyolefin increases up to 38% considering blend and laminates (i.e., items composed by more than one polymer), which accounted for 7% of the total amount of macroplastics. Unfortunately, it was not possible to identify the polymer composition of about 26% of macroplastics, probably because of the degradation or chemical alteration of the native polymer due to chemical, physical or biological weathering processes. Polyolefin represented the main polymer class also in terms of macroplastic weight. Independently of the mountain group and transects, the total weight of macroplastics made by PE, PS and PP was 16.29 g, 12.71 g and 7.77 g, respectively, with an additional contribution (4.57 g) by blend and laminates. In addition, elastomer-rubber, PET and PU accounted for 16.68 g, 8.61 g and 6.89 g on the total macroplastic weight. Multivariate analysis showed that the total weight of each polymer type did not differ between mountain groups ($F_{1,5} = 1.953$, $P = 0.085$). Similarly, when we grouped the weight of plastic items by presumed usage section, we did not find any significant difference between

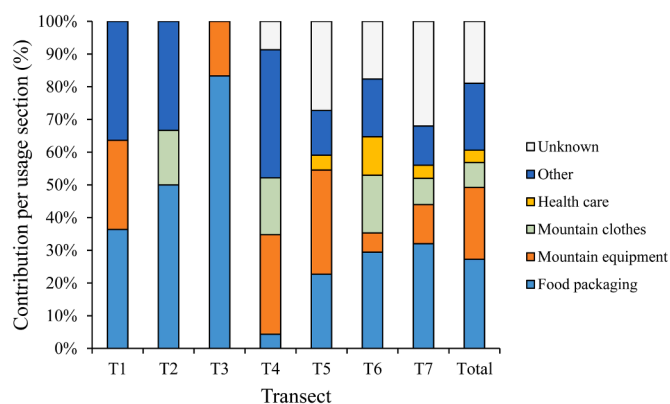


Fig. 3. Percentage contribution of specific macroplastic item collected along the transects of Ortles-Cevedale (T1-T4) and Monte Rosa (T5-T7) groups grouped per usage sector.

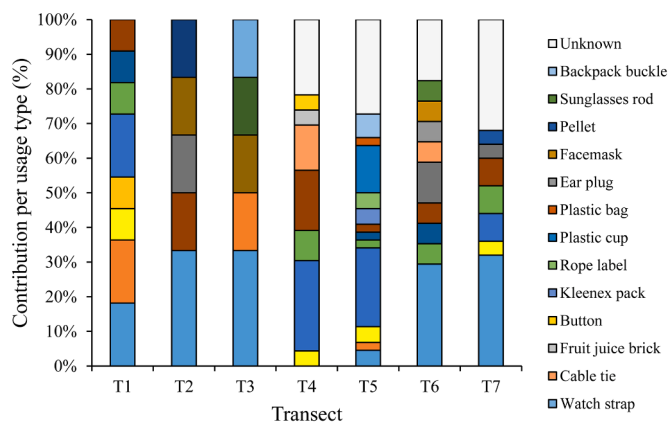


Fig. 4. Percentage contribution of specific macroplastic item collected along the transects of Ortles-Cevedale (T1-T4) and Monte Rosa (T5-T7) groups grouped according to their origin.

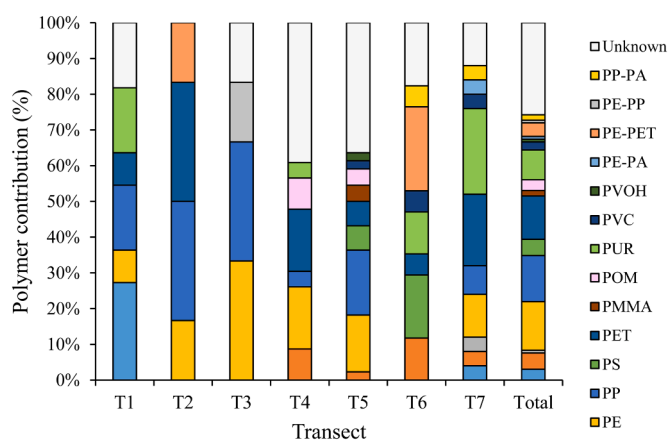


Fig. 5. Percentage contribution of polymers composing the macroplastics collected along the transects of Ortles-Cevedale (T1-T4) and Monte Rosa (T5-T7) groups. PC = polyacrylate; PE = polyethylene; PP = polypropylene; PS = polystyrene; PET = polyethylene terephthalate; PMMA = poly (methyl methacrylate); POM = polyoxymethylene; PU = polyurethane; PVC = poly vinyl chloride; PVOH = polyvinyl alcohol; PE-PA = poly-laminate of polyethylene and polyamide; PE-PET = poly-laminate of polyethylene and polyethylene terephthalate; PE-PP = poly-laminate of polyethylene and polypropylene; PP-PA = poly-laminate of polypropylene and polyamide; Unknown = the polymer was not identified.

mountain groups ($F_{1,5} = 1.046$, $P = 0.346$). The prevalence of polyolefin in the contamination fingerprint was not unexpected considering that PE, PP and PS account for 29.7, 19.3 and 6.4% of the European plastic demand in 2018 because of their extensive use in several goods of everyday usage, mainly in food packaging (PlasticsEurope, 2019). The presence of PET in our samples was related to the wear or the release of tags and threads from clothes and equipment, such as backpacks. This fingerprint of macroplastics from glaciers was similar to that already observed for microplastics (MPs). In fact, previous studies showed that PE was the prevalent polymer found in snow from the Swiss and Bavarian Alps (Bergmann et al., 2019) and in residual snow from the Italian Western Alps (Parolini et al., 2021). Similarly, the MPs found in the fine supraglacial deposit collected on Forni Glacier were largely made by PE, PET (i.e., polyester) and PP (Ambrosini et al., 2019). Interestingly, the overlapping of the polymeric fingerprint characterizing macro- and microplastic contamination of high-mountain and glacier ecosystems should suggest that the degradation and the breakage of large plastic items represent a source of MPs in addition to the atmospheric transport in these ecosystems.

The presence of macroplastics on the normal access paths we travelled was not unexpected and it was mainly related to mountaineering activities. Although some specific items were not directly attributable to common activities performed in high-mountain (i.e., confetti and pieces of plastic bags) and thus they could have reached glacier ecosystems through atmospheric transport, most of macroplastics can originate from the alpinists that every year travel normal paths to reach some of the peaks of Monte Rosa and Ortles-Cevedale groups. For instance, T5-T6 and T7 transects were along the paths leading respectively to Punta Gnifetti - Signalkuppe and Western Breithorn, two of the most visited peaks over 4,000 m of the Italian Alps. Similarly, T4 transect was along the paths to reach the summit of Monte Cevedale, the highest of the 'Thirteen Peaks' towering above the Forni Glacier. Most of the mountain equipment, technical clothes and food packaging used during mountaineering activities are made of plastic polymers and can be deliberately or involuntarily abandoned on the paths. For instance, in 1990, the "Free K2" expedition recovered about 2 tons of garbage from the second highest mountain of the planet, most of which were plastic (Ardito, 1995). More recently, during the 2019 Everest Expedition, a great amount of waste of suspected recent abandonment was observed, as well as debris from previous climbing seasons, including plastic bottles, food wrappers, oxygen bottles, and cigarette butts (Napper et al., 2020). To tackle plastic and waste pollution in these ecosystems, a series of operations have been recently planned. For instance, the government of Nepal and the Sagarmatha Pollution Control Committee have promoted debris removal operations, the Nepal government established a \$4,000 deposit, which is returned to alpinists after bringing their own waste back down (Phuyal, 2020) and banned single-use plastics in the region from January 2020 to cut down abandoned waste (BBC, 2019). Although the plastic contamination on Alpine glaciers is less severe, in terms of both abundance and total weight of the macroplastics, compared to Himalayan ones, it cannot be underestimated. This is particularly true considering that macroplastics could experience different weathering processes inducing their breakdown in MPs. However, to date no study has investigated the structural changes of macroplastics and the consequent release of MPs on glaciers, so this hypothesis needs to be further verified assessing the presence of MPs in the snow from glaciers and/or investigating pathways of macroplastic degradation in these ecosystems.

4. Conclusions

The results of the present survey showed the presence of macroplastics on normal access paths to some peaks towering above glaciers of two mountain groups of the Italian Central-Western Alps. Although the number of macroplastics found on the paths was not high, neither in terms of abundance or weight, the increasing number of trekkers and mountaineers per year, as well as the potential lack of awareness of the environmental concerns related to plastic contamination, might lead to an increase of these wastes in mountain ecosystems. Consequently, as weathering processes can cause the breakage of macroplastics into MPs, the potential increase of large-sized plastic items can exacerbate MPs contamination of glaciers and high mountain ecosystems. For these reasons, information surveys should be a priority to increase the awareness of trekkers and mountaineers on plastic pollution and to promote a more responsible behavior aimed at avoiding deliberate dispersal of plastic waste in the mountain environment. Although the release of some macroplastics was probably unintentional or related to the unavoidable wear of mountaineering equipment, the abandonment of food packaging can be surely prevented or easily managed. Indeed, as plastics are light and easily compressible, mountaineers should be encouraged to put back plastic waste in their backpack or to collect and dispose of them appropriately downhill. This virtuous behavior should reduce the permanence of plastics on mountain ecosystems and consequently prevent the genesis of small size items that can disperse more easily than large ones. Lastly, cleanup operations involving citizens or

private/public authorities to collect plastic waste and opportune policies aimed at discouraging or preventing plastic release on mountain and glacier ecosystems should be advisable to protect the integrity of these pristine ecosystems.

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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.envadv.2021.100084](https://doi.org/10.1016/j.envadv.2021.100084).

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