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Microplastic on Mountain Trails—a Case Study from the Carpathian and Sudetes Mountains in Poland

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Abstract Microplastics are becoming an increasingly common pollutant that can pose a threat to living organisms. The aim of this research was to determine the amount, type, and diversity of microplastics along mountain trails. The study includes three mountain trails, differing in terms of length, difficulty, and number of visitors. The trails were located in the massif of Babia Góra, in the Kościeliska Valley, and Izerska Meadow. During the research, microplastics were determined in snow during the winter period. The research shows high microplastic contamination along the trails. The study area was characterized by the highest content of polyurethane, polyethylene terephthalate, polyethylene, and polypropylene. The tiniest plastic below 0.5 mm dominated in all the sampling points, with a small share of sizes within the range of 3.1–4.0 mm and 4.1–5.0 mm. The isolated microplastics varied in color and shape. The conducted analyses confirm that easier, more frequented trails are characterized by a higher content of microplastics. Trails to Babia Góra, which are more demanding, are characterized by a different composition of microplastics as well as a variety of microplastics in terms of size, shape, and color. In addition, the lower-lying fragments of the examined trails were the most heavily contaminated with microplastics. The results indicate the need for further research on microplastic contamination of the soil environment along mountain trails.

Keywords Human activity · Microplastics · Mountain areas · Snow · Sources

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1 Introduction

Microplastic pollution is becoming an increasingly common threat regardless of location and development (Corradini et al., 2021; González-Pleiter et al., 2020; Österlund et al., 2023; Parker et al., 2022). Previous studies found microplastics in snow samples from a high-altitude protected area, suggesting that atmospheric transport and human activity may be the source of these pollutants (Villanova-Solano et al., 2023). A study by the University of Canterbury found 29 microplastic particles per liter of freshly fallen snow in Antarctica—one of the most remote areas in the world (Aves et al., 2022). Microplastics were found in snow and ice in the Arctic, Alps, Tibetan Plateau, Andes, and the Antarctic regions, and microplastics became ubiquitous global pollutants in both the marine and terrestrial environments (Zhang et al., 2022).

The above research results are a clear indication of the alarmingly high levels of microplastics in our environment. Environmental pollution with microplastics, i.e., plastic particles of various shapes, with sizes ranging from 1 μm to 5 mm, is a grave issue. 400 million tons of plastic are produced each year, and this number is expected to double in the coming years (PlasticsEurope, 2022). Over the last 70 years, the production of plastics has increased from around 2 million to 390 million tons, with Europe alone producing about 15% of plastic (PlasticsEurope, 2022). Primary microplastic are tiny particles designed for commercial use such as cosmetics while secondary microplastics are particles that result from the breakdown of larger plastic items such as water bottles (Jaikumar et al., 2019; Syberg et al., 2015).

Due to its ubiquity and high stability, microplastics pose a serious threat to the environment and human health. Microplastic particles can get into the digestive system, which can have negative health consequences, and it is also known that microplastics can have cytotoxic and genotoxic effects (Sing et al., 2023). Microplastics affect soil properties; either directly or indirectly, they affect plants and microorganisms living in the soil ecosystem, which ultimately leads to impacts on humans (Yang et al., 2022). Previous studies have shown that in the case of earthworms, microplastic affects the viability of their cells (Kwak & An, 2021), and therefore, it can be assumed that microplastics may cause many toxicological effects in humans including inflammatory reactions and growth inhibition (Li et al., 2022). Exposure of human tissues to microplastics can cause oxidative stress in brain cells (Xia et al., 2021) and modulation of the immune system (Prata et al., 2020). It should be remembered that microplastic particles contain other environmental pollutants, which may be an additional factor negatively affecting the condition of plants and animals. Microplastics provide a large solid surface and the amount of contaminant accumulated on the plastic surface can be higher (Atugoda et al., 2021; Martín et al., 2022). Microplastics act as sorbent for different types of hydrophobic organic pollutants such as perfluoroalkyl substances, polycyclic aromatic hydrocarbons, pesticides, and bisphenol analogues (Tumwesigye et al., 2023).

Currently, mountain tourism is becoming one of the most popular forms of leisure activity practiced in Europe. This is related to the diversity of mountains, but also to the ease of practicing this form of tourism; it is ideal for young people, families with children, and the elderly. Increasing tourist traffic in the mountains leads to changes and often to degradation. As a result of significant tourist pressure, the natural environment, especially within the impact range of tourist trails, is exposed to severe degradation. Therefore, the aim of research is to determine microplastic pollution on mountain trails. The research covered mountain trails of various lengths, difficulties, and different numbers of tourists. This study aims to address the following questions: (1) what kind of plastic are the mountain trails polluted with; (2) what microplastic in terms of size, shape, and color is on mountain trails; and (3) how much microplastic is released into the environment with melted snow?

2 Materials and Methods

2.1 Study Area and Snow Sampling

The research was carried out in the Carpathian and Sudetes mountains in Poland (Fig. 1). Three mountain trails in the Babia Góra massif, in the Kościeliska Valley, and in Izerska Meadow were selected for the study, respectively. The mountain trails covered by the research differed in length, difficulty, and number of visitors. The trail to Babia Góra is about 4.5 km long and is visited by 80,000 people a year. The length of the trail in the Kościeliska Valley is about 8.0 km and it is visited by 450,000 people a year. The trail to Izerska Meadow is about 8.0 km long and is visited annually by about 50,000 people.

Each of the trails covered by the research was divided into sections of 500 m. Every 500 m, we set a snow sampling point for further laboratory analysis. In the case of the trail to Babia Góra, it was 10 sampling points, and in the case of the Kościeliska Valley and Izerska Meadow, it was 17 points. At each point, 5 snow samples with a volume of 1 L were collected across the trail using a metal sampler. The 5 sub-samples were used to create a pooled sample. In total, microplastics were isolated from 44 aggregate samples. Snow samples for analysis were collected in February 2023.

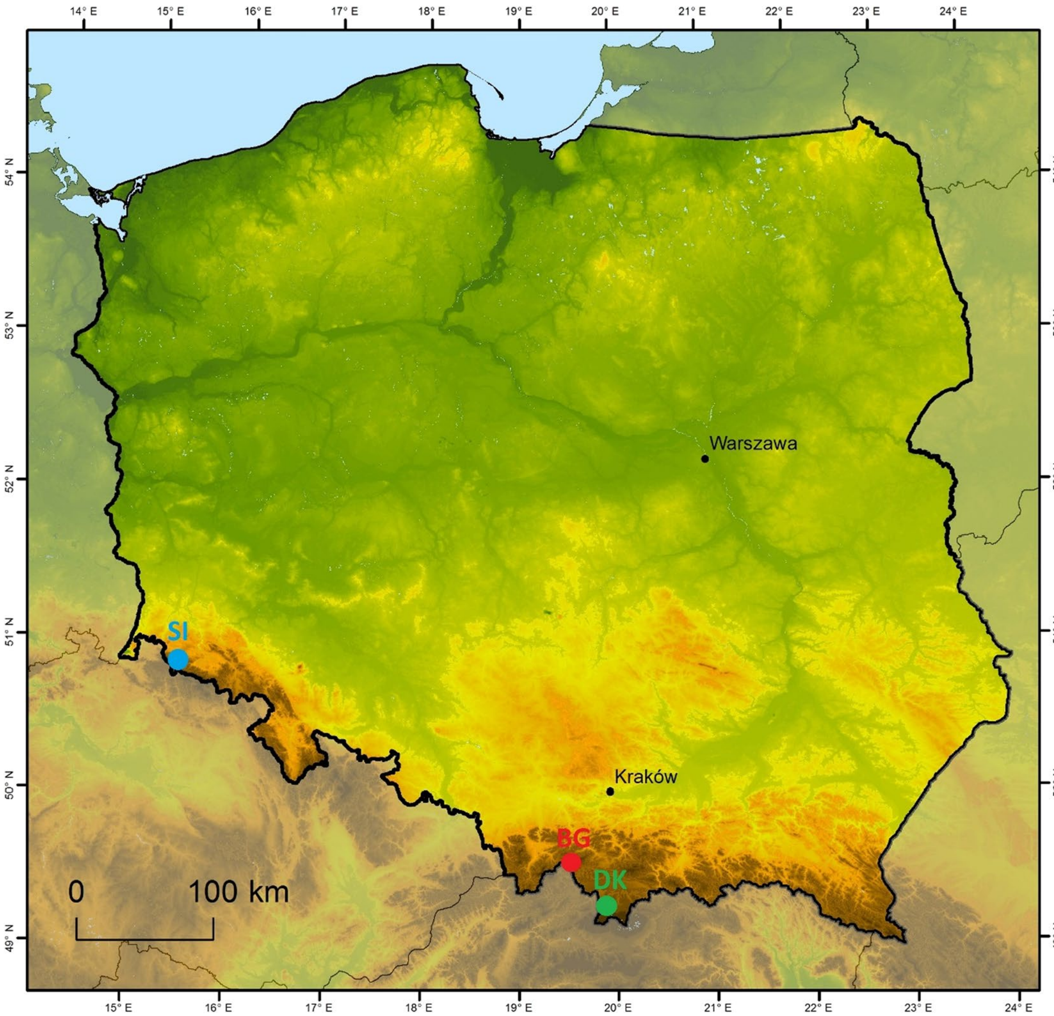

Fig. 1 Location of research plots (*SI* Izerska Meadow, *BG* Babia Góra, *DK* Kościeliska Valley)

2.2 Laboratory Analysis

After the samples were brought to the laboratory, they were melted and filtered through filters (0.45 μm glass microfiber filters). Snow samples were placed in glass beakers and melted at room temperature. The plastic was extracted on filters and transferred to a petri dish. Visual analysis and sorting were then performed. Microplastics were defined as particles made of synthetic polymers smaller than 5 mm. Separated plastic samples were subjected to spectrophotometric analysis. Qualitative identification of debris was obtained using a Nicolet iN10 FTIR microscope (Thermo Fisher Scientific Inc., MA, USA) with a cooling detector for sample mapping. Infrared spectroscopy was performed in the reflectance mode. The collected spectra were analyzed using the Omnic Spectra software with its database. To reduce possible error due to cross-contamination, the abundance of microplastic in the blank sample was used to correct for all the results. All microplastic particles were counted and classified by color and shape. At the time of analysis, the library included reference spectra for polyurethane (PU), polyethylene terephthalate (PET), polypropylene (PP), polyethylene (PE), polycarbonate (PC), polybutadiene (PB), polyamide (PA), phenoxy resin (PHR), cellulose acetate butyrate (CAB), and chloroprene rubber (CR).

2.3 Statistical Analysis

The principal components analysis (PCA) method was used to evaluate the relationships between analyzed variables. The Kruskal–Wallis test was used to assess the differences between the average values of microplastic amount between different trails. Statistical analyses were performed in the statistical programs R (R Core Team, 2022), R Studio (RStudio Team, 2021).

3 Results

The results indicate a variation in the content of microplastics in snow on mountain trails. The highest content of microplastics was recorded in the first part of the trails covered by the study (Fig. 2). In the case of the trail to Babia Góra, the amount of microplastics ranged from 1 piece/L to 15 items/L. In the case of the trail in the Kościeliska Valley, the amount of microplastics ranged from 2 to 37 items/L. In the case of the trail to Izerska Meadow, the amount of microplastics ranged from 0 pieces/L to 25 items/L (Fig. 2). The microplastic content between the described trails was not statistically significantly different (Fig. 3). The average content of microplastics on the trail to Babia Góra is 5.2 items/L, on the trail in the Kościeliska Valley 12.9 items/L, and on the trail to Izerska Meadow 9.8 items/L.

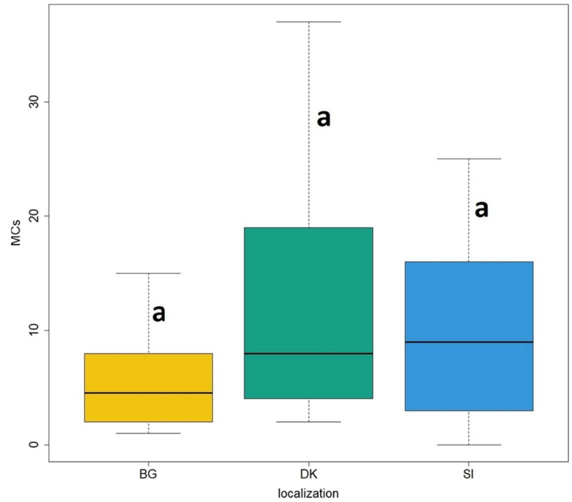

Fig. 3 Average amount of microplastics (items/L) on mountain trails covered by the study (lowercase letters indicate no statistically significant differences; *BG* Babia Góra, *DK* Kościeliska Valley, *SI* Izerska Meadow)

Ten types of microplastics were found in snow samples taken from various mountain trails. They were polyurethane (PU), polyethylene terephthalate (PET), polypropylene (PP), polyethylene (PE), polycarbonate (PC), polybutadiene (PB), polyamide (PA), phenoxy resin (PHR), cellulose acetate butyrate (CAB), and chloroprene rubber (CR). In the case of all the trails in the first part, a greater diversity of microplastics was noted (Fig. 4). The trail to Babia Góra was dominated by polyethylene terephthalate and polypropylene. Polyurethane, cellulose acetate butyrate, and polyethylene were present in smaller amounts. In the case of the trail in the Kościeliska Valley, polyethylene terephthalate, polypropylene, phenoxy resin, and cellulose acetate butyrate had the largest share (Fig. 4). In the case of the trail to Izerska Meadow, polyurethane was dominant. In one sampling point of Izerska Meadow pathway (SI 5500), no microplastics were found (Fig. 4). Microplastics below 0.5 mm (Fig. 5) dominated all mountain trails covered by

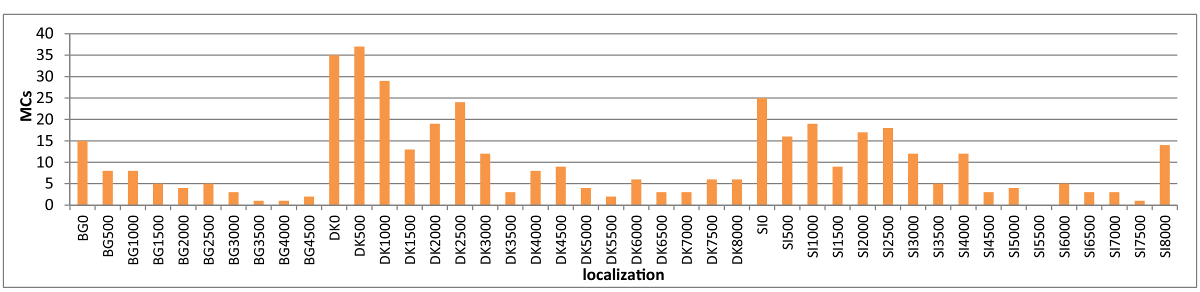

Fig. 2 Amount of microplastics (items/L) in samples taken on various mountain trails (*BG* Babia Góra, *DK* Kościeliska Valley, *SI* Izerska Meadow)

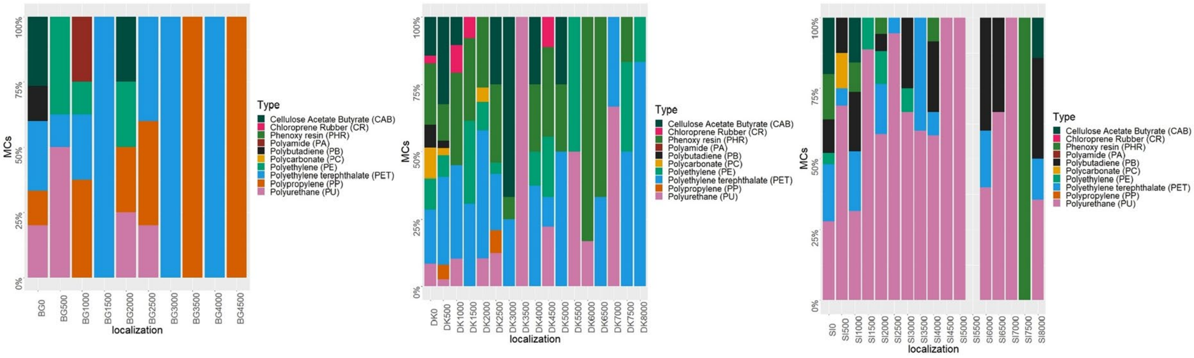

Fig. 4 Microplastic particles (MCs) characterization by type of component in snow on mountain trails (*BG* Babia Góra, *DK* Kościeliska Valley, *SI* Izerska Meadow)

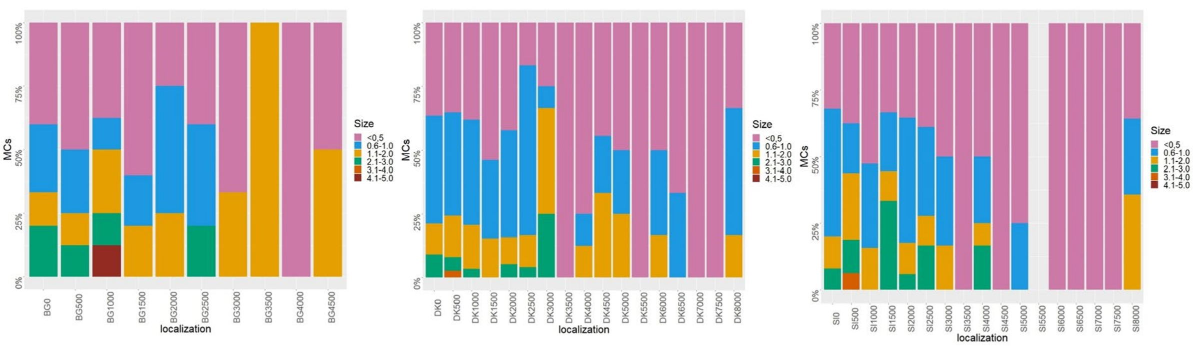

Fig. 5 Distribution of microplastic particles (MCs) by size (mm) in snow on mountain trails (*BG* Babia Góra, *DK* Kościeliska Valley, *SI* Izerska Meadow)

the study. Microplastics below 0.5 mm in many cases accounted for over 50% of the share; in selected sampling points, its share reached 100%. microplastic with dimensions of 2.1–3.0 appeared in the first part of the trails. Microplastics sized 0.6–1.0 mm and 1.1–2.0 mm had a smaller share. Microplastics of 3.1–4.0 mm and 4.1–5.0 mm appeared at single sampling sites (Fig. 5). In snow samples taken from mountain trails, black microplastics dominated, especially on the trails in the Kościeliska Valley and on the trail to Izerska Meadow. White and gray microplastics had a significant share. In addition, green, red, blue, pink, and yellow microplastics were recorded (Fig. 6). The microplastics identified in snow samples from mountain trails varied in shape (Fig. 6). The trail to Babia Góra was dominated by fragments and fiber balls of microplastic. Plastic in the form of fiber had a smaller share. In the case of the trail in the Kościeliska Valley, microplastics in the form of fiber, fiber balls, flakes, and fragment were recorded. On the trail to Izerska Meadow, microplastics in the form of a fragment dominated; a smaller share was made up of microplastics in the form of fiber, fiber balls, and flakes (Fig. 7).

The conducted PCA analysis explains about 33% of the examined features and differentiates the examined surfaces in terms of the type of plastic, its size, and quantity (Fig. 8). The conducted analysis confirms the separateness of the mountain trail to Babia Góra from the other two trails covered by the research. The trail to Babia Góra is characterized by a smaller amount of microplastics and the dominance of other types of plastic. The trail in the Kościeliska Valley and the trail to Izerska Meadow showed similarity in terms of the amount of microplastic, its type, and size (Fig. 8).

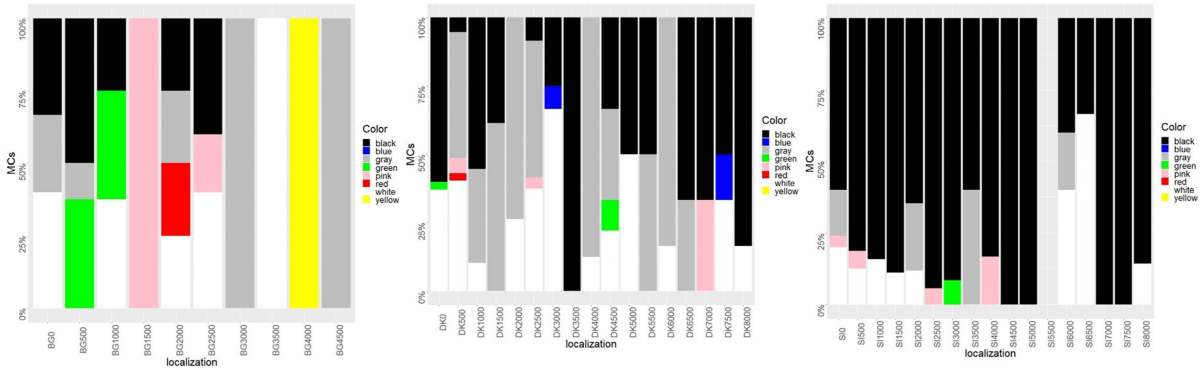

Fig. 6 Distribution of microplastic particles (MCs) by color in snow on mountain trails (*BG* Babia Góra, *DK* Kościeliska Valley, *SI* Izerska Meadow)

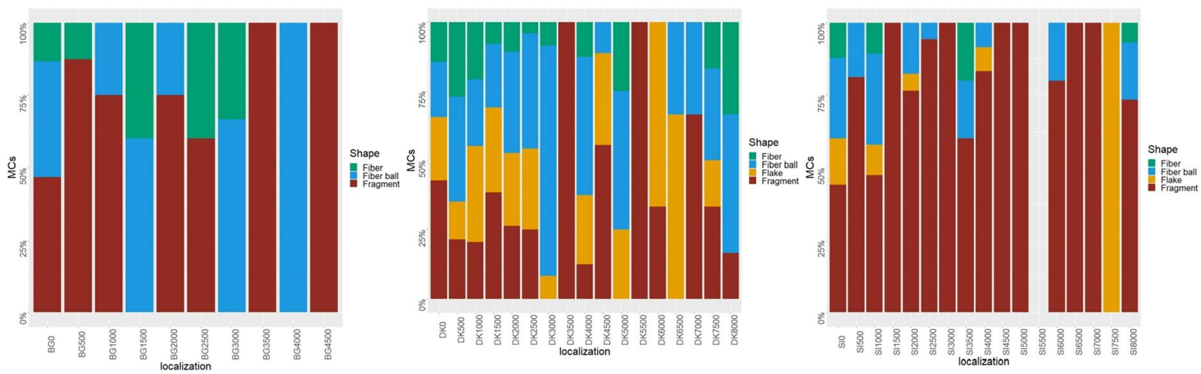

Fig. 7 Distribution of microplastic particles (MCs) by shape in snow on mountain trails (*BG* Babia Góra, *DK* Kościeliska Valley, *SI* Izerska Meadow)

4 Discussion

The research shows significant contamination of mountain trails with microplastics. Microplastics were found at 43 out of 44 snow sampling sites along mountain trails. The amount of microplastics varied within the studied trails; at some points, it was 37 items/L of snow. The observations are consistent with the results of previous studies. In the superglacial debris of the Forni Glacier (Italian Alps), microplastics were recorded in the amount of 74.4 ± 28.3 items/kg of sediment (dry weight), which is comparable to the microplastic pollution of marine and coastal sediments in Europe (Ambrosini et al., 2019). During the study of the glacier of the Antisana volcano, approximately 100 microplastics per liter were identified (Cabrera et al., 2020). Abbasi et al. (2022) indicated that snow is of great importance in the transport of microplastics. In a study conducted in Northern Iran, they measured microplastics at an average of 20 items/L. Villanova-Solano et al. (2023) noted significant amounts of microplastics in snow samples from El Teide National Park (Tenerife, Canary Islands, Spain, 2150–3200 m above sea level). The authors found significant differences in the amount of microplastics depending on the availability of the land. Inaccessible areas had microplastic amounts of 51 ± 72 items/L while areas frequently visited by people had 167 ± 104 and 188 ± 1 64 items/L in "accessible areas" and "climbing areas," respectively. In this research, the relationship between the amount of microplastic and the number of people visiting the trails was indicated. The trail to Babia Góra is visited by 80,000 people a year, trail in the Kościeliska Valley

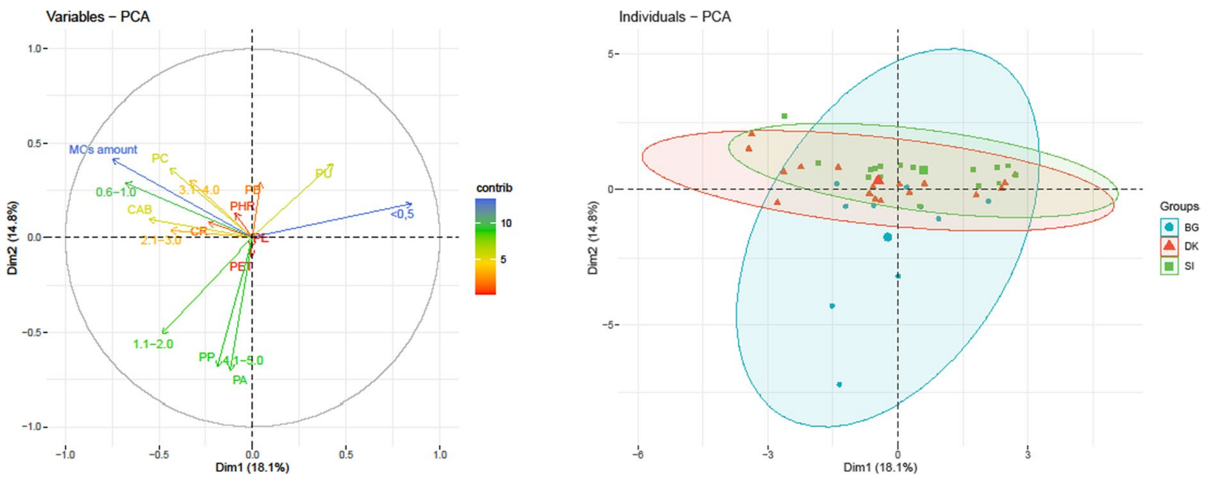

Fig. 8 Projection of variables on the plane of the first and second PCA factors (polyurethane (PU), polyethylene terephthalate (PET), polypropylene (PP), polyethylene (PE), polycarbonate (PC), polybutadiene (PB), polyamide (PA), phenoxy resin (PHR) and chloroprene rubber (CR); *BG* Babia Góra, *DK* Kościeliska Valley, *SI* Izerska Meadow)

by 450,000 people, and trail to Izerska Meadow is visited by about 50,000 people. Kościeliska Valley is located in the Tatra National Park, which in 2021 was visited by a record number of tourists—approx. 4 million 600 thousand (Młynarczyk & Wiciak, 2022). The trail to Babia Góra, which is the most demanding of the tested trails, was characterized by the smallest amount of microplastics. In the highest part of the trail to Babia Góra, we recorded the smallest amount of plastic particles. Trails in the Kościeliska Valley and to Izerska Meadow are easier trails and they are visited by whole families, regardless of age and shape. The first fragments of that trails are characterized by several times higher content of microplastics compared to the further parts of the trail, which is related to the number of people who reach the furthest points of the trails.

In the conducted research, 10 types of microplastics were marked. They were polyurethane, polyethylene terephthalate, polypropylene, polyethylene, polycarbonate, polybutadiene, polyamide, phenoxy resin, cellulose acetate butyrate, and chloroprene rubber. The easier trails were dominated by polyurethane and polyethylene terephthalate, while the more difficult trail to Babia Góra was dominated by polyethylene terephthalate and polypropylene. The dominant types of plastic noted are used for production of outdoor equipment and protective clothing used during mountain hiking. Tourists who decide to go mountain hiking are equipped with more and more specialized equipment and clothing. In recent years, there has been an increase in the use of outerwear and equipment made of plastic, which translates into the amount of microplastics found in the mountains (Napper et al., 2020). In the first studies on microplastics in sea ice, PET, PA, and PP were very common (Obbard et al., 2014). Materić et al. (2020) showed the advantage of PET in alpine snowpit studies. The dominance of PET in snow samples in alpine areas was also determined by Ambrosini et al. (2019) and Pastorino et al. (2023). PET is one of the most used plastics in the world. It is light and can be transparent—which means that it quickly becomes a competitor to the previously used glass packaging. It is used for the production of artificial fibers, e.g., polyester. Such packaging is a source of xenoestrogens that can affect our endocrine system, and improperly stored can release plastic particles into the products packed in them. In our research, we marked a significant share of PU on all the trails, regardless of their specificity. PU allows for the production of materials with increased hardness, which translates into increased durability and chemical resistance of products made of it. A significant share of PU in the snow from the trails studied by us may be the result of its use in the production of clothing and footwear, utility accessories like travel bags, and sports equipment. The obtained results correspond to commonly used materials in global production. According to the market report of Textile Exchange (Textile Exchange, 2021), PET and PP account for the significant share of global fiber production.

Microplastics that are tagged in different environments come in a variety of shapes and sizes (Leusch et al., 2022). In this research, the dominance of finer microplastics (< 0.5 mm) was noted. Microplastics in the range of 0.6–1.0 mm and 1.1–2.0 mm also had a significant share. Microplastic with the largest dimensions was present on selected, single surfaces, mostly located in the first fragments of trails, which may also be related to the number of visitors. Research on microplastics shows the strong importance of tourism in shaping its quantity and type. Research by Gül (2023) proved that both the abundance and the average size of microplastic particles increased after the tourist season associated with the potential number of visitors. Studies by other researchers have indicated the effect of microplastic size on the sorption of various chemicals (Munoz et al., 2021). Research by Ma et al. (2023) emphasize that microplastic particle size has a significant impact on soil bacterial communities and soil functions. Microplastic field studies to date have typically reported fibers (Brahney et al., 2020; Liu et al., 2019). Fiber microplastics were found in snow from Tibetan glacier and Mount Everest films and granules (Napper et al., 2020; Zhang et al., 2021). Our results are consistent with the results of previous research; on the mountain trails covered by the analysis, there was microplastic in the form of fiber, flake above the fragment. Color is a useful criterion to indicate sources of microplastics (Huang & Xu, 2022). In these studies, the predominance of black microplastics was noted, which is mainly associated with footwear and equipment used in the mountains. In addition, green, red, and blue microplastics had a large share. According to Pastorino et al. (2023), colored microplastic comes mainly from clothes.

That research shows the high risks of microplastics in mountainous areas, which are used by an increasing number of people. It should be remembered that microplastics in snow will end up in the soil and will pose a threat to many organisms and people. Pieces of plastic in the terrestrial environment will break down into smaller pieces of plastic mainly as a result of exposure to solar ultraviolet radiation, which increases the likelihood of their consumption by organisms (Saud et al., 2023). Microplastics that get into the soil can become part of a complex mixture of organic matter, making them persist for hundreds of years or more. Microplastics have a large specific surface area, strong adsorption, and hydrophobicity and absorb a large amount of potentially toxic elements and contaminants, which consequently are very dangerous for humans.

5 Conclusions

This research indicates high contamination of mountain trails with microplastics. The study area was characterized by the highest contents of polyurethane, polyethylene terephthalate, and polypropylene. The tiniest plastic below 0.5 mm dominated in all the sampling points, with a small share of sizes within the range of 3.1–4.0 mm and 4.1–5.0 mm. The amount and variety of microplastics were related to the length of the trail, the difficulty, and the number of visitors. The lowest parts of the trails are characterized by the strongest microplastic pollution, which is related to the highest human penetration. The obtained results indicate the need to continue research on microplastic pollution in mountainous areas. Research should be conducted to explain how the aging of microplastic affects its properties and, consequently, the surrounding environment.

Author Contribution Jarosław Lasota: conceived and designed the analysis, collected the data, contributed data or analysis tools, and wrote the paper.

Ewa Błońska: collected the data, contributed data or analysis tools, performed the analysis, and wrote the paper.

Wojciech Piaszczyk: conceived and designed the analysis, performed the analysis, and wrote the paper.

Sylwester Tabor: wrote the paper.

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Data Availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics Approval Not applicable.

Consent to Participate The study does not involve any human participants, human data, or human tissues.

Informed Consent All authors have read and approved the final draft of this manuscript.

Conflict of Interest The authors declare no competing interests.

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