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Atmospheric microplastic deposition in high-altitude snowpacks across Türkiye

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Abstract.

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Microplastic (MP) pollution has been increasingly documented in remote high-altitude environments worldwide, including the European Alps, Himalayas, Andes, and polar snowfields, where atmospheric transport delivers plastic particles even to regions far from emission sources. Despite this growing body of evidence, the occurrence of MPs in the mountainous regions of Türkiye remains unknown. This study presents the first nationwide investigation of MP contamination in alpine snow, conducted across eleven sites, including Mount Ağrı, Süphan, Kaçkar, Erciyes, Uludağ, and Sandras. MPs were detected at all locations, with an average concentration of 286 ± 91 MPs/L with the highest concentration detected at Sandras Mountain (908 MPs/L) and the lowest at Uzundere-Uzunkavak, Erzurum (16 MPs/L). Across the eleven sites, the mean relative shape composition was 71.2±6.1% fibres, 23.8±5.8% fragments, and 5.0±4.5% films (summing to 100% as percentages of all detected MPs). Polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), nylon (PA), and polymethyl methacrylate (PMMA) were identified as the primary polymers. Spatial variability suggested both atmospheric deposition and local human activities contributed to contamination. Backward trajectory analysis indicated that microplastic deposition in snow was influenced by both long-range atmospheric transport from Africa and the Mediterranean and short-range local emissions, highlighting the combined impact of transboundary and regional processes on microplastic distribution. These first-season findings provide a preliminary baseline that even isolated alpine snowpacks of Türkiye can receive

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measurable MP inputs of both regional and long-range origin, highlighting the need for sustained, multi-season monitoring of high-mountain ecosystems within national and transboundary mitigation frameworks.

Keywords: snowpack, microplastic, mountain, atmosphere

Introduction

Plastics have become one of the most widely produced and used materials on Earth. Global production has grown exponentially in the last decades, reaching more than 413.8 million tons (Mt), of which 36.5 million tons were recycled, in 2023 [1], and their production is projected to continue rising [2,3]. Their durability and low cost have made plastics essential across industries and daily life. But these same properties mean that plastics persist in the environment once discarded, fragmenting into tiny pieces known as microplastics (MPs) that can remain in ecosystems for decades or longer.

Over the past two decades, MPs have been reported in almost every environmental matrix studied. They have been found in oceans, rivers, lakes, soils, sediments, and even the atmosphere. Marine systems in particular have received much attention, as floating plastics and microplastics are now documented across all ocean basins [4–6]. Yet MPs are not confined to the sea. They have been detected in drinking water [7], table salt [8], and even human stool samples [9]. Studies in urban settings, such as Paris and London, have shown that atmospheric fallout can deliver thousands of plastic particles

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per square meter each day [10,11]. MPs have even been reported in indoor environments like subway stations, where synthetic fibers dominate airborne particles [12].

Recent evidence has expanded this concern to remote and high-altitude regions, including the Arctic, Antarctic, and major mountain ranges such as the Alps, Himalayas, and Andes [13–15]. These findings confirm that plastic debris has infiltrated the global biosphere, reaching locations once presumed pristine. Mountains are increasingly recognized as both sources and sinks of plastic pollution. More than half a billion people live above 1500 meters globally, many within communities where waste management and sanitation infrastructures remain underdeveloped [16,17]. Mismanaged waste from tourism, mountaineering expeditions, and local settlements contributes directly to macro- and MP leakage into alpine soils, streams, and glaciers. At the same time, mountain environments are also recipients of long-range atmospheric transport, which has emerged as a dominant vector for MP deposition in remote zones [18,19]. Airborne MPs, particularly low-density polymers such as polyethylene (PE) and polypropylene (PP), can travel hundreds to thousands of kilometers before being scavenged by precipitation and deposited through rain or snow [20]. Consequently, snowpacks and glaciers act as temporary reservoirs of atmospheric MPs, which are later released into downstream hydrological systems during melt periods [13,21]. The presence of MPs in snow has been reported in Europe (Swiss and Italian Alps), Asia (Tibetan Plateau, Mount Everest), and the Americas (Andes,

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Ecuadorian volcanoes), underscoring the global reach of atmospheric plastic pollution (Table 1). Nevertheless, significant regional gaps remain in the global dataset, particularly in the Middle East and Anatolia, where few investigations have been conducted despite the ecological and climatic significance of mountainous regions such as the Taurus, Kaçkar, and Ağrı ranges. These regions act as critical water towers for downstream ecosystems and human populations, yet their role as deposition zones for airborne MPs remains poorly characterized. In Türkiye, existing research on microplastics has primarily focused on marine and riverine environments [22,23], while atmospheric deposition and cryospheric accumulation have received little attention. In parallel, a growing body of Turkish work has documented MP contamination in indoor environments, including household floor dust [45] and the size-resolved micro- and nanoplastic burden of indoor commercial spaces [46], indicating that domestic settings constitute an additional, previously overlooked compartment of national MP exposure. Given the combined influence of intense tourism, agricultural plastic use, and regional industrialization, the potential for long-range transport and deposition of MPs onto remote snowfields warrants systematic investigation. This study aims to quantify and characterize microplastic contamination in snowpacks from some of Türkiye's highest mountain peaks, including Ağrı (Mount Ararat), Süphan, Kaçkar, Uludağ (Mount Olympus), and Sandras. By analyzing the abundance, morphology, color, and polymer composition of MPs, and interpreting atmospheric back-trajectories of air masses, we assess

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both the spatial variability and potential sources of contamination. The findings contribute to the growing body of evidence indicating that even remote alpine environments are subject to global plastic pollution pressure. Furthermore, they provide a baseline for integrating high-mountain systems into broader national and transboundary monitoring networks to better understand the ecological and hydrological implications of atmospheric MP deposition in the cryosphere.

Materials and Methods

Study area

Snow samples were collected from eleven high-altitude sites located in major mountain systems of Türkiye, spanning elevations from approximately 2000 m to 5050 m (Fig. 1; Table S1). The sampling campaign encompassed summits from western (Mount Bozdağ, Mount Sandras, Mount Uludağ) to eastern Anatolia (Mount Ağrı, Mount Süphan, Mount Kaçkar, Mount Erciyes, Mount Uzundere) (Table S1). Sites were selected to capture the geographic, climatic, and anthropogenic diversity of high-altitude regions of Türkiye, from humid Black Sea slopes to semi-arid interior plateaus and the continental eastern highlands.

Mount Ağrı, the highest summit of Türkiye (5137 m), was sampled at three elevations (4200, 4793, and 5049 m). The mountain forms part of a national park and draws an estimated 20,000 climbers annually, many of them

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international visitors. Despite this activity, the upper slopes remain largely pristine, with Doğubeyazıt (roughly 70000 inhabitants) being the nearest settlement about 15 km away.

Süphan Mountain (4018 m) lies north of Lake Van, within a sparsely populated high-plateau landscape influenced by cold, dry continental air masses. Its steep volcanic slopes are occasionally used for scientific expeditions and limited trekking, representing one of the most remote environments in eastern Türkiye.

Kaçkar Mountain (3932 m), situated within the Kaçkar Mountains National Park, typifies a humid alpine ecosystem dominated by dense forests and perennial snowfields. The area attracts mountaineers and trekkers throughout summer, benefiting from well-established climbing routes that connect local villages and highland plateaus.

Mount Erciyes (3917 m) is a dormant stratovolcano overlooking Kayseri (~1.4 million inhabitants) and serves as a major winter-sports centre. Its extensive ski infrastructure and year-round accessibility introduce a higher level of local anthropogenic influence compared with other interior sites.

Uludağ (2543 m) and Bozdağ (2159 m) represent western peaks of Türkiye. Uludağ, located 30 km south of Bursa, receives nearly one million visitors annually and functions as Türkiye’s premier ski resort and national park. Bozdağ supports mountaineering and day hiking.

Sandras Mountain (2295 m) in Muğla Province remains relatively undisturbed. Covered by pine forests and alpine meadows, it is occasionally

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used for hiking and camping but experiences limited tourist pressure compared to western ski destinations.

In Erzurum Province, two sites were established near Uzundere, at 2027 m and 2502 m, respectively. The area lies within steep valleys bordered by forests and frozen waterfalls that attract seasonal ice-climbing enthusiasts which is a form of winter adventure tourism that has recently gained popularity. Outside this seasonal activity, the region remains sparsely populated and experiences limited year-round disturbance

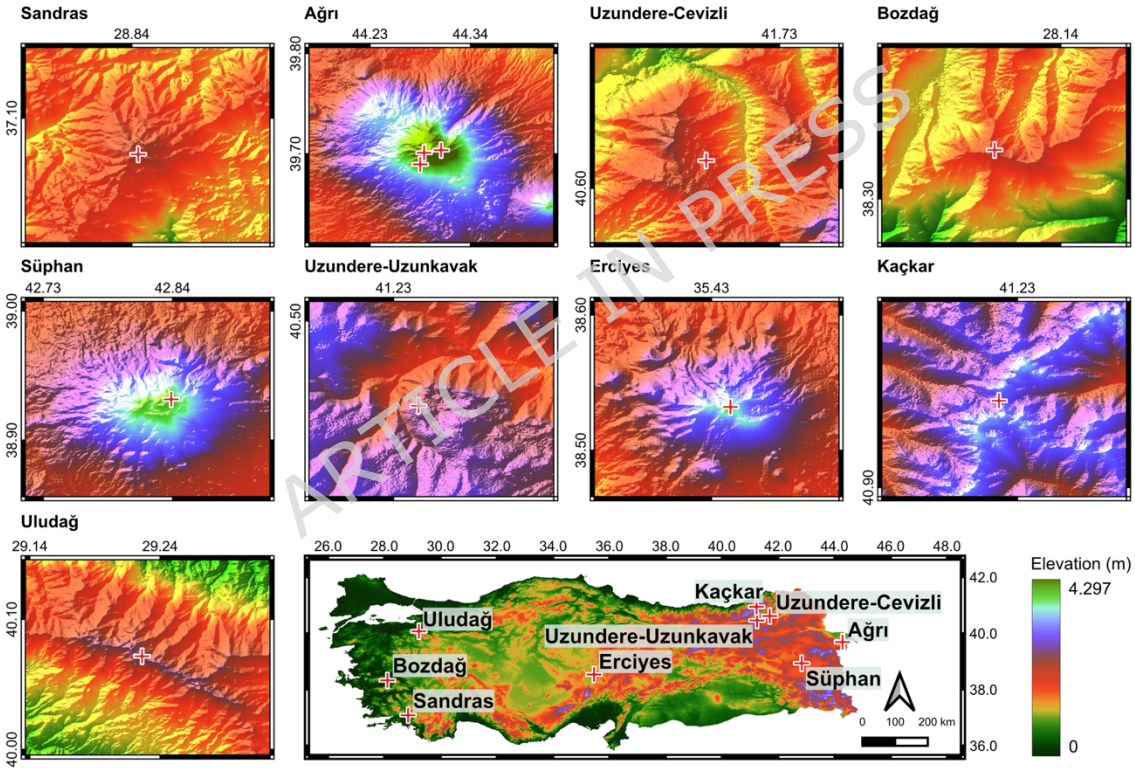


Figure 1. Snowpack sampling sites across Türkiye. Elevation gradients are indicated by color shading, and major topographic features are labelled for reference. The map is generated in QGIS (v.3.40.3, http:// www. qgis. org)

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Sampling and MP extraction

Snow samples were collected between January and March 2025 (Fig. 1). Sampling was carried out with the assistance of experienced local mountaineers. At each site, surface snow (0–15 cm) was collected by directly inserting pre-cleaned 500 mL glass jars into the snowpack. Each jar had been triple-rinsed with ultrapure water (Millipore Direct-Q 3 Milli-Q)
and sealed with a metal screw cap. During collection, climbers remained downwind of the sampling point. An empty, pre-washed jar was filled with ultra-pure water to serve as a blank. Snow sample volumes were quantified after melting at room temperature in the laboratory. Because snow has a substantially lower bulk density than liquid water, the meltwater volume obtained from each 500 mL jar ranged from 80 to 536 mL (mean ~140 mL; see Table S1); MP concentrations were therefore expressed on a per-litre-of-meltwater basis throughout. To ensure quantitative recovery of particles, each jar was triple-rinsed with ultrapure water after pouring the meltwater into the filtration apparatus, and the rinsate was passed through the same membrane. Melted snow samples were filtered using 0.45 µm pore-sized membranes, and the filters were then placed in sterile Petri dishes for subsequent microscopic and spectroscopic examination.

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Polymer identification

Particles were examined under a stereomicroscope (SZX16, Olympus, Japan) placed within an enclosed cabinet to minimize airborne contamination. Each

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particle was classified according to its size, shape, and color. Measurements were obtained using a Touptek XCAM1080PHD digital camera attached to the microscope. The categorization of MP morphology and coloration followed the criteria described by Vural et al. [24].

To avoid redundancy and ensure analytical efficiency, all observed particles were first grouped into morphologically homogeneous clusters defined by size, shape, and colour similarity, and one representative particle from each cluster was selected for chemical characterization. This cluster-based subsampling strategy ensures that the polymer diversity of the entire particle population is captured while keeping the μRaman workload feasible, in line with the protocol of Vural et al. [24]. A total of 44 representative particles, accounting for approximately 10% of all observed particles (n = 554), were analyzed for polymer confirmation using confocal μRaman microscopy (inVia Qontor, Renishaw Plc., UK). The instrument was equipped with dual excitation lasers (532 nm and 785 nm) and coupled to a Leica optical microscope. Each particle was examined under 50× magnification, ensuring accurate focusing on the particle surface. μRaman spectra were collected with an integration time of 10 s and two accumulations per scan to improve signal-to-noise ratio. The optical detection limit of the confocal μRaman microscope, governed by the diffraction limit of the 532 nm and 785 nm excitation lasers, is approximately 1 μm; accordingly, all particles examined in this study (size range 41–3864 μm) were well above the instrumental detection threshold. Spectral acquisition covered the wavenumber range of

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300–3200 cm^{-1}, with grating settings adjusted between 600 and 1800 lines/mm depending on the polymer's scattering characteristics. The obtained spectra were compared against the ST-Japan Microplastic Polymer Library, a reference database encompassing common synthetic and semi-synthetic polymers. A minimum match quality threshold of 70% was employed to confirm positive polymer identification, in accordance with established analytical protocols and current literature [12,24]. The overall analytical workflow, visual screening followed by Raman-based polymer confirmation on cluster-derived representative subsamples and stringent QA/QC, is consistent with current methodological syntheses for MP detection, isolation, and chemical characterization across environmental matrices [43].

Quality assurance and quality control

To maintain analytical accuracy and eliminate potential contamination, strict quality assurance and control (QA/QC) measures were implemented throughout sampling, processing, and analytical procedures. The overall QA/QC framework was designed following recent recommendations for preventing contamination during the laboratory analysis of atmospheric and snow samples for MPs [44]. All equipment and glassware were pre-cleaned with ultrapure water (Millipore Direct-Q 3 Milli-Q) and analytical-grade acetone (Merck 100014.2500) before use and subsequently stored in sealed glass or metal containers. Wherever feasible, plastic materials were entirely avoided in sampling and laboratory workflows. Sample handling was

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performed within a Class-4 laminar flow cabinet (Esco Technologies Inc.) to minimize airborne particle contamination. The μRaman microscope and associated optical components were housed in enclosed laboratory environments, with working surfaces wiped with acetone before and after each session. All solvents and filtration solutions were pre-filtered through 0.45 μm GF/C Whatman glass fiber filters using a Rocker 400 vacuum filtration system (Rocker Scientific Co., Ltd., Taiwan). During all operations, sample containers were covered with aluminium foil, and laboratory personnel wore cotton laboratory coats to reduce the introduction of synthetic fibers. Both procedural blanks and field blanks were prepared and processed alongside real samples using identical procedures. These blanks were subsequently analyzed under both stereomicroscopic and μRaman spectroscopic conditions to verify contamination-free processing. Counts of suspected particles observed on procedural and field blanks were recorded prior to μRaman screening to allow a blank-correction step; in all blanks the number of suspected airborne fibres remained below 1 particle per filter, which was below the inter-replicate variability of the field samples and is therefore reported as a blank-corrected zero. This very low background, comparable to the values reported under similarly controlled laminar-flow conditions in Bhat et al. [44], reflects the combination of (i) handling all samples inside a Class-4 laminar flow cabinet, (ii) processing each field jar and its paired blank under identical conditions, and (iii) restricting personnel to cotton garments. The very low blanks should therefore not be interpreted

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as evidence that airborne MPs are absent from the laboratory atmosphere, but as the result of these specific control measures. Because blank counts were effectively zero (< 1 particle per filter), no further numerical subtraction was applied to the sample data, and reported MP concentrations are uncorrected raw values.

Data Analysis

To investigate the potential atmospheric transport pathways influencing microplastic deposition at each sampling site, 72-hour backward air-mass trajectories were computed using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model developed by the NOAA Air Resources Laboratory [25]. For each sampling location and date, trajectories were initialized at three arrival heights (500, 1000, and 1500 m above ground level) to capture vertical variability in air-mass movement within the lower troposphere. These levels represent typical transport layers associated with boundary-layer and free-tropospheric inflows during winter. Meteorological input data were obtained from the Global Data Assimilation System (GDAS, 1°×1° resolution), and all simulations were conducted using HYSPLIT v5.2.1 via the READY online platform [26]. Data summarisation was performed using R. The data were expressed as mean±standard error of the mean.

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Results

A total of 554 microplastic-like particles were extracted from the samples. The overall average MP density in snow samples was 286.44±91.36 MPs/L. The highest densities were recorded at Sandras (908.05 MPs/L), Ağrı-2 (757.14 MPs/L), and Uludağ (399.25 MPs/L), while the lowest were Uzundere-Uzunkavak (16 MPs/L), Bozdağ (40.82 MPs/L), and Uzundere-Cevizli (42.45 MPs/L) (Fig. 2).

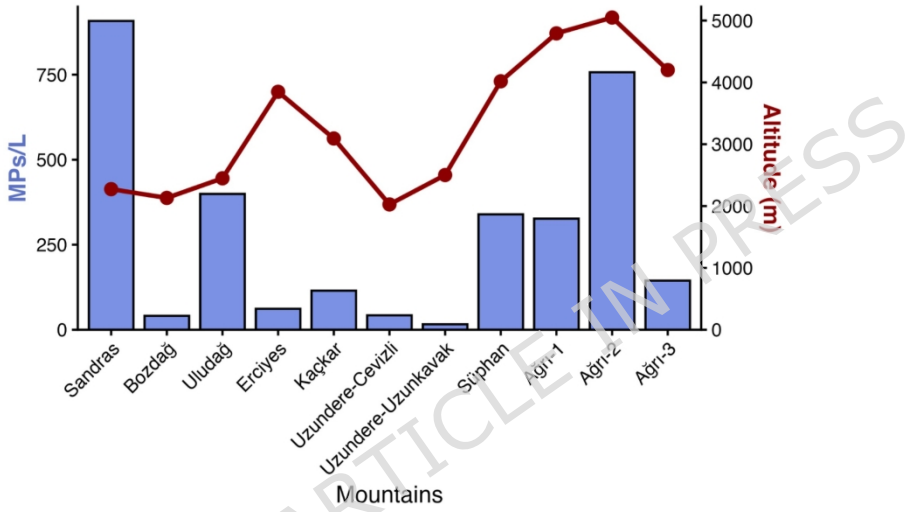


Figure 2. Microplastic (MP) concentration (MPs/L) in snow samples from each sampling site.

The polymeric composition of microplastics isolated from the mountains revealed marked spatial variability (Fig. 3). PET/Polyester (58.3±8.33%), PE (45.5±4.18%), Nylon-6/Polyamide (43.3 ± 0.84%), PP (39.2± 3.94%), and PMMA (33.3%) were the polymer types detected across sites. PE was the most commonly found polymer detected at every station. It dominated the polymer composition at Ağrı-3 (66.7%), Uludağ (66.7%), and Bozdağ (60%).

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Nylon-6/Polyamide was the dominant polymer at Ağrı-1 (66.7%) and Kaçkar (66.7%). PET/Polyester and PMMA were the least common polymers.

Analysis of microplastic morphologies revealed three distinct shapes: fibers, fragments, and films. The distribution of these shapes varied considerably across the 11 sampling locations (Fig. 3). Overall, fibers were the most dominant shape, accounting for most particles at 9 of the 11 sites. The relative shape composition (i.e., the percentage of fibers, films, and fragments out of the total MPs at each site, with absent shapes counted as 0% at sites where they were not detected) averaged across the eleven sites was 71.2 ± 6.1% fibers, 23.8 ± 5.8% fragments, and 5.0 ± 4.5% films. These values represent shape proportions per site and are independent of absolute MP concentrations. Fibers constituted over 90% of all identified MPs at Erciyes (94.7%), Uludağ (92.5%), and Ağrı-2 (92.4%). Fragments were the second most frequently observed shape. Notably, at Uzundere-Cevizli, fragments were the predominant type, making up 66.7% of the particles. Films were the least common morphology, detected at only two locations: Bozdağ (50%) and Süphan (5.26%).

A total of seven color categories were identified across the snow samples: transparent, blue, black, white, red, purple, and yellow (Fig. 3). Overall, black (48.1±4.0%) and blue (26.2±3.7%) MPs were the most common color groups. Black particles were the most common color at Ağrı 3 (69.2%), Ağrı 2 (56.6%), and Kaçkar (56.5%). Blue particles were also highly prevalent, dominating the samples from Erciyes (47.3%), Ağrı-1 (38.8%), and Sandras (32.9%).

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Transparent particles were also observed, at most sites, ranging between 5 to 50%. Yellow (25%) colored MPs were only observed at Uzundere-Uzunkavak. Purple was the least common color, detected at only four sites in low abundances (< 5%).

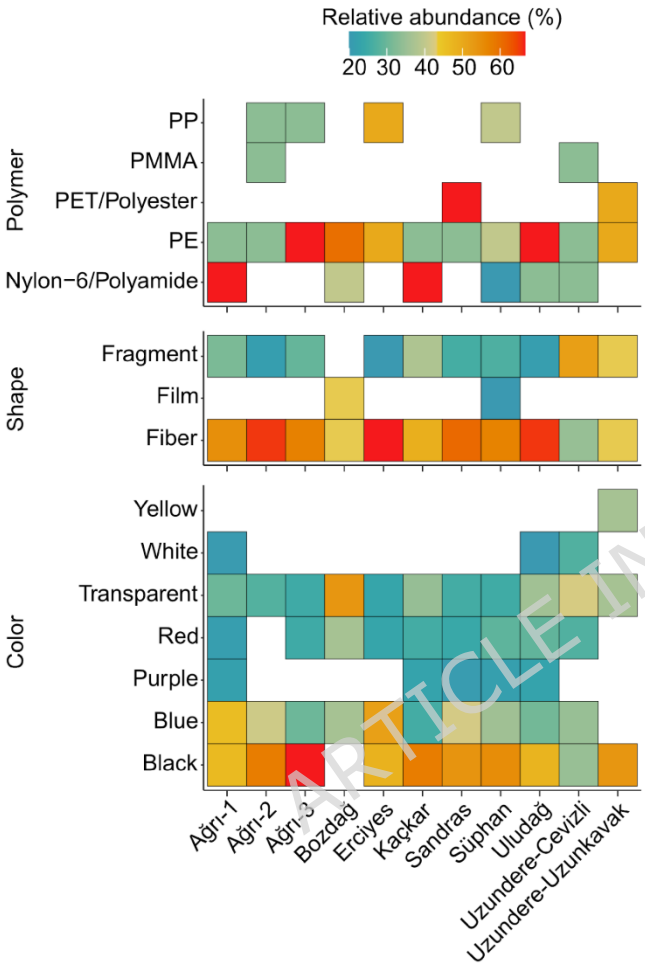


Figure 3. Relative abundance (%) of microplastic (MP) polymers, shapes, and colors identified in snow samples from the different sampling locations.

The size of MPs varied between 41 µm to 3864 µm with an overall average of 744.7±69.9 µm (Fig. 4A). The size of microplastics differed among shape categories. Fibers ranged from 141 to 3864 µm, with a mean size of 861.7 ±

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92.8 µm. Films ranged from 229 to 1014 µm, with a mean size of 494.1 ± 260.0 µm. Fragments ranged from 41 to 3319 µm, with a mean size of 566.1 ± 106.4 µm (Fig. 4B).

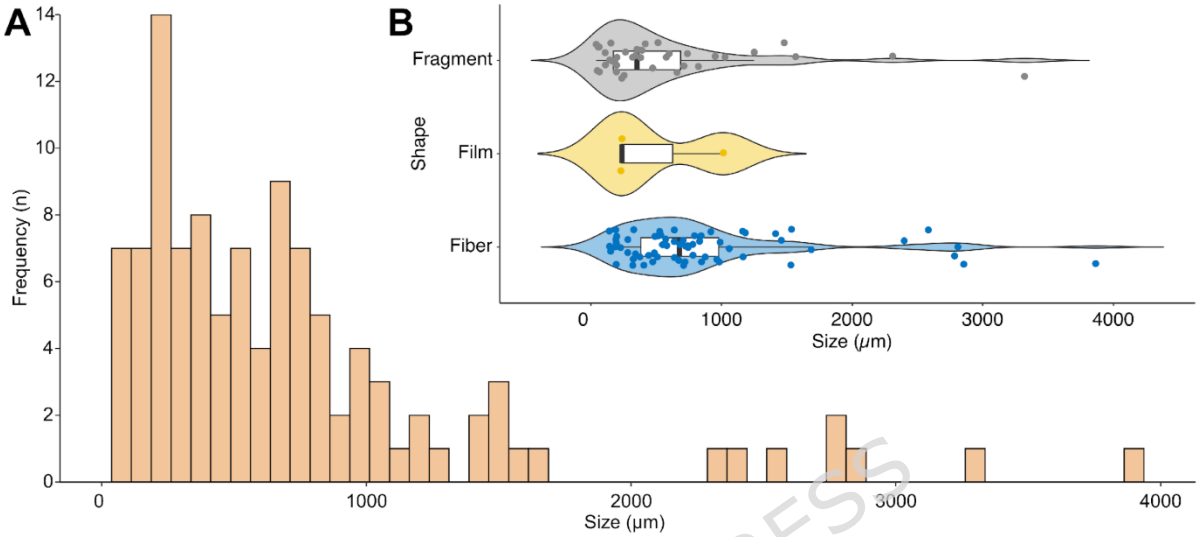


Figure 4. Size distribution of microplastics. Frequency distribution of particle sizes (A). Violin plots showing size ranges of fragments, films, and fibers (B).

Figure 5 shows the 72-hour backward trajectories used to identify the main transport directions and potential source regions of air masses arriving at each site. The multi-level trajectories reveal the influence of long-range transport, helping to explain the spatial variation in microplastic concentrations in the snow samples. In Sandras, Bozdağ, and Uludağ, the air masses originated from North Africa and the Mediterranean, indicating possible long-range dust transport. In contrast, Uzundere-Cevizli, Süphan, Ağrı-2, Ağrı-3, and Erciyes were mainly influenced by relatively short-range transport, suggesting a stronger impact from local atmospheric sources. In addition, at the Uzundere-Uzunkavak and Kaçkar sites, air mass transport

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occurred in similar directions at all levels. Meanwhile, at the Uzundere-Cevizli and Ağrı-1 sites, transport from the north was particularly notable.

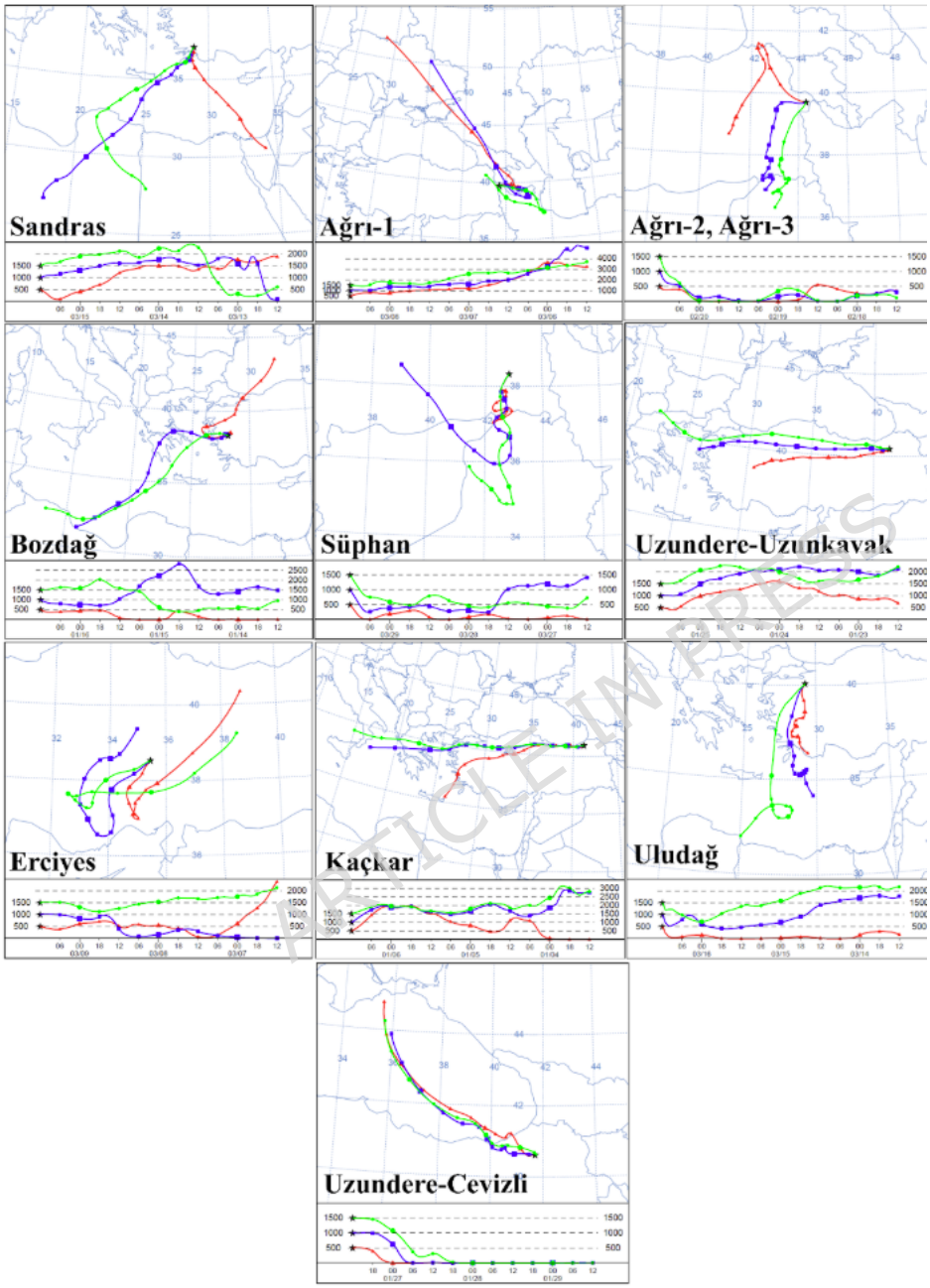


Figure 5: 72-hour backward air-mass trajectories computed using the HYSPLIT model for different sampling sites. Each graph illustrates the potential atmospheric transport pathways of air parcels arriving at the

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corresponding sampling locations on the respective sample dates. The map is generated using Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT v5.2.1, http://ready.arl.noaa.gov/HYSPLIT.php) *model.*

Discussion

The mean concentration of microplastics detected in alpine snow across Türkiye (286 ± 91 MPs L^{-1}) confirms that even high-elevation and seemingly remote environments are affected by plastic deposition. The observed range (16–908 MPs/L) is comparable to those reported in remote mountain regions worldwide. For instance, Bergmann et al. [13] observed 369–1111 MPs/L in snow from the Svalbard Archipelago, while Cabrera et al. [15] reported 358 MPs/L on Ecuador's Antisana volcano. Similarly, Napper et al. [14] measured 3–119 MPs/L on Mount Everest, and Villanova-Solano et al. [32] found 51 ± 72 MPs/L in the snow of El Teide National Park, Spain. Although the highest value recorded in Türkiye (908 MPs/L at Sandras) does not reach the extreme values found in densely polluted European Alps (up to 17,600 MPs/L; Germany-Bavarian Alps [13], it clearly indicates substantial deposition even at sites far from major emission sources (Table 1).

The backward trajectory analysis indicates that air masses arriving at the sampling sites were influenced by both long-range and regional transport processes. The recurring presence of airflows originating from North Africa and the Mediterranean region suggests that dust-laden air masses could have contributed to the deposition of MPs in the collected snow samples [33].

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Previous research has shown that Saharan dust transport can carry not only mineral particles but also anthropogenic plastic fibers and synthetic fragments across continental scales [19,34]. Similarly, Allen et al. [18] reported substantial MP deposition in the Pyrenees, hundreds of kilometers away from urban centers, emphasizing that long-range transport represents an overlooked component of the global plastic cycle. Although the high MP concentrations observed at the Sandras, Ağrı, Uludağ, and Süphan sites can be associated with intensive tourism activities, the analysis of air mass movements indicates that long-range atmospheric transport also played a significant role at these locations.

Although previous studies suggest that only particulate matters smaller than approximately 10 µm can remain suspended over such long distances [27–30], the MPs detected in this study, starting from about 41 µm, may undergo extended atmospheric transport due to their fibrous morphology, low density, and aerodynamic characteristics, which enhance suspension and delay gravitational settling [30,31]. Consequently, atmospheric circulation likely facilitates the transfer of MPs from urban or coastal emission sources to remote alpine environments. The trajectory analyses further revealed that prevailing westerly and south-westerly air masses may transport airborne plastics from industrial and agricultural zones of western and central Anatolia, while easterly currents from the Caucasus region likely contribute to deposition in the eastern highlands. The coexistence of these transport mechanisms, combined with limited local human inputs such as seasonal

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tourism and fiber shedding from mountaineering activities, highlights the multifactorial origins of MP contamination in alpine snow across Türkiye's mountain systems. The dominance of short-range trajectories in some events points to the contribution of local and regional emission sources, such as road traffic, urban activities, and the resuspension of deposited materials. This observation is consistent with the findings of Zhang et al. [35] and Gasperi et al. [36], who demonstrated that a significant portion of MPs in high-altitude and terrestrial environments originates from near-source atmospheric inputs. The predominance of fiber-shaped microplastics observed on snow surfaces further supports this interpretation, as their low density and aerodynamic characteristics facilitate both short- and long-range atmospheric transport.

However, the spatial variability observed among sites suggests that MP inputs cannot be attributed solely to atmospheric deposition. Mountains with high visitor frequency, particularly Uludağ, Erciyes, and Mount Ağrı, recorded some of the highest MP densities. This analysis of local human impact is further substantiated by comparing site pollution with visitor frequency. Regions with elevated recreational activity, such as Uludağ, attracting around half a million people yearly [37] and had markedly high MP concentration (399.25 MPs/L) Mount Ağrı not only represents Türkiye's highest peak but also is a key destination for recreational and mountaineering activity [38]. This supports our interpretation that elevated microplastic concentrations at the site of Mount Ağrı (757.14 MPs/L) may reflect not only atmospheric deposition but also intensified human presence and equipment-

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related shedding in this region. In contrast, rural locations with limited outdoor attractions, like Uzundere-Uzunkavak (16 MPs/L), exhibited the lowest concentrations. This robust positive correlation indicates that local human activities, presumably from the shedding of synthetic fabrics and equipment wear, serve as a substantial local source that enhances the background air deposition. These areas host annual climbing expeditions, ski tourism, or recreational traffic that can directly introduce synthetic fibers through clothing abrasion, equipment wear, or litter fragmentation. The presence of elevated MP counts near base camps and popular trails at Mount Ağrı and Mount Uludağ supports this interpretation. In contrast, Uzundere sites (16–42 MPs/L) and Süphan, which experience minimal tourism or local activity, showed markedly lower concentrations, indicating that atmospheric fallout alone yields smaller deposition loads in isolated zones.

The polymeric composition of MPs identified in the Turkish snow samples was dominated by PE, PP, PET, nylon-6/PA, and PMMA. These polymers are the same major types repeatedly reported in alpine and polar snow worldwide [13–15,39] (Table 1), indicating common global emission and transport pathways. The prevalence of PE and PP, light-density polymers widely used in packaging materials, single-use films, and synthetic textiles, suggests that a large fraction of the particles originated from atmospheric fallout of urban and industrial emissions. Their low density facilitates long-range aerial transport, and their dominance across nearly all sites aligns with findings from the Alps and Svalbard, where airborne fibers and fragments of these

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polymers were linked to continental dust plumes [18,19]. The occurrence of PET and nylon-6 points toward fibrous sources such as synthetic clothing and outdoor garments. These materials are commonly used in outdoor apparel and climbing ropes, making them plausible indicators of both local human activity (e.g., climbers, trekkers, and resort visitors) and regional atmospheric inputs. Elevated proportions of nylon-6 at Mount Ağrı and Kaçkar, both popular climbing destinations, support this dual origin. Similarly, PET/polyester fibers are known to dominate airborne MPs in urban atmospheres and indoor environments, highlighting the possibility of regional redistribution from populated lowlands to alpine snowpacks. Detection of PMMA, though less abundant, is noteworthy because it often derives from paints, coatings, and vehicle components. Its presence in remote mountains such as Ağrı and Uzundere may therefore reflect aerosolized traffic- and industry-related emissions carried over long distances rather than local deposition. Overall, the polymer composition of the studied snowpacks mirrors the global pattern observed in high-altitude and polar regions, reinforcing the notion that light, fiber-forming synthetic polymers dominate atmospheric MP transport. At the same time, the enrichment of clothing-related polymers (PET, PA) at tourism-intensive peaks implies that direct human activity amplifies atmospheric deposition locally.

The morphological distribution of MPs in snow was dominated by fibers (71.2 ± 6.1%), followed by fragments (23.8 ± 5.8%) and films (5.0 ± 4.5%). Fibers were the most abundant shape at nine of the eleven sites, exceeding 90% of

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all particles at Erciyes, Uludağ, and Ağrı-2, while fragments were the most common shape only at Uzundere-Cevizli and films were scarce overall. This fiber dominance is consistent with global reports from snow and ice environments, including the Alps and Svalbard [13], Mount Everest [14,15], Antisana Glacier (Cabrera et al., 2020), and the Tibetan Plateau [39] (Table 1). Fibers are typically derived from synthetic textiles such as PET/polyester, PA, and acrylic, which are shed during the use and washing of clothing and are easily entrained into the atmosphere. Their elongated morphology and low density enhance aerodynamic lift, allowing them to travel long distances before deposition by precipitation. In Türkiye, the widespread use of synthetic fabrics in outdoor garments, combined with the strong westerly winds influencing mountain weather systems, likely explains their prevalence across all sites. Elevated fiber proportions at Uludağ, Erciyes, and Ağrı also point to local shedding from outdoor and skiing apparel, consistent with the high recreational intensity at these locations. Fragments and films, although less common, provide complementary insights into MP sources. Fragments, often produced from the breakdown of larger plastic debris or secondary abrasion of packaging materials, were more frequent in Uzundere samples, possibly reflecting localized resuspension of soil-derived MPs or minor contamination from nearby roads. Films, detected mainly at Bozdağ and Süphan, likely originated from lightweight plastic packaging or agricultural mulch transported by wind from lower altitudes. The scarcity of films compared with fibers supports the interpretation that atmospheric fallout is

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the primary deposition pathway, since fibrous particles possess higher atmospheric residence times and greater potential for long-range transport. Several methodological considerations should be borne in mind when interpreting these results. First, polymer identification was performed using a cluster-based subsampling strategy. Morphologically homogeneous groups of particles (defined by size, shape, and colour) were formed, and one representative particle from each group was analysed by μRaman microscopy [24]. While this approach captures the polymer diversity of the entire particle population (44 particles, roughly 10% of total), it does not chemically verify every individual particle, and the possibility that a fraction of the visually classified particles are non-plastic in origin (i.e., false positives) cannot be entirely excluded. The implicit assumption that visually similar particles share the same polymer composition will introduce uncertainty in the reported polymer proportions, and the reported polymer composition should therefore be regarded as a representative characterization. Complementary tests such as the hot-needle method, which would have been informative for visually ambiguous fibres, were not employed because their destructive nature would have prevented μRaman confirmation of the representative subset. Second, the 72-hour HYSPLIT backward trajectories represent a synoptic snapshot at each sampling date and do not capture the full deposition history integrated within the 0–15 cm snowpack, which can span weeks to months of accumulation. Our trajectory analysis should therefore be interpreted as indicative of dominant late-winter transport pathways,

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consistent with the well-established regional climatology of westerly and south-westerly flow over Anatolia and intermittent Saharan/Mediterranean dust intrusions [27–29], rather than as definitive source attribution in the absence of quantitative source apportionment models or chemical/isotopic tracers, the identification of specific emission sources remains qualitative. Third, the sampling campaign was restricted to a single late-winter window (January-March 2025) and to snow surface (0–15 cm). Because alpine snowpacks can vary substantially with individual snowfall events, synoptic-scale atmospheric circulation, and melt–freeze cycles, our dataset cannot resolve seasonal or interannual variability, nor can it disentangle freshly deposited from previously stored MPs. Fourth, our results are expressed as MP concentrations per litre of meltwater (MPs/L) and not as deposition fluxes (MPs/m^2/day), without paired air sampling, snow water-equivalent measurements, and accumulation chronology, direct comparison with the atmospheric MP-deposition literature is therefore limited. Fifth, although the Raman optical detection limit (aroun 1 µm) is well below the smallest observed particles, the 0.45 µm filtration step inevitably excludes nanoplastics and the smallest submicrometre fragments, so total particle counts should be regarded as a lower bound of the true MP burden. Finally, data summarisation was restricted to descriptive statistics (mean ± standard error), inferential testing (e.g., one-way ANOVA across sites, correlation with elevation or visitation intensity, and multivariate ordination such as PCA or cluster analysis) was not undertaken given the small number of replicates per

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site and the heterogeneous spatial design. Future work integrating event-based snowfall sampling paired with concurrent trajectory analyses, seasonally resolved deposition campaigns, multi-decadal wind climatologies, paired air sampling, nanoplastic-capable filtration, and formal multivariate statistical analysis will be necessary to refine source identification, flux quantification, and trend detection for MP deposition in the Turkish cryosphere.

Table 1. MP levels found in snow samples from high altitude areas

Conclusion

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This study provides a first, single-season baseline assessment of MP contamination in surface snowpacks across Türkiye's major mountain systems, spanning from the Mediterranean to the eastern highlands. The detection of MPs in every sampled site, including some of the most remote environments, confirms that plastic pollution has reached even the highest elevations of Anatolia. Concentrations varied considerably among sites, reflecting the combined influence of atmospheric deposition and local human activity. Western mountains such as Sandras, Uludağ, and Erciyes exhibited higher MP densities, consistent with greater urban proximity and recreational use, whereas more isolated summits like Süphan and Uzundere recorded the lowest concentrations. The polymeric composition mirrors global reports from other mountain and polar snow studies, supporting the hypothesis that atmospheric fallout of synthetic fibers is a primary vector for

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contamination. However, the enrichment of textile-related polymers and fibers at climbing and skiing destinations underscores the importance of local contributions such as clothing abrasion, equipment wear, and tourist-related litter. Backward trajectory analysis indicated that air masses influencing several western and eastern sites originated from North Africa and Mediterranean, suggesting that long-range transport likely contributed to MP deposition. Because the present dataset is restricted to a single late-winter campaign across a single country, the broader claim that high-mountain snowpacks act as quantitative sinks for global MP fallout cannot yet be made. The values reported here should therefore be regarded as a first national baseline. Future work integrating multi-season sampling, paired atmospheric deposition flux measurements, nanoplastic-capable filtration, and source apportionment tools (e.g., wind-rose climatology, isotopic/chemical tracers, and multivariate ordination) would be ideal to confirm and contextualise these findings and to quantify the relative roles of long-range and local sources at the national and transboundary scale.

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Author contributions

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The study was conceptualised by KG, RÇÖ, YT, and SG. SE performed and organized sampling. KG performed laboratory analysis. YT performed data analysis and visualization. CA carried out model simulations and analysed model results. YT, RÇÖ, KG, and SG wrote the manuscript draft. All authors contributed to writing and revising the manuscript, and approved the final version for submission

Data availability

The datasets used and analysed during the current study available from the corresponding author on reasonable request.

Ethics approval and consent to participate

Not applicable.

Competing interests

The authors declare no competing interests.

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Table 1. MP levels found in snow samples from high altitude areas

Country	Location	Sampling Year	Number of Stations/Samples	Altitude (ASL)	Sample type	MP Abundance	polymer types	shape	color	size	References
Norway	Svalbard	2018	5	NA	snow	369-1111 items/L	PE PP PS PC PA PVC C PESU CR PLA PCL EVA	Fiber	Black Blue Dark blue Purple Red White Others	11-475 µm	[13]
Switzerland	Swis Alps	2018	5	NA	snow	191-154137 items/L					
Germany	Bavarian Alps	2018	3	NA	snow	2000-17600 items/L					

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							Rubbers				
Italy	Forni Glacier, Italian Alps	2018	1/6	2580	glacier	74.4 ± 28.3 items/kg	PP PA PP PE	Fiber Fragment	Black Blue Transparent Red Light Blue Violet	>100 μm	[40]
Nepal	Mount Everest	2019	6/11	5300, 6000, 6500, 8000, 8440	snow	3-119 items/L 30±11 items/L	PES PMMA PA PP	Fiber Fragment	Red Blue Clear Black Purple	36-3800 μm	[14]
Ecuador	Antisana volcano	2019-2020	6	5100-5600	glacier	358 items/L		Fiber Film Fragment Sphere	Transparent Blue White Red	60-2500 μm	[15]
Tibetan Plateau	Qilian Mountain Qiangyong Glacier	2018	2/10	4260-5600	glacier		PA PE Rubber P POM PS PC V PMMA PVOH PVC PAM PP PTFE C	Fiber Fragment Film	Black Red Green Blue	10-100 μm	[39]
Italy	Aosta Valley	2019	4/12	>2500	residual snow	0.39±0.39-4.91±2.48 items/L	PE PET HDPE P LDPE PP PU	Fiber Fragment	White Blue Light Blue Pink/Purple	50-1910 μm	[41]
Spain	El Teide National Park	2021	3/63	2150-3200	snow	51±72 items/L	C PES PMMA PA PP Azlon	Fiber Fragment Film	Blue Black White Red Pink Yellow Grey	80-4989 μm	[32]

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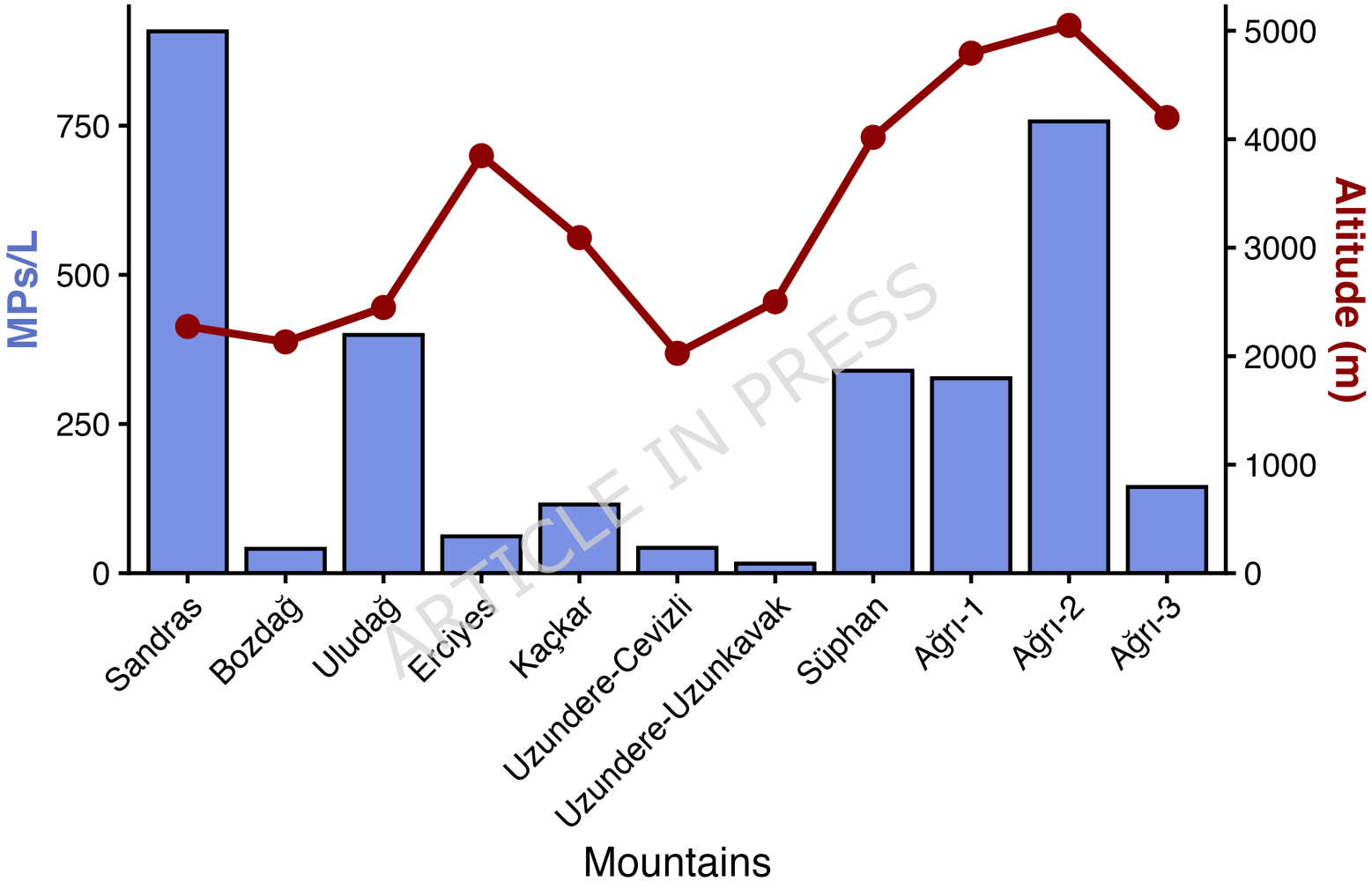
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									Purple Green Orange Brown		
Iceland	Vatnajökull Ice Cap	2020	1/7	>1400	glacier core		PUR PVC PA ABS Cellulose	Fragment Fiber	Transparent Green Red Blue/pink	30-3000 μm	[21]
Italy	Friuli Venezia-Giulia Region	2020	3/12	1872	snow	0.11 ± 0.19 items/L	PET	Fragment	Blue	220 μm	[42]
Türkiye	Anatolia	2025	10	2000-5050	snow	286 ± 91 items/L	PE PP PET PA PMMA	Fiber Fragment Film	Transparent Blue Black White Purple Yellow	41-3864 μm	This study

polyethylene-PE; polypropylene-PP; polystyrene-PS; polycarbonate -PC; polyamide-PA; polyvinyl chloride-PVC; polyether sulphone-PESU; polymethyl methacrylate-PMMA; cellulose-C; polychloroprene-CR; polylactic acid-PLA; polycaprolactone-PCL; ethylene vinyl acetate-EVA; polyester-P; polyoxymethylene -POM; Varnish-V; polyvinyl alcohol-PVOH; polytetrafluoroethylene-PTFE; polyacrylamide-PAM; high density polyethylene-HDPE; low density polyethylene-LDPE; polyurethane-PUR

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