

Article

Pilot Study of Microplastics in Snow from the Zhetysu Region (Kazakhstan)

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Abstract

The pilot study is devoted to the assessment of both the accumulation and spatial distribution of microplastics in the snow cover of the Zhetysu region. The height of snow cover in the study area varied from 4.0 to 80.5 cm, with a volume of melt water ranging from 1.5 to 143 L. The analysis of 53 snow samples taken at different altitudes (from 350 to 1500 m above sea level) showed the presence of microplastics in 92.6% of samples in concentrations from 1 to 12 particles per square meter. In total, 170 microplastic particles were identified. The main polymers identified by Raman spectroscopy were polyethylene (PE), polypropylene (PP), and polystyrene (PS). These are typical components of plastic waste. The spatial distribution of microplastics showed elevated concentrations near settlements and roads. Notable contaminations were also recorded in remote mountainous areas, confirming the significant role of long-range atmospheric transport. Particles smaller than 0.5 mm dominated, having high aerodynamic mobility and capable of long-range atmospheric transport. Quantitative and qualitative characteristics of microplastics in snow cover have been realized for the first time both in Kazakhstan and in the Central Asian region, which contributes to the formation of primary ideas and future approaches about microplastic pollution in continental inland regions. The obtained results demonstrate the importance of atmospheric transport in the distribution of microplastics. They indicate the need for further monitoring and microplastic pollution analyses in Central Asia, taking into account its detection even in hard-to-reach and remote areas.

Keywords: microplastics; pollution; snow cover; atmospheric transport; migration



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1. Introduction

Microplastics are synthetic particles less than 5 mm in size [1]. Their presence has been detected in the last decades in almost all natural environments, including the atmosphere and snow cover. Studies in recent years prove that snow plays an important role in the transport, deposition, and distribution of microplastics, especially in high-altitude and

polar ecosystems. The detection of microplastics in snow cover in the most remote areas of the world emphasizes the scale of atmospheric transport and the relevance of this problem.

Recent researches confirm the global distribution of microplastics (MPs) in snow cover in different regions of the world, emphasizing the important role of atmospheric transport as the main mechanism of their delivery. The presence of microplastics was detected in snow sampled from the Alps to the Arctic [1]. MP concentrations ranged from low in the Arctic ($0\text{--}14.4 \times 10^3$ particles per liter) to high in European regions (up to 154×10^3 particles per liter), with varnish, rubber, polyethylene, and polyamide being the predominant polymers. Microplastics in snow from Antarctica (Ross Island) were found with an average concentration of 29 particles per liter. The predominant ones are polyethylene terephthalate (PET) fibers, the sources of which are associated with both long-range atmospheric transport (up to 6000 km) and with local anthropogenic translocations [2]. High concentrations of microplastics (73–3099 particles per liter) with predominance of particles smaller than 50 μm have also been recorded in snow on the Union and Schanz Antarctic glaciers, which indicates the need to take into account smaller fractions when monitoring pollution [3]. Snow analyses from the west coast of North America have confirmed significant microplastic content (from 5.1 to 325 $\mu\text{g/L}$ meltwater) in fresh and old snow samples [4]. Yu et al. [5] found a significant presence of microplastics and microfibers in 70 surface snow samples collected both in the Greater Toronto Area and in distant and sparsely populated areas of the Yukon and Northwest Territories, as well as in the unpopulated high latitudes of the Arctic in Canada. Particle concentrations and fractions of anthropogenic origin were conservatively estimated after corrections for ‘background’ and ‘anthropogenic origin’, based on visual analysis and micro-Fourier transform infrared spectroscopy (μFTIR) [5]. Microfibers were predominant (95–100%) with varying concentrations in different regions among the MP compositions [5]. Microfibers were classified into synthetic, regenerated semi-synthetic, anthropogenically modified cellulose, and natural cellulose or protein fibers. Microfibers with a confirmed anthropogenic origin were dominated by polyester/PETF (8–22%) and semi-synthetic viscose (1–18%), while anthropogenic cellulose accounted for a small proportion (3–7%) in all regions [5]. The effects of global warming on the accumulation of microplastics in the cryosphere and their possible release as a result of ice melting were considered, highlighting the risks to ecosystems that may arise from climate change, since the melting of glaciers and permafrost may lead to an additional release of microplastics accumulated over long time periods [6]. A study of microplastics deposited on snow in the upper reaches of the Colorado River basin found that these particles can affect albedo [7], promoting more intense absorption of solar energy and thereby accelerating melting [8]. Research [2] indicates that the presence of microplastics on glaciers and snow in remote northern and mountainous regions can enhance ablation (melting), as does black carbon, since microplastics in the atmosphere can participate in cloud formation processes, i.e., plastic microparticles can act as condensation and ice formation centers. This means that an increase in the concentration of microplastics in the air could theoretically affect the nature of clouds and precipitation, which could lead to additional anthropogenic pollution (including plastic) in these ecosystems [2].

The first assessment of microplastics in Arctic snow from Svalbard and Fram Strait using Py/GC-MS revealed the spatial variability in the concentrations and polymer composition of microplastics in snow [8]. The results of this work suggest that harmonized methods should be developed to facilitate regional comparisons. Snow sampling in remote areas and high altitude glacier sites was carried out by trained mountaineers. Micro and nanoplastics analyses were performed in laboratories by specialists using highly sensitive TD-PTR-MS (proton thermodesorption–transfer reaction–mass spectrometry) [9].

Detected particles $< 1 \mu\text{m}$ were analyzed for the presence of common polymers and revealed nanoplastic concentrations in a range of 2–80 ng/mL at 5 of 14 sites. The dominant polymer types detected in this study were tire wear particles, polystyrene, and polyethylene (41%, 28% and 12%, respectively) [9]. Lagrangian dispersion modeling [10,11] was used to reconstruct possible sources of micro- and nanoplastic emissions for these observations, which appear to be mainly west of the Alps. Sources in France, Spain, and Switzerland are the largest contributors to the modelled emissions [9]. This work also confirmed that fine plastic particles can be transported over long distances and deposited in remote regions such as high altitude glaciers. This emphasizes the importance of microplastics monitoring in such inaccessible areas, where microparticles can remain for long time periods affecting the environment. For example, between 7 and 300 microplastic particles per liter of melted snow have been found in glaciers on the Himalayas and Tibetan Plateau [12]. Microplastic contamination of snow was also investigated for the first time at the summit of Mount Amanos in the Hatay region, southern Turkey [13]. The amount of microplastics varied up to 16 MP particles per liter. In total, 519 particles were identified. Most of the identified MPs were black fibers ($>99\%$) with 0.5–2.5 mm size (62%) and polyester (35%). Local wind and trajectory analyses indicated that MPs that appeared in the sampling area originated from the nearby Amik Plain and/or were transported from remote areas with northwesterly and southerly air currents.

Another study [14] investigated the occurrence, composition, size ($>30 \mu\text{m}$), and shape of MPs in snow samples from different conservation areas as well as from urban areas in Hokkaido. Various polymer-type MPs with concentrations ranging from 1.5×10^2 to 4.2×10^3 particles per liter were found among the samples. The results showed that the prevalence of microplastics generally decreased concomitantly with increasing remoteness of the sampling sites. The observed MP features at different locations and their relationship with geographical conditions showed that the ubiquitously observed fine particles (mainly alkyd, ethylene vinyl acetate, and polyethylene) could be attributed to long-range atmospheric transport, whereas rubber and larger particles were especially detected near motorways and cities and originated from local sources of plastic. Taken together, these results suggest important implications for elucidating the nature and distribution of atmospheric MP.

The presence of microplastics in the snow cover of Karelia and Kamchatka (both Russia) has been predominantly recorded in the form of polyester and polyethylene fibres [15]. The totality of these studies demonstrates how microplastics spread over long distances, including remote areas, and emphasizes the potential environmental risks associated with their accumulation and release as a result of climate change.

In summary, polyethylene (PE), polyester (PES), and polypropylene (PP) are the most commonly found microplastics in snow cover due to their widespread use in plastic production. The analysis of microplastic forms shows a clear predominance of fibers, which are recorded in all studied regions. The sources of pollution are unevenly distributed. Both atmospheric transport and distribution by tourism are most frequent, which emphasizes the need to develop international monitoring and control systems even for MPs pollution in sensitive natural areas.

Therefore, microplastics deposited on a snowpack lower its albedo, leading to quicker absorption of solar energy and faster snowmelt. In the long term, this can affect the region's water resources by altering hydrological processes, and it poses a new threat to natural ecosystems, namely, soils [16–18].

Once in the soil, plastic persists for many years, undergoing mechanical and biological stress, ultraviolet radiation, and fluctuations in temperature and moisture.

When microplastic concentrations are compared across environmental compartments, seasonal snow emerges as the most contaminated medium in terms of particle number density. Freshly fallen Alpine and Arctic snow can contain 190–154,000 particles m^{-3} —several orders of magnitude higher than in any other natural matrix [19].

For comparison, atmospheric concentrations range from 0.01 particles m^{-3} over the remote Pacific Ocean to 2502 particles m^{-3} at roadside sites in London—three to five orders of magnitude lower than in fresh snow [20].

Surface ocean waters typically hold only 0.002–62.5 particles m^{-3} (global mean ≈ 2.76 particles m^{-3}), two orders of magnitude below snowpack values [21].

In soils that have accumulated microplastics over decades, background levels seldom exceed 13,000 particles kg^{-1} ; only the application of sewage sludge pushes concentrations above 71,000 particles kg^{-1} , approaching—but rarely surpassing—those of seasonal snow [22].

Thus, the seasonal snowpack functions as an extraordinarily efficient yet temporary atmospheric filter: when it melts, it releases a concentrated flux of microplastics into the soil, completing the transfer pathway “air $\rightarrow$ snow $\rightarrow$ soil”, which remains obscured when each medium is examined in isolation.

At present, there are no direct studies in the scientific literature devoted to the presence of microplastics in the snow cover of Central Asian countries. However, analysis of publications concerning microplastic contamination in other natural environments of these countries allows drawing certain conclusions about the potential contamination of snow cover as well. In Uzbekistan, in 2023, a study of surface water and bottom sediments of the Karadarya and Chirchik rivers, which are tributaries of the Syr-Darya, was conducted [23]. A significant content of microplastics was found in these rivers, where the dominant forms were microfibers (from 84 to 95%), and the main polymer was polyethylene terephthalate (PET). Sources of pollution were identified as wastewater discharges and ineffective waste management, particularly in the textile industry, indicating the widespread presence of microplastics in Uzbekistan’s water systems and, by analogy, allowing for their presence in atmospheric deposition and snow cover. A wider regional review covering Central Asian countries, including Kazakhstan, Uzbekistan, Turkmenistan, Kyrgyzstan, and Tajikistan, highlights the very limited research on microplastics, which is due to both the inaccessibility of high mountainous areas and the lack of laboratory facilities for reliable analysis of microparticles. The authors of the review [24–26] pointed out the need to expand the monitoring of microplastic pollution, especially under conditions of a changing climate and increasing anthropogenic load. Due to the geographical location of Kyrgyzstan, Tajikistan, and Uzbekistan within Central Asia and the presence of mountain systems there with stable snow cover and activities in valleys and foothills, it can be assumed that microplastics are also deposited in the snow cover of these regions, arriving both with air masses and from local sources. Thus, despite the lack of direct snow cover studies in these countries, indirect data indicate a high probability of contamination by microplastics. This requires targeted research concepts.

This study aims to fill this gap by assessing the microplastic pollution of snow cover in Kazakhstan, in particular within the Zhetysay region, for the first time. The choice of the territory was determined by the combination of the high mountain relief, industrial load, and potential influence of atmospheric transport. The aim of the study is to identify the content, morphology, and polymer composition of microplastics in snow, as well as to determine possible sources of pollution previously unstudied under the conditions of Central Asia.

In the last few years, separate studies have been conducted in Kazakhstan on microplastic contamination of various components of the natural environment, but no direct

publications concerning the presence of microplastics in snow cover have been presented yet. In particular, in Akmola Oblast, studies were conducted at solid domestic waste landfills, where the presence of microplastics in the environment was detected [27,28]. Special attention was paid to surface waters and bottom sediments of lakes and rivers in the region. Microplastic particles were detected there too. Both micro- and macroplastic contaminants expressed by fragments of fishing nets, foam plastic, plastic bags, and bottles were detected in the high-mountain lake Markakol in the east of Kazakhstan [29].

Studies of snow cover contamination in Kazakhstan have not yet been conducted or published. Nevertheless, in the adjacent regions of the southern part of Western Siberia (Russia), microplastic particles were detected in snow samples in 16 out of 18 samples, including fibers, granules, and film fragments. The results confirm atmospheric transport of microplastics over long distances and their subsequent deposition in snow [30]. Also, in southeastern Kazakhstan (including areas of Zhetysu and Almaty oblasts), studies on other types of snow cover pollutants, such as heavy metals and polychlorinated biphenyls (PCBs), were previously conducted, which proves the suitability of snow as an indicator of atmospheric pollution [31–33]. These facts confirm the relevance and necessity of comprehensive studies of microplastics in the snow environment of Kazakhstan, especially in high-mountainous and industrially loaded areas, where snow is capable of accumulating particles coming from both local sources and as a result of transboundary air mass transport.

2. Materials and Methods

2.1. Research Area

The object of the study is the territory of the Zhetysu region, located in the southeastern part of Kazakhstan. The Zhetysu region occupies an important physiographic position within Central Asia. Its climatic features are formed under the influence of inland continental climate, of mountain systems, and of the path of transboundary air masses transport. Large parts of Central Asia are characterized by aridity, high temperature amplitudes, and a strong continental climate. The Zhetysu region stands out against this background due to its proximity to the northern slopes of the Tien Shan and Zhongar Alatau mountains. These mountain massifs play a key role in the accumulation of precipitation, including snow, especially in the winter–spring period.

The relief of the region varies from flat areas (around lakes Alakol and Balkhash) to high-mountainous zones, where stable snow covers are formed. In its mountainous and foothill areas (for example, in the area of Ketmen and Zhetysu Alatau ridges), precipitation falls in the form of snow from late autumn to early spring. The thickness of snow cover in these areas can exceed 50–80 cm, while on the plains it is usually insignificant and unstable. Thus, snow cover in the Zhetysu region has a mosaic character, with mountainous areas acting as natural depositing environments [34,35]. The plains are largely treeless and therefore wind-open, covered by steppe and desert-steppe vegetation.

Central Asia in recent years has been increasingly considered as a region prone to transboundary pollution, including microplastics, which can be transported by air masses over long distances. Due to its location between China, Siberia, and the southern regions of Kazakhstan, the Zhetysu region falls within the zone of potential deposition of atmospheric pollutants coming from both the west (via Almaty region and north-eastern regions) and the east (via Dzhungarian Gate and Xinjiang/China). Local sources such as agriculture, road transport, tourism, and activities along large water bodies can also contribute to snow cover pollution. The Zhetysu region is part of the accelerated infrastructure development within the Chinese Belt and Road Initiative of the so-called New Silk Road.

Consequently, the geographical location of the Zhetysu region within Central Asia, its relief, and climatic conditions create prerequisites for both microplastic input through

atmospheric precipitation and its local accumulation, especially in mountainous and foothill areas with stable snow cover. That is why this region becomes an important object for snow cover monitoring as an indicator of transboundaries and local pollution.

2.2. Snow Sampling

During the field study from 10 January to 25 February 2025, snow sampling for microplastics was carried out from a pre-marked $1 \times 1 \text{ m}^2$ area at 53 defined points (Figure 1). During snow sampling, only stainless steel metal scoops and pre-washed glass containers were used. All work was carried out in a precautionary manner: employees wore clean cotton clothing, gloves, and masks to prevent foreign fibers from entering the samples.

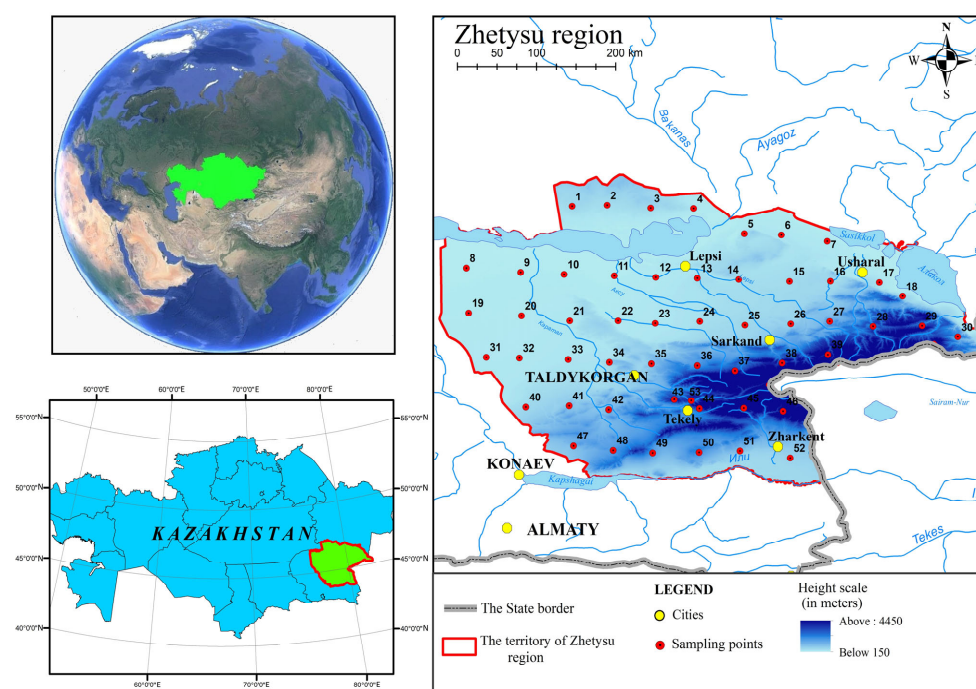


Figure 1. Location of Kazakhstan and the Zhetysu region with snow sampling points.

2.3. Sample Preparation

Under laboratory conditions, snow was left at room temperature until complete melting. The resulting melt water was successively filtered through stainless steel sieves with 5.0 mm, 1.0 mm, and 0.3 mm mesh according to the method [36], which allowed the separation of microplastic particles of different size classes. The particles retained on the sieves were washed with distilled water and collected in glassware for further purification.

2.4. Cleaning and Filtration

After sieving the material using a set of sieves [37–43], the solids were transferred to a pre-weighed clean beaker and dried at 90 °C for 24 h in a desiccator [36,44–47]. A 30–35% solution of hydrogen peroxide (H_2O_2) and 20 mL of iron (II) sulfuric acid catalyst was used to remove organic matter [44,48,49]. After oxidation, 6 g of sodium chloride [50–52] was added for every 20 mL of sample to increase the density of the solution. The treatment was carried out at 75 °C with stirring on a magnetic stirrer [41,51], until the reaction stopped and the contents were discolored; then, the solution was transferred to a density separator for 12 h. The remaining precipitate was visually inspected for the presence of MP particles, and the residue was filtered through a 0.315 mm sieve. The separated MP particles were visually examined at 40× magnification using a Levenhuk MED D25T LCD

Digital Trinocular Microscope by Levenhuk Company (Tampa, FL, USA) [36,52,53], which allows the visual identification of plastic particles.

Detected microplastic (MP) particles are examined visually under $40\times$ magnification with a microscope [36,54,55], whose authors describe protocols for the microscopic visual identification of plastic particles. The principal criteria are lustre, brightness, or an atypical color—features that can indicate plastic, especially when the particles display properties typical of polymeric materials [37,50]. Elasticity or hardness, which can be assessed with tweezers, is another useful indicator [53]. MP particles larger than 1.0 mm can be isolated visually according to the following rules [50,54,56,57]: absence of cellular structure or other organic forms (to exclude biogenic matter); uniform coloring and fiber thickness; and a clean, even tone, i.e., a homogeneous color without inclusions or blotches. This approach enables the preliminary attribution of a particle to plastics during microscopic inspection.

In a number of cases, it is recommended to disregard particles that are white, transparent, or black because they may be confused with biological debris or other substances that can be mistakenly identified as plastic [54,56]. For the reliable and rapid identification of larger MP particles, methods such as pyrolysis–gas chromatography/mass spectrometry (Pyr–GC/MS), Fourier-transform infrared spectroscopy (FTIR, μ -FTIR), Raman spectroscopy (Raman, μ -Raman), several modes of scanning electron microscopy (SEM, FE-SEM, SEM-EDS, ESEM-EDS), Nile Red fluorescence staining, holographic imaging coupled with machine learning, and various portable optical-sensor systems (laser, interferometric, diffraction-based, etc.) are advisable.

2.5. Spectroscopic Analysis

The polymer composition was subsequently determined using a Raman spectrometer Solver Spectrum (from NT-MDT company, Zelenograd, Russia) with a 473 nm wavelength solid-state laser (in the laboratory at the National Nanotechnology Laboratory of the open type of the Kazakh National University KazNU, named after Al-Farabi). The laser was focused through a lens with a magnification of $100\times$, forming a spot with a diameter of about 2 μ m on the sample.

3. Results and Discussion

The Zhetysu region is characterized by a variety of natural and climatic conditions that affect the accumulation and distribution of microplastics. The snow cover height varied from several centimeters (4.0 cm) to several tens of centimeters (80.5 cm). Accordingly, the volume of snow sampled and the meltwater volume obtained from it differed markedly: the minimum meltwater volume was about 1.5 L (indicating a very thin snow layer), while the maximum reached ~143 L (corresponding to a significantly thicker snow cover). Such differences reflect the variability of snow density and height at different locations: for example, in the mountains, dry loose snow at high altitudes may show a relatively small volume of water, whereas in the lowlands, wet snow even at lower altitudes provides a comparable water equivalent.

Analysis of 53 snow samples collected at different altitudes (from about 350 m a.s.l. in the plain to about 1400–1500 m a.s.l. in the foothills) showed the presence of microplastic in most samples (92.6%). MP concentrations ranging from 1 to 12 particles per square meter, with a total number of 170 microplastic particles (Figure 2), indicated its widespread occurrence in lowland, highland, and semi-desert landscapes.

The identification of microplastics in snow cover is considered as a result of the combined effect of local emissions, secondary wind transport of particles from contaminated surfaces, and long-range atmospheric transport with deposition in the form of dry and wet atmospheric deposition.

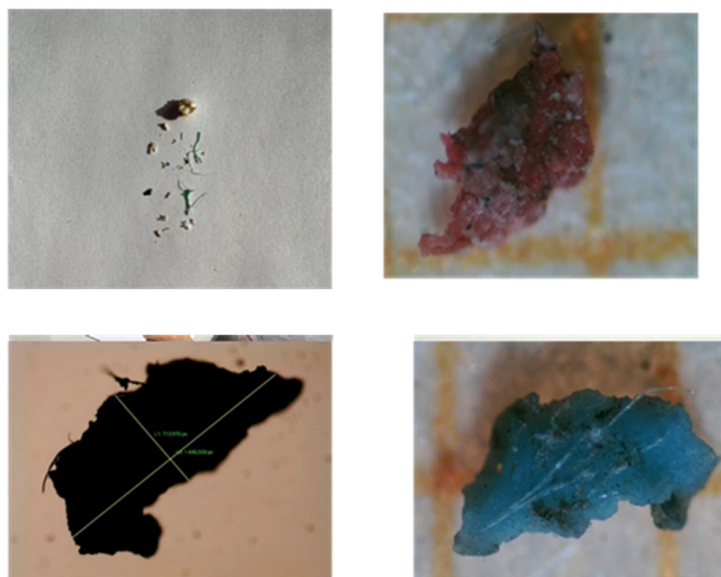


Figure 2. Processing of snow samples for the identification of microplastics and examples of microplastic particles found in the snow cover of the Zhetysu region, Kazakhstan.

The Raman spectrometry analyses of microplastic samples show differences in the location and height of the peaks, which helps to determine the composition of the materials. Each material has a unique set of peaks corresponding to specific chemical bonds in its structure. The X axis of the graphs shows the Raman shift between 0 and 3000 cm^{-1} . The Y axis represents the intensity in arbitrary units (a.u.) (Figure 3).

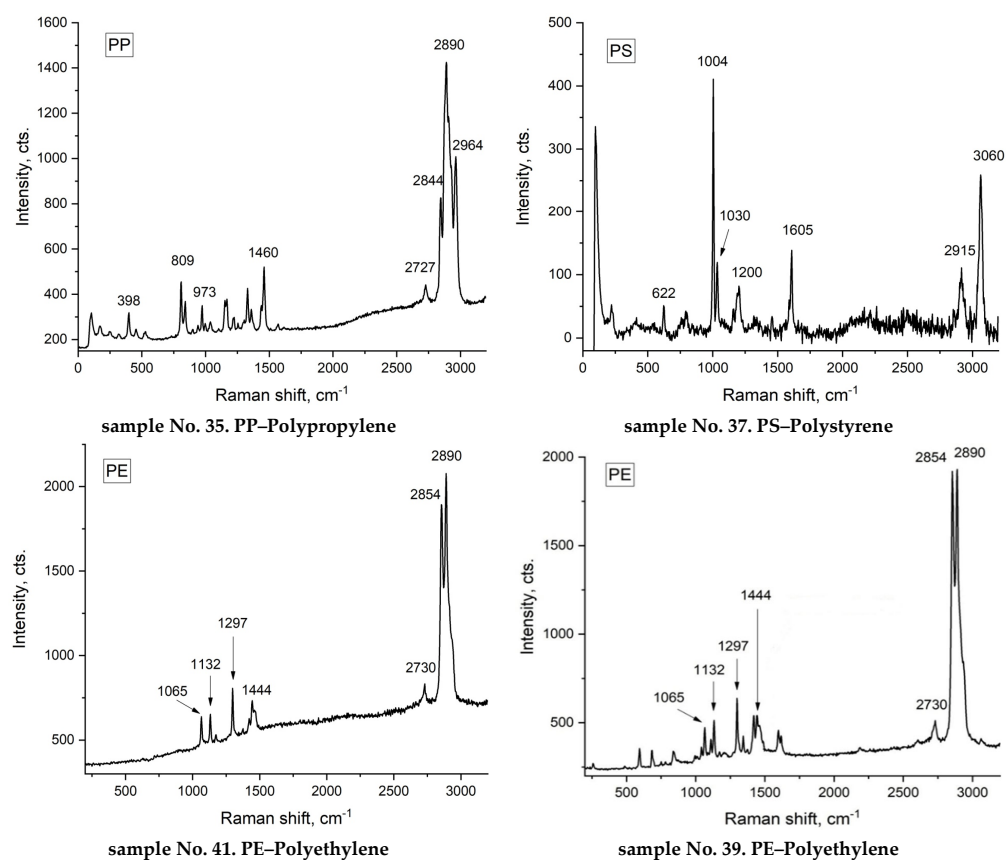


Figure 3. Microplastic Raman spectra of selected snow samples.

Sample No. 35 (polypropylene, PP) shows the spectral peaks in the ranges of about 810, 841, 972, 1155, 1330, 1458, and 2882 cm^{-1} , which correspond to valence and strain vibrations of C-H and C-C bonds, typical for the structure of polypropylene. The graph of sample No. 37 (polystyrene, PS, foam) shows bright peaks around 620, 1001, 1032, 1158, 1452, 1585, 1602, and 3056 cm^{-1} , among which the 1001 cm^{-1} peak is particularly pronounced, characteristic of the ring breathing vibrations of the aromatic bonds of polystyrene. In sample No. 41 (polyethylene, PE, presumably a package), the spectrum is characterized by the presence of peaks in the region around 1062, 1128, 1295, 1439, 2848, and 2883 cm^{-1} , corresponding to the symmetric and asymmetric vibrations of the C-H bonds intrinsic to polyethylene.

The Raman spectroscopy spectrum graph for sample No. 39, representing polyethylene (PE), shows typical peaks that correspond to chemical bonds in its structure. Several characteristic peaks can be identified on the spectrum of PE in the ranges of approximately 1062, 1128, 1295, 1439, 2848, and 2883 cm^{-1} . These peaks are due to symmetric and asymmetric C-H bond vibrations, which are typical for polyethylene. The peak around 1062 cm^{-1} is typically associated with C-C vibrations in the polymer chain, and the peaks between 2848 and 2883 cm^{-1} are related to C-H valence vibrations, which also confirms the presence of polyethylene in the sample.

Polyethylene (PE), polypropylene (PP), and polystyrene (PS) are the main components of plastic waste, most frequently found in the snow cover of the Zhetysu region, often as a result of anthropogenic activities, including improper handling of packaging and household waste. Polyethylene and polypropylene are widely used in the production of packaging. Polystyrene is also used in packaging materials, which contributes to their accumulation in natural ecosystems.

The spatial distribution analysis of microplastic showed that high pollution is observed not only near settlements and roads but also in remote areas, including high-mountain areas. Figure 4 shows microplastic contents in the snow cover of the Zhetysu region in four different perspectives for a more detailed visualization of the spatial distribution of plastic particles. Thus, at point No. 50 (Ainabulak village, 1284 m above sea level), despite the minimum height of snow cover (4 cm), the concentration reached 12 particles/m^2 , with the dominance of 0.1 mm fractions, indicating a high degree of local or near-atmospheric pollution, probably associated with the domestic and agricultural impact. However, at point No. 28 (Chimbulak village, 1513 m), located in a remote mountainous area and characterized by the maximum snow cover height (80.5 cm), seven particles/m^2 of microplastics were detected, including 0.2–0.3 mm (PE, PS). Taking into account the relief, the remoteness from cities, as well as the unlikelihood of local pollution at such points, the results allow us to speak about the confirmed role of transregional atmospheric transport of microplastics, including at altitudes above 1500 m. Similar results were recorded at points No. 27 (Baizeren village, 1157 m) and No. 44 (Araltobe village, 1564 m), where concentrations were found to be 5 and 10 particles/m^2 (PE, PS), respectively.

Considering the morphometric characteristics of microplastics, the predominance of particles smaller than 0.5 mm can be noted. Particles 0.1 mm in size were recorded in more than 80% of all samples, including isolated sites, such as point No. 19 (Saryesik-Atyrau Sands, 5 particles, all 0.1 mm), which confirms the dominance of fine particles (PE, PS), which have high aerodynamic mobility and the ability for long-term suspension in the atmosphere. Such suspended particles are able to be transported by air streams for hundreds of kilometers and fall out together with snow in remote areas, which fully corresponds to modern ideas about the global circulation of microplastics in the atmosphere [58]. Large particles up to 6 mm in size were detected at some points, such as No. 29 (Koktuma station), which indicates a local origin but does not exclude the possibility of secondary

redistribution from the underlying surface due to wind erosion or local pollution. Thus, the simultaneous presence of coarse and fine fractions in one sample is interpreted as the result of overlapping local and atmospheric transport and the interaction of MP deposition and re-deflation.

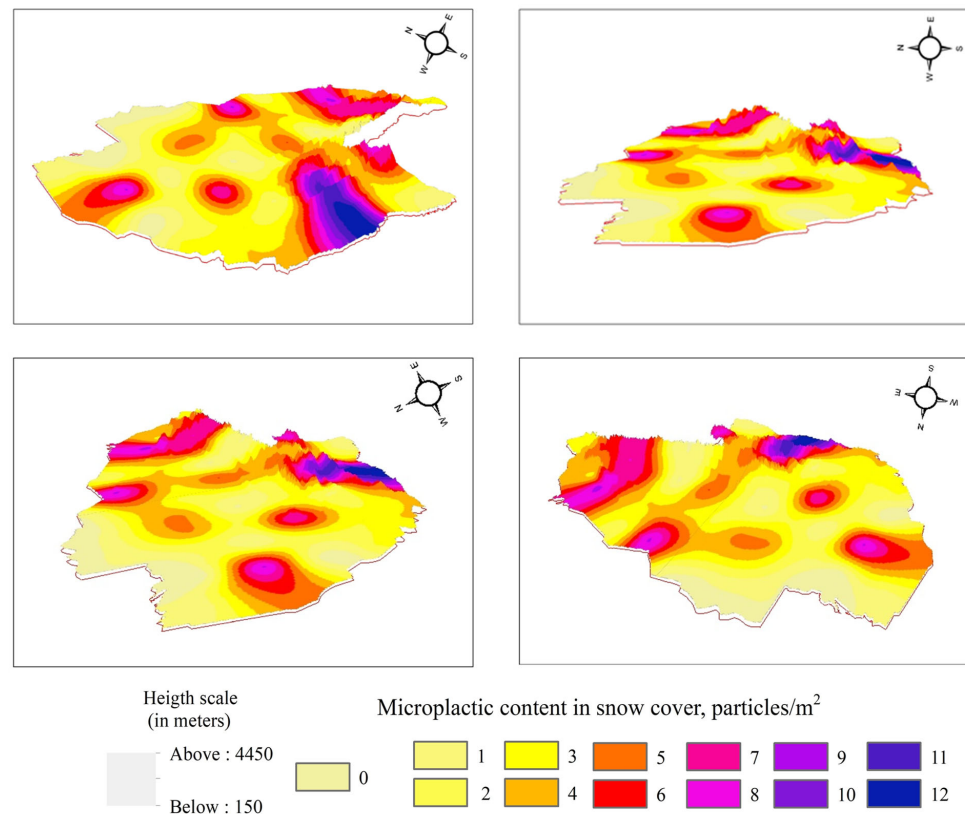


Figure 4. Spatial distribution of microplastics (particles/m²) in the snow cover of the Zhetysu region, presented in four different angles for a more detailed visualization of the plastic particle concentration in the study area.

The snow cover height varied widely, from 4 to 80.5 cm. But no direct correlation between snow thickness and microplastic concentration was established. Thus, at minimum snow cover heights (4–6 cm), points No. 50 and No. 51 recorded 12 and 4 particles/m², respectively, whereas at maximum values (e.g., point No. 30, 60 cm of snow), the MP concentration was 3 particles/m², with PE and PS predominance. These values confirm that the deposition of microplastics with precipitation can be intensive even with low snowfall. Their amount in the snow cover depends more on the intensity of precipitation and wind direction than on the total amount of snowfall.

The influence of the proximity of large cities is also manifested in the form of a moderate correlation between the urbanization of the area and the microplastic concentration. Higher values were recorded in areas close to the cities of Zharkent (point No. 50–12 particles/m², No. 49–7 particles/m²), Tekeli (point No. 44–10 particles/m²), Taldykorgan (points No. 34 and No. 37–7 and 4 particles/m² each), and Usharal (point No. 5–8 particles/m²). However, in remote and sparsely populated areas (e.g., point No. 31–2 particles/m², point No. 28–7 particles/m²), concentrations also remain significant, which confirms the dominance of the diffuse and background nature of the pollution. This is especially relevant for regions with open relief and pronounced wind activity, such as the foothills of Zhongar Alatau and flat areas, where microplastics can migrate tens of kilometers from the emission sources.

The role of atmospheric transport is particularly evident in the dominance of small particles (less than 0.5 mm), which, due to their aerodynamic characteristics, are able to stay in the air medium for a long time and travel considerable distances [58]. Such particles have been detected even in the most remote and inaccessible mountainous areas, which is consistent with the data from the scientific literature on the global distribution of aerosol pollutants of anthropogenic origin [59].

The results indicate a significant contribution of atmospheric transport of microplastics. The observed presence of plastic microparticles even in high-mountainous, poorly affected areas indicates that microplastics have become a global atmospheric pollutant. The smallest particles (<0.5 mm) can be transported by air currents for tens and hundreds of kilometers, and they can fall with snow [2]. According to other studies, the daily deposition of microplastics in remote mountainous areas reaches up to hundreds of particles per m² [60]. Our observations in the Zhetysu region are consistent with this order of magnitude of microplastic presence, even far from direct sources. It is likely that the main sources of microplastics deposited with precipitation in our study area are distant cities, agricultural land (e.g., microfibers from agro-film degradation), and dust storms carrying plastic particles from far-located polluted areas. Additionally, it is necessary to consider the migration of plastic after snowfall, as the migration capacity of microplastics directly depends on their size and density. Small particles (up to 1 mm) are highly mobile and can travel both in the air and with water flows, spreading over long distances. In the Zhetysu region, this is particularly important as most of the territory is covered with snow cover, which serves as an accumulator for microplastic particles, which then get into water bodies and soils after snow melting.

Based on literature sources [1,2] and our own data, it can be noted that the level of microplastic pollution in snow depends on several factors.

First, there is the proximity to microplastic sources: areas located near cities, industrial facilities, and motorways usually display higher concentrations, whereas remote, sparsely populated places show lower MP levels.

For example, a study of snow in northern Japan [13] demonstrated that concentrations reached $\sim 4 \times 10^3$ particles L⁻¹ near highways and urban areas, while they fell to $\sim 10^2$ particles L⁻¹ in distant protected zones. This confirms that local sources (tire wear, urban dust, illegal littering, etc.) strongly influence the microplastic content.

Second, atmospheric transport plays an important role: small plastic particles can be carried by wind over long distances, so even in comparatively clean regions, microplastics transported by air masses from elsewhere may be present. Wind can also redistribute snow, including microplastics, over short distances.

Third, climatic and geographical features add to the variability: the precipitation regime (snowfall intensity), local relief, and prevailing wind directions determine how many microparticles are deposited with atmospheric precipitation.

Finally, the temporal factor (seasonality) is also important: snow accumulates pollutants throughout the entire deposition period, so winter sampling reflects several months of deposition.

When the snow cover melts, the particles either can infiltrate into the upper soil layers or can concentrate on the surface. They can also be re-transported by erosion and surface flows, as well as by the wind, after the surface becomes dry. Thus, microplastic, first found in snow, can further move to other ecosystem compartments—soil, surface water—demonstrating the cyclicity and wide migration ability of this pollutant, which in turn poses a potential threat, not only to soil and aquatic organisms [61,62], but also to human health. Microplastics are carriers and adsorbents of toxic pollutants such as heavy metals, polychlorinated biphenyls, polyaromatic hydrocarbons, and pesticide residues [63].

Once entrained in snow, such “loaded” microplastic particles can, upon melting, transfer the sorbed toxins into soil and water, thereby raising their local concentrations. In addition, the presence of microplastics together with other contaminants can produce a combined negative effect on living organisms; for example, an organism that ingests plastic particles simultaneously receives a dose of the chemicals adsorbed on their surfaces.

The analysis of the presented images of wind directions over the Zhetysu region of Kazakhstan presented from <https://earth.nullschool.net/> (accessed on 30 April 2025) for the period from November 2024 to February 2025 shows that in November and December, westerly and north-westerly winds prevailed, contributing to the transfer of microplastic pollution from western and north-western territories of Kazakhstan (Figure 5).

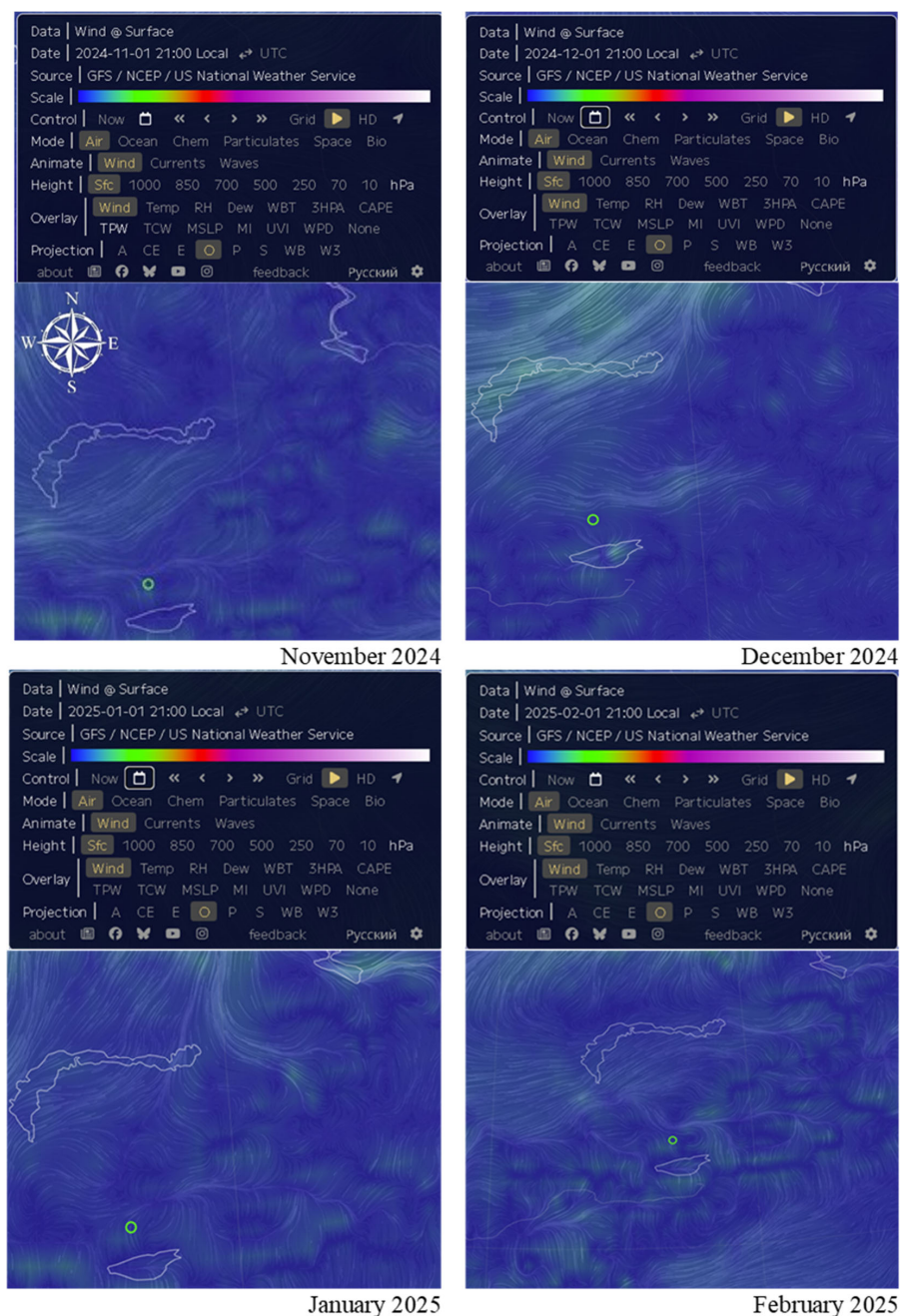


Figure 5. Wind directions over the territory of the Zhetysu region. (Presented from <https://earth.nullschool.net/> access site, accessed on 30 April 2025).

In December, there are also air flows from south-west direction (Figure 5), which increases the probability of pollution transfer from southern areas and neighboring countries such as Uzbekistan and Kyrgyzstan. In January, the wind direction becomes predominantly northerly and north-westerly, which increases the possibility of pollution transport from northern regions of Kazakhstan as well as north-western areas of China. February is characterized by a more complex wind pattern: wind flows from west, north, and south-east, which significantly expands the potential pollution sources and increases the probability of microplastic input from various, including distant, territories of China and Central Asia. In winter, snow plays an important role, which effectively captures and precipitates atmospheric pollutants, including microplastics, significantly increasing the range of their transfer and causing pollution of the Zhetysu region to be highly probable, not only from domestic sources but also from abroad, primarily from China, Uzbekistan, and Kyrgyzstan.

Thus, contamination of the snow cover of the Zhetysu region with microplastics is caused by a complex combination of factors, among which the leading role is played by the long-range atmospheric transport and migration ability of particles, mediated by the altitude of the terrain, local climatic and meteorological conditions, and proximity of cities and agricultural areas.

4. Conclusions

The Zhetysu region is characterized by a variety of natural and climatic conditions affecting the accumulation and distribution of microplastics. The analysis of 53 snow samples revealed the presence of microplastic in 92.6% of the samples, which confirms its wide distribution throughout the region, including both plain mountain foreland and high-mountainous areas. The concentration of microplastic varied from 1 to 12 particles per m², with the maximum concentration (12 particles per m²) observed at the point of minimum snow cover height (Ainabulak village, 1284 m above sea level). The majority of samples were dominated by small microplastic particles less than 0.5 mm in size (more than 80% of samples), which indicates the high aerodynamic mobility of particles and their ability to be transported over long distances. The main polymers identified by Raman spectroscopy were polyethylene, polypropylene and polystyrene, which are typical components of plastic waste.

It was found that the presence of microplastics is recorded not only near settlements and transport highways but also in remote and inaccessible mountainous areas of the region, which confirms the significant role of atmospheric transport of microplastics over long distances, including its transboundary transport. The results obtained demonstrate the scale of microplastic distribution in the region and the need for its further study and monitoring throughout Central Asia.

Average microplastic concentrations in the snow of the Zhetysu region (according to our pilot study) are comparable to those reported for relatively remote sectors of Antarctica (~30 particles L⁻¹) and for areas near industrial centers of the mid-latitudes. In the mountains of Central Europe, tens of thousands of microplastic particles per liter of snow have been recorded, with polyethylene (PE), polypropylene (PP), and polystyrene (PS) dominating—evidence of the universal character of the main pollution sources (packaging, synthetic textiles, etc.).

In conclusion, several strategic measures can be proposed to mitigate microplastic contamination in snow-covered regions.

Reducing microplastic sources: Limit the release of plastics into the environment by expanding recycling technologies and improving waste-management practices. For instance, strengthen collection and disposal rules in mountain tourist areas and settlements such that plastic litter is not dispersed by wind or incorporated into the snowpack.

Education and environmental awareness: Engaging residents and tourists helps to reduce the input of macro-litter that later fragments into microplastics.

Monitoring and scientific research: Regular monitoring of microplastics in snow and air, together with further studies on their effects on snow ecosystems, is essential for evidence-based management decisions.

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