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High-mountain lakes as indicators of microplastic pollution: current and future perspectives

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Abstract

As a key component of mountain ecosystems, high-mountain lakes are recognized indicators of global change. In the analysis of the effects induced by local or global human activities, microplastic (MP) pollution is of critical environmental concern for mountain ecosystem compartments and for high-mountain lakes in particular. This minireview reports on current knowledge of MP occurrence, source, distribution, and characteristics in high-mountain lake ecosystems. The literature search returned only nine studies mainly from the Tibet plateau (China). Generally, the two most often investigated compartments were water and sediment, followed by snow and fish. Plastic particles were found as fragments and fibers of polypropylene and polyethylene, which are primarily utilized in food packaging and supplies brought by tourists and then discarded on site. Tourism and atmospheric long-range transport from lowlands were identified as the main sources of MP pollution. Precipitation events (snow and rain) were reported as key events in MP deposition and fallout. Further studies are needed to better understand the effects of MP pollution on aquatic food webs and ecosystem resources (e.g., drinking water) in these key ecosystems.

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Keywords: Atmospheric transport, fibers, fragments, polyethylene, polypropylene, tourism

INTRODUCTION

High-mountain lakes share numerous similarities[1], the foremost of which are pristine naturalness and environmental constraints[2]: low water temperature, low nutrient concentration (e.g., of phosphorus), and prolonged ice cover all limit primary production[3]. Here, the food webs are simpler than those of lakes located at lower altitudes. Many are relatively shallow, shortening the theoretical time of water change to a few days during the late spring-summer thaw[4]. Deep mountain lakes are generally dimictic with two periods of stratification: one direct in summer and the other inverse under the winter ice cover[4]. Since mountainous rock is resistant to erosion, lake waters are poorly mineralized and have a low buffering capacity against acid loads, which is the reason for the low total alkalinity[5]. Although mountain lakes are generally much less influenced by human activity than other habitats, global and local anthropogenic threats can alter their natural environment. The most serious are water exploitation[6], alien species introduction[7], climate change[8], and medium- to long-range atmospheric transport of contaminants[9-11].

Microplastics are emerging contaminants[12], increasingly found also in these pristine ecosystems[13]. Plastics generate an enormous quantity of waste: about 70% of the world's plastic is recycled or reused for energy production, while the remaining 30% is transported to landfills and, together with the plastic waste, directly released into the environment, where it contaminates the soil, rivers, lakes, and ultimately the oceans[14-16]. The world's annual production of plastics was 1.7 million tons in the 1950s[17], totaling 368 million tons in 2019, 57.9 million tons (16%) of which was produced in Europe[18]. In the first decade of this century, plastic production equaled the total amount generated in the previous century, characterizing our current era as the "Age of Plastic"[19]. Plastics break down physically into smaller and smaller fractions, termed microplastics (MPs, 1 μm-5 mm)[20]. Microplastics are characterized by stable chemical properties, small size, and low density and are classified as primary and secondary[21]. Primary MPs are manufactured plastic particles that go into a variety of products (e.g., cosmetics), while secondary MPs are formed during the use and disposal of plastic products (e.g., degradation of plastic bottles) or in the decomposition of macroplastics into MPs[22].

The degradation of plastic wastes is thought to be an important factor in the creation of MPs[23]. Degradation of synthetic polymers can generally be classified as biotic or abiotic, following different mechanisms, depending on a variety of physical, chemical, or biological factors. Abiotic degradation of plastics is defined as a change in physical or chemical qualities caused by abiotic elements such as light, temperature, air, water, and mechanical forces[22]. Instead, biotic degradation refers to the deterioration of plastics caused by organisms[23]. Organisms can degrade plastics either physically by biting, chewing, or digestive fragmentation[24] or biologically by biochemical processes[25]. Microorganisms, including bacteria, fungi, and insects, are mainly responsible for the biological degradation of plastics[26]. Even though knowledge of environmental degradation of plastics and creation of MPs is currently limited and requires improved understanding, it is crucial in determining their fate and impacts[23].

Surface runoff[27], atmospheric deposition[28], discharge from wastewater treatment plants (WWTPs)[29], and decomposition of large plastic materials represent the main sources of MPs in freshwater[24,30]. According to the literature, up to 80% of MPs in freshwater watercourses come from drainage following treatment at WWTPs[31]. For example, Murphy *et al.*[32] investigated the effluent of a large secondary sewage treatment plant (daily treatment capacity 260.954 m^3) in Glasgow (Scotland) and discovered that, despite a final MP removal rate of 98.41%, approximately 6.5×10^7 particles of MPs were discharged into the aquatic environment every day. Furthermore, rainfall-induced surface runoff is the primary means of transporting different plastics from land to surface waters[33,34]. According to a recent study, the highest concentration of MPs (66-191 particles/L) occurred during periods of heavy rainfall[35]. After heavy rain, the highest concentrations of MPs were found in three out of four estuaries in the Chesapeake Bay area[36]. Some MPs that enter surface waters are trapped in sediments, while others continue to be transported downstream, ending up into the seas and oceans where currents bring MPs further out to sea and/or closer to land[36]. Ocean circulation patterns, marine currents, and MP drift have also been identified as key drivers of plastic dispersal in the Arctic environment[37].

Several plastic particles are also released in the atmosphere. These fibers can be transported to far areas by the wind, where they can then be dry or wet deposited on land or in water[33,38]. On this path, it is well documented how MPs can reach remote and pristine ecosystems, even when there are no local point sources of plastic[13]. These findings, taken together, are noteworthy because they emphasize the broad spatiotemporal dimensions of the processes that determine the sources, fate, and effects of MPs on the environment, including humans. Indeed, because they are ubiquitous (oceans, surface waters, wastewaters, soils, sediments, atmosphere, food, *etc.*), they impact on environmental and human health[39].

The high surface area and hydrophobicity of MPs facilitate their ingestion by both terrestrial and aquatic organisms and increase the risks of toxic chemical and pathogens adsorption and desorption in water, with possible negative consequences not only for humans but also for the biodiversity[40].

The question arises about the MP pollution of high-mountain lakes, which are recognized sentinels of global change and ecosystem sensors in the analysis of the effects of local and global human activities on biocenoses and biodiversity (e.g., alien species and contaminants)[1-4]. They also constitute a natural laboratory for basic ecological studies in mountainous regions sensitive to global climate change, representing a good candidate as indicators of MP pollution[13]. Thus, this minireview seeks to answer the question by summarizing recent research into these highly comparable ecosystems.

LITERATURE SEARCH

We queried the electronic databases Google Scholar (https://scholar.google.it/) and Scopus (https://www.scopus.com/) first using the search terms "mountain" AND "microplastics" OR "plastic" to retrieve studies on MPs source and transport in mountain environments. We then repeated the search using the terms "mountain lakes" OR "altitude lakes" AND "microplastics" OR "plastic" to narrow the search to the occurrence of MPs in high-mountain lakes *sensu stricto*[1]. The first query yielded about 116 records and the second retrieved only nine studies on MPs in high-mountain environments.

SOURCE OF MICROPLASTICS IN MOUNTAIN ENVIRONMENTS

The source of MPs in high-mountain ecosystems is human activities and atmospheric conditions with seasonal variability[41]. The principal drivers of MP deposition are primarily atmospheric transport from an urban point source[38] and precipitation events (rain and snow)[13,42]. Snow works as a scavenger, trapping pollutants and particulate matter in the atmosphere, which is carried by atmospheric transport (wind, storm, and/or rain), and then deposited on the ground. Due to their low density, MPs are lifted into the upper layers of the atmosphere by wind currents, and then deposited by snowfall or rainfall in higher altitude habitats where they may pose environmental risks[43]. Microplastics can readily reach isolated ecosystems and propagate into terrestrial and aquatic ecosystems[44]. Through atmospheric transport and deposition, MPs have been found in such remote ecosystems as the polar regions of the Arctic[37], the deep-sea environment[45], sea surfaces[46], and glaciers[47-49].

Microplastic pollution can remain in glaciers indefinitely since they are trapped in snow deposits in high alpine areas[49]. As the glaciers melt, they release MPs into freshwater and marine systems[47]. Supraglacial debris is typically high in MPs deposited by wind or snow, and the glacial flow transports the imbedded MPs and other contaminants down the valley, where they accumulate downstream in rivers or lakes[50].

Microplastics can also be introduced into remote environments, mountainous terrains and foothills, and high-mountain lakes by the deterioration and fragmentation of plastic items washed up on beaches and then carried back into the sea by the wind[51]. In large cities, because MPs are aerosolized pollutants, they are quantified by source-specific and remote atmospheric sampling[52]. Finally, MPs have been found in a variety of remote ecosystems, indicating that they travel from major industrial areas or other anthropogenic sources via medium- to long-range transport from low-lying locations[3,38,53,54].

Studies investigating MP pollution in extreme environments have shown that Mount Everest (8850 m above sea level)[55] and the Vatnajökull Ice Cap, which were long thought to be clean, are contaminated[56]. Mountain climbers and trekkers typically wear clothing made from synthetic textiles, and MP fibers shed by synthetic fabrics may be a source of direct MP deposition[47]. Many synthetic fibers, such as polyesters and polyamides from tourist garments, are regularly found in remote regions[47,48]. Figure 1 illustrates the potential sources of MPs and their transport to high-mountain ecosystems.

MICROPLASTICS OCCURRENCE IN HIGH-MOUNTAIN LAKES

The literature search retrieved only nine studies on MP occurrence in high-mountain lakes (altitude > 1500 m a.s.l.), mainly from the Tibet plateau (China). Table 1 presents the country, altitude, sample(s) type, sampling method(s), detection, polymer(s), shape, size, color, abundance, and potential MPs source reported by each study. The most often investigated matrix was abiotic samples, mainly sediment and water. Although aquatic high-altitude environments are populated by native macroinvertebrates, only two studies investigated other biotic matrices (e.g., non-native fish)[13,57]. Stainless steel tools for sediment and trawl/plankton nets for water were typical sampling instruments[58].

In the studies here analyzed, stereomicroscopy was generally used to determine particle color and morphology and Fourier-transform infrared spectroscopy (FTIR) to identify chemical type. Stereomicroscope, FTIR, scanning electron microscopy (SEM), pyrolysis-gas chromatography-mass spectroscopy (Pyr-GC/MS), and Raman spectroscopy are commonly employed for identification and quantification of MPs[58]. Stereomicroscope cannot accurately distinguish between natural and synthetic particles. On this path, Free *et al.*[33] used a light microscope to detect MPs; however, this method is operator-dependent and can result in wide variation between observers[58]. For instance, direct visual detection of MPs in beach sediments by multiple observers varied between 60% and 100% depending on operator experience and fatigue and leading to overestimation (biologic material mistaken for black fragments) or underestimation (white fragments) of certain types and colors of MPs[59]. Misclassification of other material as plastics, confirmed by subsequent chemical analysis, was reported for about 70% of presumed MPs[60]. Thus, it is highly recommended to utilize both microscopy and other analytical methods to identify the target samples. SEM is also a common instrument used in identification of MPs. In particular, the combination of SEM and energy-dispersive X-ray spectroscopy (SEM-EDS) can provide information on the elemental composition of particles. FTIR and Raman spectroscopy are typically used to characterize MPs and identify their polymer types, while Pyr-GC/MS can determine the chemical composition of MPs with additive. However, this method is time-consuming and destructive. Thus, FTIR and Raman spectroscopy are highly recommended[58].

Table 1. Microplastics occurrence in high-mountain lakes worldwide

Country	Lake	Altitude (m a.s.l.)	Sample type	Sampling method	Detection techniques	Polymer(s)	Abundance	Dominant Shape	Size (μm)	Colour(s)	Potential source	Ref.
China	Gangtang Co	4872	Sediment	Stainless-steel tools	Stereomicroscope, FTIR	PA, PET	406.85 ± 262.18 items/kg	Fibres, films, fragments	50-500	Black (51.65%), traspartent (27.78%), blue (14.64%), red (5.93%)	Long-range transport, surface runoff	Liang *et al.*[61]
	Yibug Caka	4559					2643.65 ± 1716.25 items/kg					
	Tangqung Co	4469					269.26 ± 371.98 items/kg					
	Dagze Co	4472					507.51 ± 543.06 items/kg					
	Chaxiabu Co	4499					701.89 ± 227.02 items/kg					
	Guojialun Co	4532					185.55 ± 265.56 items/kg					
	Pongcê Co	4536					250.12 ± 412.68 items/kg					
	Bangkog Co	4531					297.39 ± 61.87 items/kg					
	Gogen Co	4675					640.94 ± 157.70 items/kg					
	Bobsêr	4609					143.45 ± 268.38 items/kg					
	Yangnapeng Co	4633					17.22 ± 29.66 items/kg					
	Angdaer Co	4854					389.03 ± 505.71 items/kg					
India	Anchar Lake	1583	Sediment	Van Veen grab	Stereomicroscope, ATR-FTIR	PA, PET, PS, PVC, PP	606 items/kg	Fibres, films, fragments	30-2000	White (51%), red (26%), black (8%), blue (8%), yellow (5%), green (2%)	Anthropogentic activities	Neelavannan *et al.*[62]
Russia	Dzhulukul Lake	2199	Surface water	Glass jars	SEM/EDS	ND	5 items/L	Fragments, foams	0.06-0.48	ND	Anthropogentic activities	Malygina *et al.*[65]
	Talmen Lake	1531	Surface water				8 items/L	Foams, films	0.03-0.12	ND		
Italy	Dimon	1872	Snow	Steel spoon	μ-FTIR	PET	0.11 ± 0.19 items/L	Fragments	220	Blue	Long-range transport	Pastorino *et al.*[13]
			Surface water	Apstein net (plankton)		-	-	-	-	-	-	

			Sediment	Van Veen grab		-	-	-	-	-	-	
			Macroinvertebrates	Surber net		-	-	-	-	-	-	
			Fish	Electrofishing		-	-	-	-	-	-	
Turkey	Crater	2380	Surface water	Glass bottles	SEM, μ-Raman	PE, PP		Fragments	15	ND	Anthropogentic activities	Çomaklı *et al.*[67]
Switzerland	Sassolo	2074	Surface water	Glass bottles	Optical microscope, FTIR	PB, PE, PET, PMMA, PP, PS	2.6 items/L	Pellets, fragments, films	> 125	ND	Anthropogentic activities	Negrete Velasco *et al.*[61]
			Sediment	Scraping with plastic containers		PE, PP	33 items/kg	Fibres	125-500	ND	Anthropogentic activities	
China	Qinghai	3260	Surface water	Trawl net	Stereomicroscope, Raman	PP, PE, PET	180,900 ± 229533 items/km^2	Fibres, fragments, foam, sheets	100-500	Trasparent, blue	Tourism	Xiong *et al.*[57]
			Sediment	Stainless-steel shovel		PP, PE, EVA, PVC, nylon, PC	50-1292 items/m^2	Fibres, fragments, foam, sheets	ND	ND		
			Fish	ND		PE, PS, PP, nylon	5.4 ± 3.6 items/specimen	Fibres, sheets	ND	ND		
China	Siling Co	4530	Sediment	Shovel	Raman, SEM	PE, PP, PS	563 ± 1219 items/m^2	Fragments, sheet, foams	500-1000	ND	Atmospheric deposition	Zhang *et al.*[63]
	Geren Co	5780				PE, PP, PET, PVC	42 ± 47 items/m^2		500-1000			
	Wuru Co	4700				PP	117 ± 126 items/m^2		500-1000			
	Mujiu Co	5306				PP, PE	17 ± 20 items/m^2		500-1000			
Mongolia	Hovsgol	1645	Surface water	Manta trawl net	Optical microscope		20,264 items/km^2	Fragments, films, fibres	ND	ND	Atmospheric deposition, tourism	Free *et al.*[33]

Studies are reported from the most recent to the oldest date of publication. EVA: Ethylene-vinyl acetate; ND: not determined; PA: polyamide; PMMA: polymethylmethacrylate; PC: polycarbonate; PE: polyethylene; PEST: polyester; PET: polyethylene terephthalate; PP: polypropylene; PS: polystyrene; PTFE: polytetrafluoroethylene; PU: polyurethane; PVC: polyvinyl chloride; FTIR: Fourier-transform infrared spectroscopy; SEM: scanning electron microscopy; SEM/EDS: scanning electron microscopy and energy-dispersive X-ray spectroscopy.

Microplastic abundance varied widely between the studies (country of sampling) and matrices (mainly water and sediment). For example, Pastorino *et al.*[13] measured MP pollution in sediment samples from a high-mountain lake (Carnic Alps, Italy) and found no particles. Negrete Velasco *et al.*[61] reported low (33 items/kg) occurrence in a remote uninhabited lake (Sassolo Lake, Switzerland). Recently, Neelavannan *et al.*[62] found a mean of 606 items/kg in Anchar Lake located in the Kashmir Valley (Himalaya, India). Zhang *et al.*[63] reported a range of 8-563 items/m^2 in six high-mountain lakes of the Tibetan Plateau

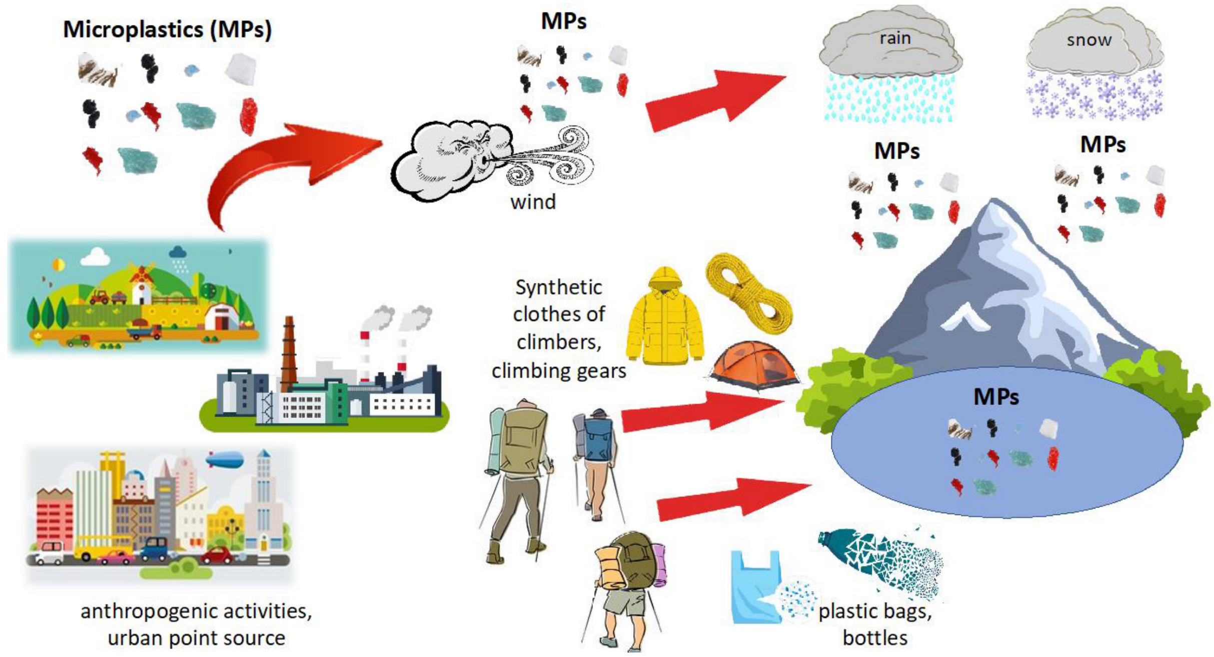

Figure 1. Main sources and transportation of microplastics in high-mountain lakes.

(China). A similar range (5.4-1292 items/m^2) was found in Qinghai Lake (Tibetan Plateau, China) by Xiong *et al.*[57]. Greater abundance (mean value: 2644 items/kg) was reported by Liang *et al.*[64], who also measured MP occurrence in 12 lakes of the Tibetan Plateau.

There was also great variability in MP abundance in the water samples. Free *et al.*[44] and Xiong *et al.*[57] found high levels of MPs (20,264 and 180,900 particles/km^2, respectively). It should be noted, however, that both lakes are tourist campsites, which may explain their elevated MP pollution compared to the low values (5-8 particles/L) recorded by Malygina *et al.*[65] in two remote lakes (Dzhulukul Lake and Talmetn Lake; Siberia, Russia) or the absence of particles in Dimon Lake (Carnic Alps, Italy)[13].

Microplastics vary in size, shape, color, and polymer composition according to source, degradation, and residence period. Because of their many sources (e.g., urban, suburban, rural, and other sites), atmospheric MPs range widely in size and chemical composition[43]. Microplastics start to deteriorate in water. Abiotic processes, such as ultraviolet (UV) photooxidation combined with mechanical abrasion, gradually break the plastics down into fragments[66]. Xiong *et al.*[57] identified characteristic peaks (corresponding to C=O) in the Raman spectrum of MPs compared to virgin polymer, reflecting oxidative weathering of the particles. Zhang *et al.*[63] found that particles 1000-5000 μm in size occurred most often in the sediment samples from seven remote lakes of the Tibetan Plateau (China). Neelavannan *et al.*[62] reported that the most frequent MP size in the sediment samples from Anchar Lake (Himalaya) ranged between 300 and 1000 μm. Smaller particles (ranging 50-500 μm) were reported in sediment samples by Liang *et al.*[64] in 12 remote lakes of the Tibetan Plateau. The same results were shared by Xiong *et al.*[57] who reported MPs ranging in size between 100 and 500 μm in both water and sediment samples from the high-altitude Qinghai Lake (China) and by Negrete Velasco *et al.*[61] for Sassolo Lake (Switzerland), who recorded particles ranging in size between 125 and 500 μm. In Dimon Lake, a single particle measuring 220 μm was detected in a snow sample[13], while in the sediment samples of Crater Lake (Turkey) were 8-15 μm in size[67], much smaller than those reported for other high-mountain lakes. Finally, the smallest particles (0.03-0.48 μm) were recorded by Malygina *et al.*[65]

in two remote Siberian lakes. This may have been due to the oxidation and deterioration of plastic polymers by exposure to UV radiation. In addition, large variation in diurnal temperature may accelerate the dissipation of particles in small debris[63].

On average, the colors typically recorded in most samples were white, transparent, blue, and black. The diversity of colors can be attributed to differences in origin and provide information about possible sources[68,69]. White MPs originate from packaging materials and tote bags[70], while colored MPs are usually attributed to garments, ropes, and fishing nets[71]. Transparent MPs commonly result from fishing nets and lines[72].

Polypropylene (PP) and polyethylene (PE) were two frequent polymer types recorded in the samples from high-mountain lakes, and they are also common MP contaminants in European freshwater ecosystems[73]. Polyethylene is extensively used in packaging (e.g., plastic bags), while PP is used widely in everyday objects such as packaging trays, plastic bottles, household products, and battery cases, among others. Polypropylene has the lowest density (0.90-0.92 g/cm^3) of the resins used in packaging; this characteristic allows for atmospheric transport and deposition[43]. Polyamide (PA) and polyethylene terephthalate (PET) were also detected in several samples, indicating just how widespread these polymers have become. Polyamide is held together with amide bonds and therefore highly resistant to abrasion. Widely employed in textile manufacturing, it is also used in the automotive and transportation industries. Because polyamide fibers were originally developed as an alternative to silk, they are soft and flexible, which enhances wearing comfort, while PET is used in applications ranging from packaging to electronics.

The MPs from the high-mountain lakes came largely in the shape of fragments and fibers. The fragments displayed various surface features: sharp edges with cracks, rounded shapes with smooth surfaces, or degraded rough surfaces. Although the sources of the fragments were not identified, their appearance may be related to their origin or history of degradation in the environment[74]. In oligotrophic lakes, high UV penetration and decreased biofouling (shielding of plastics from UV radiation) can hasten the fragmentation rate of plastics[75], while duration of the ice cover may also influence MP degradation. Since high-mountain lakes with a short ice-free season are far less exposed to UV radiation, plastic degradation rates are slower there[43].

Fiber can come from a variety of sources, including fishing, shipping, and textiles[76,77]. Anthropogenic sources of MP fiber pollution were associated with tourist access points, campsites, and recreational areas[33,57]. Due to a lack of outflow of water from the lake, Qinghai Lake has copious fiber deposits generated by tourism and acts as a sink for MP accumulation[57].

The major mechanisms for MP occurrence in the remote, high-mountain Dimon Lake are thought to be atmospheric depositions[13]. Liang *et al.*[64] suggested that atmospheric long-range transport, glacial meltwater, and surface runoff are potential pathways for carrying MPs from elsewhere to remote lakes in Tibet. Microplastics were detected in Lake Crater (Turkey), which is far from settlement sites[67]; because of their low specific density, they are transported to higher altitudes via wind currents, and then settle over sediments during precipitation events[51]. In addition, Zhang *et al.*[63] suggested that wind currents of the Tibetan Plateau facilitate the deposition of MPs and the formation of mechanical erosion processes.

The isolated Sassolo Lake is inhabited; during the winter, it is covered by a 3 m thick ice sheet. Hiking, diving, pasturing, and other human activities are the primary causes of MP pollution[61]. The same conclusions were also shared by Malygina *et al.*[65] in two remote Siberian lakes without permanent populations, in which concentrations and configuration of MPs depend on local human activities (fishing, transport, landfilling). Finally, Neelavannan *et al*.[62] reported that the MPs in Anchar Lake have a complex source derived mostly from the automobile, textile, and packaging industries.

CONCLUDING REMARKS AND FUTURE PERSPECTIVES

This minireview summarizes current research on MP pollution in high-mountain lakes, which are considered a good indicator of global change in mountain ecosystems. Mountainous ecosystems have a significant impact on global climate change and are essential natural resources. Knowledge about MP occurrence in these pristine ecosystems is important.

Generally, variations among research groups are found in all sampling steps. For instance, there is no standard net, pore, or mesh size, leading to different sizes of MPs being sampled in each study. Representativeness and reproducibility of most results is uncertain, amplified by uncareful methodology descriptions lacking important details, such as volume of samples. Moreover, the detection technique to identify MPs was noted to progress from early to later studies. Thus, there is an urgent need for a validated, quick, and simple methodology.

Microplastic occurrence in high-altitude ecosystems such as glaciers, snow, and lakes may lead to biodiversity loss and disease. The abundance of MPs in the remote lakes of the Tibetan Plateau is cause for environmental concern[61] since particles can contaminate water for drinking or agricultural purposes. In addition, the high concentration of MPs found in lake sediments can have a negative effect on the health of local inhabitants and aquatic life.

Moreover, the ecology and physiology of aquatic organisms may be impacted by MPs[78,79]. Although high-mountain lakes were originally fishless[2], other native organisms such as phytoplankton and zooplankton or aquatic macroinvertebrates can interact with plastic particles[80]. Blocked gills and intestinal obstruction are known to lead to a reduction in the size of aquatic organisms and result in diseases[81,82]. Microplastics are often composed of a complex mixture of chemicals, namely additives and monomers in the ingredients of the plastic material and byproducts of manufacturing, and chemical contaminants in water accumulate on plastic when it becomes litter (i.e., persistent organic pollutants and metals), with serious consequences for the life of aquatic organisms[16,82].

The material, shape, and color of particles found in remote lakes point to tourism as a major source of MP pollution. Frequently found in all samples, PP and PE are mainly used for food packaging, and supplies and are often carelessly left behind by tourists.

Because MPs are ubiquitous in many ecosystems, global collaborative efforts are needed to investigate their abundance and potential sources in ecosystems, particularly environments at high elevation. In addition, corrective/intervention measures are needed. For example, the Sagarmatha Pollution Control Committee recently began plastic trash removal operations, while other activities to remove visible waste deposits on Mount Everest are also underway (https://adventuretravelconservationfund.org). Public agencies should encourage greater awareness of plastic waste management and recycling among tourists and climbers. Citizen science programs should be encouraged to equip community members with knowledge, skills, and confidence to participate in enjoyable scientific research activities while generating data to inform sustainable community solutions[83]. Moreover, national framework strategies for managing plastic waste should be implemented in these sensitive ecosystems[84].

For these reasons, priority should be given to research to better understand the occurrence, source, and pathways of MP pollution in high-mountain lakes:

• Atmospheric deposition and transport of MPs in remote areas, linked with data on precipitation, wind speed, and direction;

• Impact of natural fibers on aquatic ecosystems as substitutes of synthetics in climbing and trekking gear;

• Impact of high-mountain lake water on downstream freshwater ecosystems;

• Impact of MPs on native aquatic species (e.g., macroinvertebrates) by (eco)toxicological testing;

• Trophic transfer of MPs along aquatic food webs in high-mountain lakes.

DECLARATIONS

Authors' contributions

Conceptualization, data curation, methodology, writing - original draft: Pastorino P
Conceptualization, methodology, writing - reviewing and editing: Prearo M, Pizzul E, Elia AC, Renzi M, Ginebreda A, Barceló D
Supervision: Barceló D

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Ethical approval and consent to participate

Not applicable.

Consent for publication

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