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Review

# Microplastic pollution characteristics and its future perspectives in the Tibetan Plateau

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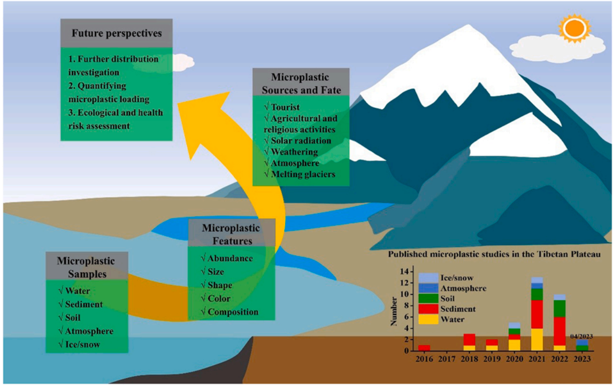
## HIGHLIGHTS

- Microplastics are ubiquitous in all the environmental media of the Tibetan Plateau.
- The contribution of plastic waste from tourists is higher than local residents.
- Robust weathering condition enhanced the production of secondary microplastics.
- Atmospheric transport facilitates long range diffusion of microplastics in this area.
- Ecological risk assessment on microplastics in this fragile ecosystem is urgently needed.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Microplastics are an emerging and persistent pollutant due to their threat to global ecological systems and human health. Recent studies showed that microplastics have infiltrated the remote Third Pole – the Tibetan Plateau. Here, we summarize the current evidence for microplastic pollution in the different environments (rivers/lakes, sediment, soil, ice/snow and atmosphere) of the Tibetan Plateau. We assess the spatial distribution, source, fate, and potential ecological effects of microplastics in this broad plateau. The integrated results show that microplastics were pervasive in biotic and abiotic components of the Tibetan Plateau, even at the global highest-altitude, Mt. Everest. Although the concentration of microplastics in the Tibetan Plateau was far below that found in the densely populated lowlands, it showed a higher concentration than that in the ocean system. Tourist populations are identified as a substantial source of anthropogenic plastic input rather than local residents due to

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the rapid development of the tourism industry. In the sparsely inhabited remote area of the Tibetan Plateau, long-range atmospheric transport facilitates allochthonous microplastic diffusion. Robust solar radiation in the Tibetan Plateau might enhanced production of secondary microplastics by weathering (UV-photooxidation) of abandoned plastic waste. A rough estimation showed that the microplastic export flux from melting glaciers was higher than that measured in most of the world's largest rivers, which affects local and downstream areas. Since the Tibetan Plateau is vital for Asian water supply and numerous endangered wildlife, the potential human and ecological risk of microplastics to these fragile ecosystems needs to be fully evaluated within the context of climate-change impacts.

## 1. Introduction

Plastic is one of the most widely used materials in industry and human daily life due to its lightweight, strength, durability and low cost. Since the 1950s, plastic production increased rapidly and reached 390.7 million tonnes globally in 2021 [58]. Every year, approximately 19–23 million tonnes of mismanaged plastic waste are transferred from terrestrial environments to aquatic systems globally, which accounts for 60–80 % of anthropogenic litter [8,17]. Because of the durability of plastic, it can persist in the environment for long periods leading to accumulations in aquatic and terrestrial ecosystems.

Microplastics are categorized as plastic particles smaller than 5 mm, and are of increasing concern worldwide due to their environmental and human-health threats [2,22,72]. Microplastics comprise either intentionally manufactured microbeads used in personal care products or industrial production (primary source), or debris derived from fragmentation and degradation of large plastic products (secondary source) [13,68]. These microplastics can affect soil microbial biodiversity and carbon/nitrogen cycle through physico-chemical changes in soil properties and structure [47,93]. For organisms living in the aquatic environment, the small dimensions of microplastics increase their uptake probability during ingestion [64]. Thus, microplastics can be easily transferred along aquatic food webs, and hence enter the human body through food consumption [15,59]. Microplastics can also be ingested by humans through drinking water or inhalation [14,90]. Microplastics can further breakdown to nanoparticle size that present enhanced organismal health impacts as these nanoparticles can pass through biological membranes and enter into the circulatory system [60]. Therefore, microplastics are considered as one of the most urgent environmental issues worldwide due to a myriad of harmful effects on aquatic/terrestrial ecosystems and human health [49,63]. Thus, understanding the source, transport pathways and potential ecological effects of microplastics in different environments is essential for the risk assessment of this urgent pollutant.

While conspicuous microplastic pollution is widely reported to accompany intensive human activities, recent studies show its penetration into remote and pristine areas with very low intensity of anthropogenic activities, including alpine regions, deep ocean and polar regions (e.g. Alps, Tibetan Plateau, Mariana Trench and Arctic) [5,6,56,91]. The Tibetan Plateau is the highest and largest plateau in the world, with an average altitude of 4000 m and an area of 2.6 million km$^2$, which is often referred to as the world's Third Pole. This region plays a key role in water resource supply, wildlife habitat and biodiversity protection, thereby providing valuable ecological services to the surrounding Asian countries [76,86]. However, the high altitude dictates a unique environment of low temperature, thin air, intense radiation and physical/chemical weathering, making the local ecosystem highly vulnerable to human perturbations [43,85].

Microplastic pollution is ubiquitous in various environments throughout the Tibetan Plateau [26,80,91]. These microplastics are distributed in the rivers, lakes, soils, and snow/ice both in urban and pristine areas [24,26,77,82], which may threaten the fragile high mountain ecosystems. The Tibetan Plateau is the largest global store of frozen water after the polar regions, making it Asia's water tower, which provides a reliable water supply to almost 2 billion people [86]. However, microplastic pollution might influence the drinking water safety of downstream countries (e.g., China and India). Moreover, the unique topography of the Tibetan Plateau makes the region extremely sensitive to global climate change. For example, the warming rate in the Tibetan Plateau was 0.42 ℃ per decade, which is twice that of the global average [86]. Climate-induced shifts might further alter the plastic cycle by affecting the hydrological and meteorological conditions of the Tibetan Plateau. Several recent studies investigated the distribution and sources of microplastics in different environments, such as water, sediment, soil and snow/ice, on the Tibetan Plateau [26,77,82]. However, an integrated synthesis of the distribution, sources, fate and transport pathways of microplastics among the different environments in the Tibetan Plateau is still lacking.

Herein, we summarize the recent literature that focuses on the characteristics, distribution and potential sources of microplastics in the Tibetan Plateau in an attempt to distinguish (1) to what extent microplastics invade this highest and most remote area on earth; (2) the fate (e.g., transport and aging) of microplastics in the Tibetan Plateau and the exchange with surrounding regions; and (3) the potential impact of microplastics on wildlife and ecosystem functions, and the health risks to humans in this area. We also envision how microplastic pollution dynamics in the plateau's ecosystems will be altered under rapid and intense global change, and discuss potential mitigation strategies to address microplastic pollution in the Tibetan Plateau.

## 2. Data collection and analysis

The first investigation of microplastic pollution in the Tibetan Plateau was published in 2016 [89]. Herein, we summarize the data from 34 papers published from 2016 to 2023, which include microplastic studies in rivers, lakes, sediments, soil and atmospheric deposition on the Tibetan Plateau (Fig. 1). The investigation of microplastics in sediments is the most common (13 studies), followed by water bodies (10 studies, including rivers and lakes), soil (6 studies) and snow/ice (3 studies). Only two studies investigated microplastics in atmospheric deposition and one examined airborne microplastic sampling methods in the Tibetan Plateau. These studies cover the south, central and northeast portions of the Tibetan Plateau (see Tables S1–S4 for details); however, we found no reports from the northwestern region (Qiangtang) (Fig. 1). These studies were further categorized based on the primary issues investigated, including the abundance, composition, distribution and source tracing.

The sampling and analysis methods used in these microplastic studies on the Tibetan Plateau were not consistent as they were conducted by 13 different research groups (Tables S1–S4). As such, comparisons among various studies must proceed with appropriate caution. Water and melted snow/ice samples in most studies were filtered through a 0.2–0.45 μm filter (n = 9), while three studies used a 1.2–1.6 μm filter. For sediment and soil samples, microplastics were suspended in $CaCl_2$, $ZnCl_2$ or $Na_2WO_4$ solutions, which have a similar density (1.4–1.6 g/mL). Differences in filter pore size, sieve mesh size and separation solutions undoubtedly change the microplastic detection limit and render microplastic abundance comparisons tenuous. For example, the smallest detectable microplastic in Yang et al. [83] was 100 μm, whereas it was 20 μm in Feng et al. [26]. Since smaller-sized microplastics are usually most abundant in environmental media (Tables S1–S4), a lower detection limit could lead to much higher abundance results. Given these methodological differences, it is challenging to systematically compare the microplastic abundance and distribution among studies. Hence, the adoption of standardized methods for investigation of microplastics in environmental samples to allow for direct comparison between future studies is highly recommended. This standardization is essential for better assessment of sources, transport pathways and potential risks of microplastics in the environment. Therefore, in this review, all comparisons of microplastic abundance or distribution on the Tibetan Plateau were derived from the same group or studies having generally comparable detection methods. Further, to better compare microplastic pollution in the study area, the various units for microplastic enumeration among different studies were converted to a uniform unit. For example, microplastics in liquid samples were expressed as items/L, soil/sediment samples as items/kg, and the single atmospheric deposition samples as items/m$^2$/d. Microplastics in snow/ice samples are also expressed as items/L due to it measured after melting.

## 3. Spatial distribution of the abundance and composition of microplastics in the Tibetan Plateau

### *3.1. River and lake waters*

Studies on microplastics in water bodies were primarily concentrated on rivers and lakes in the southwest, south and northeast portions of the Tibetan Plateau, whereas there were few studies in the northwest (Fig. 1). The overall abundance of riverine/lacustrine microplastics ranged from 0 to 64 items/L (Fig. 2; Table S1). The highest average abundance of microplastics (21 ± 13 items/L) in water was observed in Renuka Lake, Lesser Himalayas, India [1]. In general, microplastic abundance was higher in the southeast compared to the northeast ($p < 0.05$) (Fig. 2). Microplastic abundance in downstream rivers or lakes near urban/agricultural areas were also higher than headwater areas [26,27].

In terms of size, microplastics in most regions were dominated by small-size categories (< 1 mm), which accounted for 55–95 % of total particles (Table S1). The larger microplastic fraction (1–5 mm) was prevalent only in river inflows to Qinghai Lake and a Mount Everest stream [51,80]. Regarding particle shapes, 43–100 % of microplastics were composed of fibers, especially in the Himalayas region where more than 90 % of microplastics were fibers [51,83]. The percentage of transparent microplastics (37–50 %) was higher than colored microplastics in most regions, with blue (43 %) and red (50 %) particles most dominant in the Himalayas [51,83] Regarding polymer composition, the most frequently observed microplastic types were polypropylene (PP, 32–72 %) and polyethylene (PE, 36–38 %). High percentages of polyethylene terephthalate (PET, 44 %) and polyester (57 %) were also detected in the Nam Co basin and Everest, respectively [20,51].

### *3.2. Sediment*

The investigation areas for sediment and water body microplastics were similar, which facilitated their comparison (Fig. 1). Abundance of sediment microplastics varied from 10 to 2644 items/kg (Fig. 2). The highest abundance of sediment microplastics was detected in Yibug Caka located near the center of the Tibetan Plateau [42], followed by the Indus River (1865 items/kg) and Qinghai Lake (1150 items/kg) [35,73]. In the southern region, microplastic abundance gradually increased downstream along the Yarlung Zangbo River, especially toward the outer plateau (Fig. 2b). Overall, microplastic abundance showed a generally low level in most regions of the northeast and south (< 500 items/kg), but showed no significant spatial differences ($p > 0.05$) [25,26]. The distribution of microplastics in surface water and sediment in the northeast and south of the Tibetan Plateau revealed a decoupling pattern, with microplastics having a high abundance in surface water but a low abundance in sediment. On the contrary, high levels of microplastics were found in both surface water and sediment of the central Tibetan Plateau. Most microplastic samples from the northeast and south of the Tibetan Plateau were collected from rivers, while those from the central regions were from lakes. Therefore, hydrological conditions (e.g., lotic versus lentic) might be an important regulation factor for microplastic dynamics in surface waters and sediments. In the northeast and south regions, microplastics are transported in river runoff (particularly in mountain valleys) and are gradually deposited

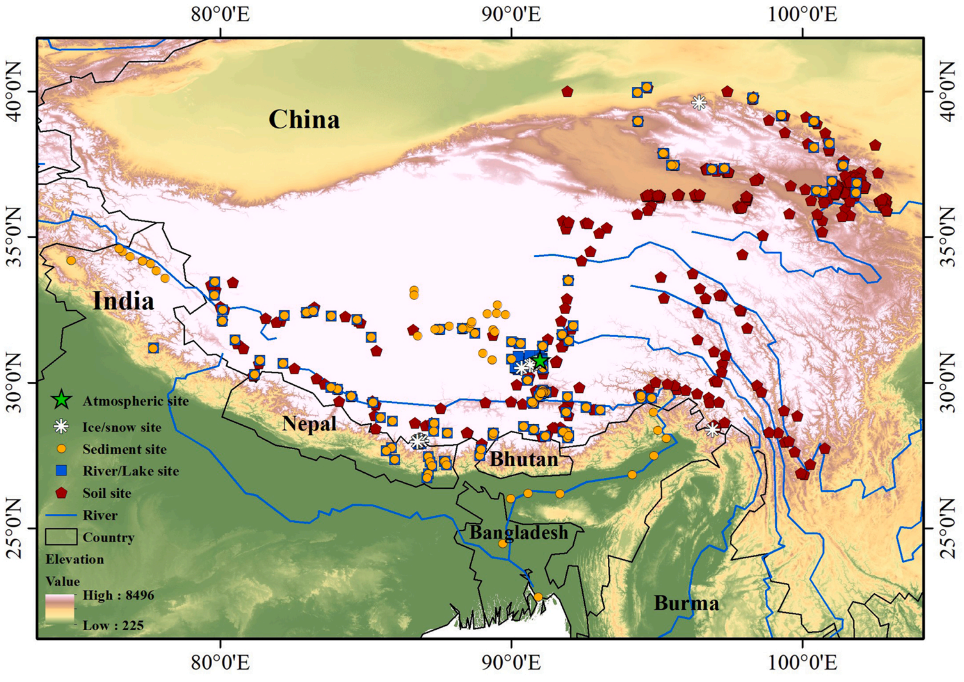

**Fig. 1.** Microplastic studies in the Tibetan Plateau and adjacent regions.

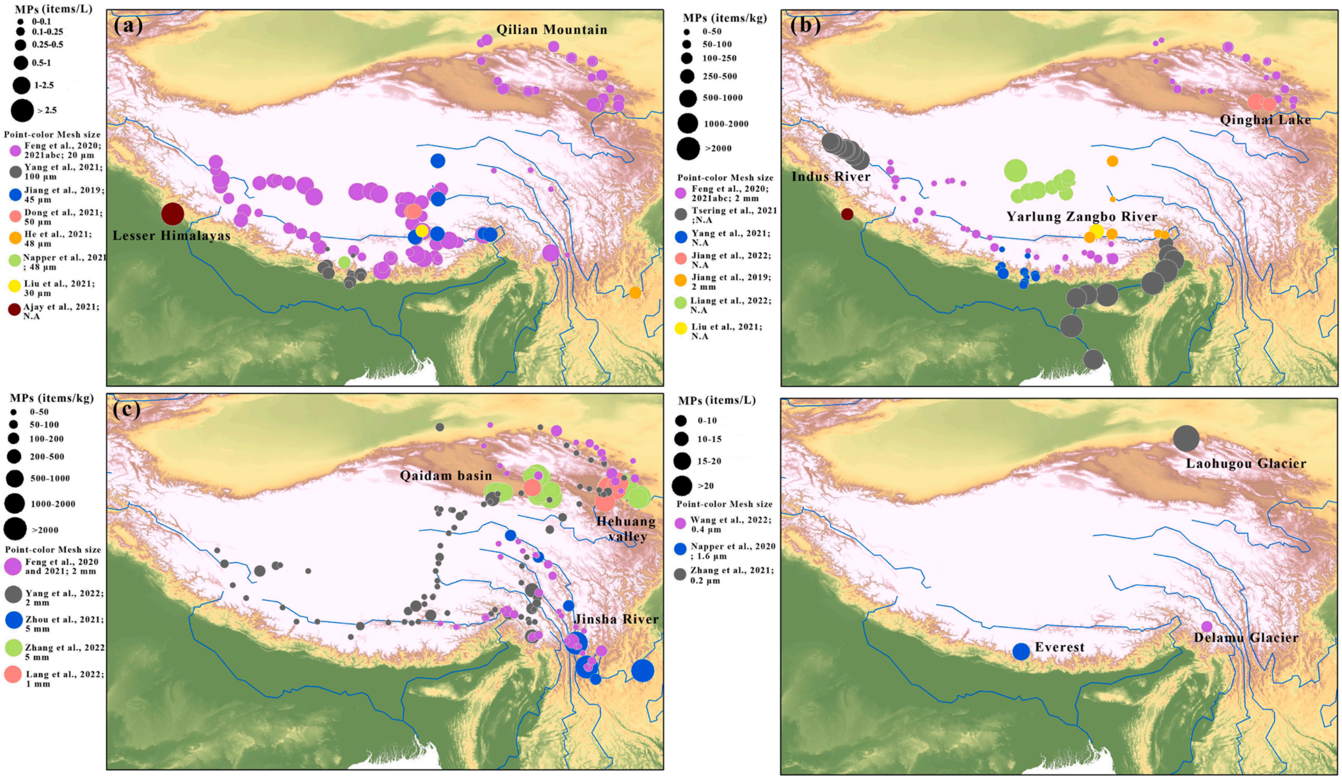

**Fig. 2.** The distribution of microplastic abundance in water (a), sediment (b), soil (c) and snow/ice (d) in the Tibetan Plateau. Multiple samples from small areas were averaged to facilitate effective plotting of points.

along the river channel [25,26]. In contrast, the lentic hydrological conditions associated with lakes should result in accelerated deposition of plastic particles [42].

The most abundant size of sediment microplastics was < 1 mm, with a range of 40–98 % (Table S2); 40–88% of total microplastics were < 500 μm. Smaller microplastics showed a higher percentage in the southwestern Tibetan Plateau and northern Qilian Mountains (93–98 %), whereas a lower percentage was observed in the central Tibetan Plateau (Siling Co, 40 %) (Fig. 2). MP shapes in sediment from the Tibetan Plateau predominantly consisted of fibers (39–95 %) and fragments (36–90 %). Transparent particles (39–52 %) were the dominant color in most areas of the Tibetan Plateau, whereas microplastics in the Himalayas were colorful (primarily blue, black, and red) [83]. Polypropylene was the prevalent composition (26–80 %), except for the Himalayas region where PE comprised 44–45% of microplastics (Table S2).

### 3.3. Soil

Microplastics were common in soils of the Tibetan Plateau, with abundances ranging from 0 to 4814 items/kg (Table S3). Microplastic abundance in bare soils of the southwestern and central Tibetan Plateau was generally low (< 200 items/kg) with little spatial variation (Fig. 2c). In the southeast region, microplastics in riparian soils increased from the upstream to downstream of the Jinsha River [94]. The highest microplastic abundances showed a patchy distribution centered on the northeastern agricultural area, such as the Qaidam basin and Hehuang Valley. The highest average abundance of microplastics (2796 ± 1701 items/kg) was detected in greenhouse soil in the Hehuang Valley [88].

Small microplastics (< 1 mm) accounted for 83–99 % of total plastic particles in soil, which was higher than that found in water bodies and sediment (Tables S1–S3). Fibers (44 %) were the main morphological category in non-managed lands of the Tibetan Plateau [45], whereas films (51–67 %) predominated in agriculture and animal husbandry regions. Transparent (30–76 %) particles were the most common color of soil microplastics across the Tibetan Plateau, which resembled the microplastic color characteristics in water bodies and sediments. Polyethylene was the major polymer composition and accounted for 30–63% of total microplastics.

### 3.4. Snow/ice and atmosphere

The sample number for snow/ice microplastics was far less than water bodies, sediment and soil. Snow/ice microplastic investigations were done on the northern Laohugou glacier, southern Demula glacier and Everest [51,77,91]. The abundance of microplastics in snow/ice was 650–920, 9.6 ± 0.9 and 17 ± 14 items/L in Laohugou glacier, Demula glacier and Everest, respectively. Only a few studies reported atmospheric deposition of microplastics in the Tibetan Plateau, with fluxes of 5.8–52 items/m$^2$/d at the Nam Co basin and 21–26 items/m$^2$/d at the Demula glacier [20,77]. Another study reported very low airborne microplastic concentrations of 0.15–0.25 items/m$^3$ during testing of a flow-through passive sampler in a suburb of Lhasa city [21].

Snow/ice microplastics were dominated by small size classes (< 1 mm, > 90 %) in Demula glacier and Laohugou glacier, whereas a high proportion of large plastic particles (41 %) was detected at Everest (Table S1). The shape and color of microplastics in snow/ice were typically fibrous and colorful (e.g., black, blue and red) (Table S4). Both the atmospheric deposited samples collected from the Nam Co basin and airborne samples collected from the Lhasa suburb were dominated by transparent, small size and fibrous microplastics [20,21]. The dominant polymer types of snow/ice, atmospheric deposition and airborne microplastics were highly variable, including PET, PP, PE and cellophane.

## 4. Sources of microplastics in Tibetan Plateau

### 4.1. Anthropogenic sources

Previous studies demonstrated that microplastic pollution is strongly related to population density and urbanization [4,77]. In the densely populated plain city, delta and lake regions, the highest abundance of microplastics among water bodies, sediment and soil could reached 187 particles/L (Dutch delta, water bodies), 335,714 particles/kg (Lake Huron, sediment) and 67,500 particles/kg (Sydney, soil) (Fig. 3). As much of the Tibetan Plateau is sparsely inhabited, relatively low domestic plastic pollution might be expected. Even in the biggest city on the Tibetan Plateau (Lhasa City), the average microplastic abundance in water (0.83 ± 0.71 items/L) and sediment/soil (241–436 items/kg) was two- or three-orders lower than in the densely populated lowlands [45,82]. However, microplastic concentration in soils of Tibetan Plateau are comparable with long-term agricultural areas in China's Loess Plateau (931–1325 items/kg) (Fig. 3), which demonstrates anthropogenic impacts on this remote area.

As a high-altitude nature reserve, the Tibetan Plateau features several inhospitable climatic conditions and a limited residential population (e.g. 0.6 million in Lhasa in 2014); however, the growing tourism industry increased 586 % from 2008 to 2014 (e.g. 9.26 million tourists visited Lhasa in 2014) [19]. Feng et al. [25] found no correlation between microplastic abundance in water or sediment/soil and residential population density in the northeastern Tibetan Plateau. However, the microplastic abundance was significantly correlated with the 'night-light' index, implying that the tourist industry might be an important source of microplastic trash in the Tibetan Plateau. For instance, the operation of the Qinghai-Tibet Railway resulted in an increase of tourist trash from 3 % to 20 % from 2008 to 2014 in Lhasa [19]. Moreover, a local study found that trash generated by tourists contains a higher proportion of plastics (~ 35 %) [44]. Anthropogenic activities even directly influenced the remotest Himalayas areas [51,70]. For example, microplastics were found in the snow samples from Everest (elevation 5000–8800 m), indicating that microplastics are ubiquitous in the region. These microplastics were colorful (e.g., black and red) and fibrous with a high proportion of polyester, consistent with popular construction materials for tents, clothing and climbing ropes used by mountaineers (Fig. 4a, b).

Ubiquitous prayer flags might be an important source of microplastics in the Tibetan Plateau (Fig. 4c–h). The majority of prayer flags in modern days are made of synthetic fibers, such as PA and PET [42]. While new prayer flags are hung on the top of houses, temples, mountains and bridges at important festivals each year, the old flags are not removed, but rather breakdown and disperse into the environment over time.

Local agricultural activities are another source of microplastics in the Tibetan Plateau [39,88]. Agricultural activities are concentrated in the low-altitude northeast (Qinghai Province) and the central and southern valley areas (e.g. Lhasa River basin and Yarlung Zangbo Valley) due to limitations of climate and topography [28,88]. In Qinghai Province (about 2300–3400 m), the agricultural center of the Tibetan Plateau, arable land (highland barley, wheat, rape and peas) are the main agricultural crops [39]. Soil microplastics on facility lands (e.g. greenhouses) of Qinghai province were 16–51 times higher than that in southern agricultural areas (Tibet, Yunnan, and Sichuan) and unmanaged areas [29,39]. Due to limitations owing to aridity and low temperatures (average 0–8 ℃ annually), plastic film mulching and greenhouse technologies are widely utilized in local agricultural production to maintain appropriate temperature and moisture conditions [88]. The extensive use of plastic film cover, fertilizer bags and pesticide containers significantly increase the accumulation of plastic debris in agricultural fields [36]. Additionally, the rough soil surface and crop canopy may increase the capture of atmospheric particles (microplastic) leading to their buildup in the surface soil [7].

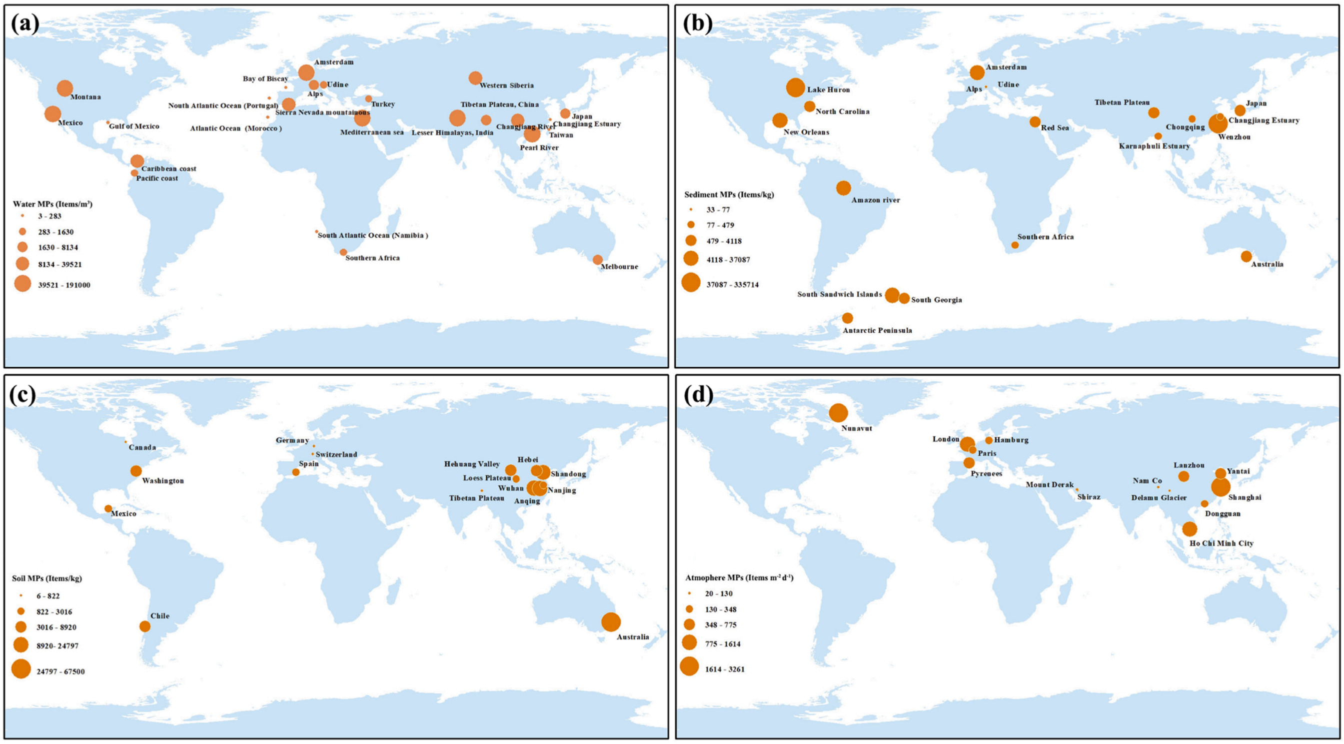

**Fig. 3.** The distribution of microplastic abundance in global waters (a), sediment (b), soil (c) and atmospheric deposition flux (d). (The maximum microplastic abundance or deposition flux from each investigation was selected to represent the pollution level in the figure.
For more details and references for the data source, please see Tables S5–S8.).

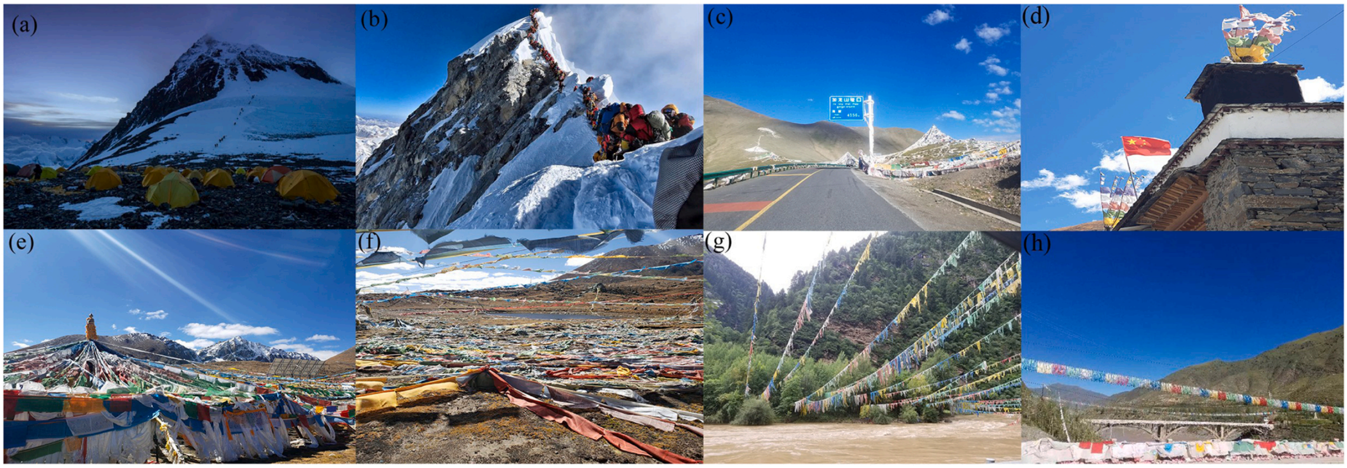

**Fig. 4.** Pictures of potential microplastic sources in the Tibetan Plateau. Figs. a and b (mountaineers equipped by plastics) were cited from Napper et al. [51] and CNN [53]. Figs. c–h showing ubiquitous prayer flags were taken by the authors.

### 4.2. *Atmospheric transport*

Recent studies demonstrate that long-range atmospheric transport and fallout play important roles in microplastic deposition on remote regions [23,92]. For example, the average microplastic flux from atmospheric fallout in remote area of the French Pyrenees and Ireland (100–365 items $m^{-2}$ $d^{-1}$) are close to that in metropolitan areas, such as Paris and Dongguan (118–313 items $m^{-2}$ $d^{-1}$) (Fig. 3d). In Nam Co, the deposition flux of atmospheric microplastics into the lake was 5.2–52 items $m^{-2}$ $d^{-1}$ [20], which is far lower than the above regions. However, atmospheric deposition flux was approximately 3300 kg of microplastic to Lake Nam Co during the monsoon season, while microplastics in river runoff was only 522 kg. These results demonstrate that atmospheric transport can play a significant role in delivering microplastics to lake/river water and sediments in the central Tibetan Plateau.

Previous studies showed that aerosols from the Indo-Gangetic Plain can be transported over the Himalayas to the inland Tibetan Plateau, especially in southeastern Tibet. Many anthropogenic pollutants, such as polycyclic aromatic hydrocarbons and black carbon, were detected in captured particles [75,81]. Simulation results suggest that some smaller particles (1–10 μm) might even originated from farther away, such as Central Asia and Northern Africa [91]. These allochthonous particles are eventually deposited and accumulate in glacial snow/ice. Wang et al. [77] reported that microplastics in snow on Demula glacier (southeastern Tibetan Plateau) were significantly higher during the monsoon versus non-monsoon season, which further confirms the contribution of long-range, trans-boundary atmospheric transport of microplastics to the Tibetan Plateau.

Internal short-range transport within the Tibetan Plateau may also influenced the distribution of microplastics. Due to strong atmospheric convective activities, gale-force wind events (> 17 m/s) are prevalent across the Tibetan Plateau, with a maximum average number of ~ 160 days with gale-force winds annually [71]. Zhang et al. [88] found that soil microplastic abundance was negatively correlated with average wind speed, implying that winds carry microplastic across open-field areas. Model analyses indicate that atmospheric fallout of microplastics in the Nam Co basin is mainly sourced from local regions within 300–400 km [20]. Thus, atmospheric microplastic pollution levels in the central Tibetan Plateau might be largely regulated by redistribution from local anthropogenic sources.

Overall, the extreme wind conditions induced by the Tibetan Plateau's unique topography increase microplastic transport and promote the spread of plastic pollution. Notably, the size of atmospheric microplastics varies greatly. The percentage of large microplastic (> 1 mm) in Nam Co basin atmospheric fallout samples reached 45 %, whereas they accounted for only 10 % in snow samples from Demula glacier. The smallest detected size of microplastic in Dong et al. [20] and Wang et al. [77] were similar (0.4–0.45 μm), thus the difference in microplastic size of both studies is generally comparable. Because Delamu glacier receives very few tourists, atmospheric deposition is likely the primary source of the snow/ice microplastics. Furthermore, the absence of large microplastics in Demula glacier suggests that the monsoon-carried large plastic particles were deposited before reaching the Tibetan Plateau. Thus, the weight and aerodynamic characteristics of large microplastic particles appear to regulate their atmospheric transport range.

### 4.3. *Plastic weathering*

Secondary microplastics originating from the weathering (i.e., physical/chemical breakdown) of abandoned plastic wastes by ultraviolet (UV) radiation exposure and mechanical abrasion are important autochthonous sources of microplastics. UV radiation results in embrittlement at the surface of polymers leading to cracks and fractures, which eventually result in detachment of smaller particles [68]. A simulation experiment showed that fragmentation of polypropylene after one year of UV irradiation was 570 times higher than treatments without irradiation [68]. As a high altitude region, UV-B radiation levels in the Tibetan Plateau (Lhasa City) are ~ 60 % higher than in Dar-Es-Salaam (sea level in the equatorial zone) and Oslo, Norway (sea level) [55]. Owing to the sparse population density (1.5–5.5 people/$km^2$) and limited industrial production of plastics in the Tibetan Plateau, primary microplastics are relatively rare [82]. Even in the more densely populated Qinghai Lake region, the microplastics detected in water samples and nearshore sediments were mostly secondary microplastics [80]. These microplastics showed characteristic peaks (corresponding to C═O) in Raman spectra indicating prominent photooxidation of microplastics. Thus, we posit that the small microplastics prevalent in Tibetan Plateau largely consist of secondary microplastics generated by the high intensity of UV radiation and physical weathering processes.

Lang et al. [39] found that the number and proportion of small microplastics (< 500 μm) in soils of high-altitude areas (> 3000 m) were significantly higher than that found in low altitude areas. This was ascribed to the higher UV radiation at high altitudes that enhances the fragmentation and subsequent spread of plastics. Hanging plastic lungtas and prayer flags are ubiquitous in Tibet (e.g., temples, mountaintops, bridges and rooftop of each home) as an expression of religious ceremonies for local residents (Fig. 4). Most of these flags are made of colored plastic fibers of PA or PET [42]. Prolonged exposure to the outdoor environment causes ageing due to physical/chemical weathering by strong wind abrasion and irradiation, with the released particles capable of entering nearby soils, rivers and lakes [34,42]. These secondary microplastics could further degrade in the aquatic environment. The dominant size of microplastics in surface waters (0.1–0.5 mm) of Qinghai Lake was smaller than from inflowing rivers (1–5 mm), supporting the autochthonous source of smaller microplastics from the in situ breakdown of larger plastic particles within the lake due to high-intensity UV irradiation, abrasion from waves and suspended sediments, and biotic activities [80].

In agricultural regions, mechanical abrasion from tillage operations, in conjunction with UV irradiation, turns large plastic materials (e.g., plastic mulch) into smaller debris [36]. In Qinghai Province of northeastern Tibetan Plateau, the percentage of small microplastics ($<$ 100 μm) in greenhouse, farmland and orchards was 19 % higher than in adjacent grasslands [88]. As the mulching duration increased on facility agricultural lands (e.g., greenhouses), the abundance and morphology of microplastics were progressively altered. Greenhouses with 10–15 years of plastic mulching had 85 % more microplastics than lands with 0–5 years of mulching [29]. Meanwhile, the percentage of large particles ($>$ 100 μm) decreased by 18 %, while the proportion of small particles ($<$ 100 μm) increased by 19 % with increased mulching time.

## 5. Climate change effects on microplastic pollution in the Tibetan Plateau and surrounding regions

The Tibetan Plateau (Asia's water tower) contains the largest store of frozen water ($7.6 \times 10^{11}$ km$^3$) outside the polar regions [33], and delivers water to Asia's largest rivers, such as the Yangtze River, Yellow River, Brahmaputra River, Salween River and Indus River [86]. Ice entrains microplastics during its formation and releases it during melting, hence affecting the abundance and spatial distribution of microplastics in the environment [20,77]. Very little is known about transport processes of microplastics between the Tibetan Plateau and surrounding areas because of scarce measurements. Available data indicate that ablation of the Demula glacier could export 5.9 ($\pm$ 1.3) $\times 10^9$–6.6 ($\pm$ 1.4) $\times 10^9$ items yr$^{-1}$ of microplastics into surrounding rivers. The ablation volume of the Demula glacier is 6.2–7 $\times 10^5$ m$^3$ and accounts for less than 1/100,000 of the total glacier ablation volume from the Tibetan Plateau (2.1 billion m$^3$) [66]. The microplastic flux released from melting ice across the entire Tibetan Plateau was estimated as 1.8–2.2 $\times 10^{14}$ items yr$^{-1}$, which is three orders of magnitude higher than the export flux of the Pearl River [50]. We fully acknowledge that additional data for microplastics (e.g., abundance, weight and deposition flux) and hydrology (e.g., precipitation and glacier runoff) from different melting glacial areas are required to better constrain this estimation. However, there is no doubt that microplastics exported from melting glaciers profoundly influence downstream drinking water safety and aquatic ecosystem health.

Although they are generally thought as separate issues, climate change and plastic pollution are directly and indirectly linked, and are amongst the biggest ecological challenges facing the global community, especially in the Tibetan Plateau. A recent study demonstrated that microplastic export from glacial melting only accounted for 8 % of total atmospheric inputs to the glaciers [20], which indicates that microplastics could be stored in glaciers for a long time. However, the glacial melting on the Tibetan Plateau is rapidly accelerating under global warming [41,86]. The high abundance of plastic particles on the ice cover can absorb radiation, which also enhances glacial melting [62]. The estimated average glacial mass loss increased from 16.3 $\pm$ 3.5 Gt yr$^{-1}$ during 2000–2016 to 21.1 $\pm$ 3.5 Gt yr$^{-1}$ during 2000–2019 [10,32]. A glacier mass balance indicated that glacial ablation was concentrated on exorheic basins. According to simulations by the CMIP5 model, ice mass loss in exorheic basins is projected to be 37.7–71.8 % by the end of the century across low-to-high emission scenarios. Further, runoff from these exorheic rivers (e.g., Indus River, Brahmaputra River and Salween River) are projected to increase by 16–49 % in 2100 versus 2000 due to glacial melting [86]. This implies that the source-sink dynamics for microplastics in the Tibetan Plateau may change in the future. Thus, future investigations should focus more efforts on measuring the exchange of microplastics from the Tibetan Plateau to surrounding downstream regions.

## 6. Ecological effects of microplastic on Tibetan Plateau

Soils are directly and broadly impacted by microplastics with subsequent effects on the entire terrestrial ecosystem. High intensity of microplastic pollution could directly induce soil macrofauna (e.g., nematodes) toxicity and alter the microbial metabolic environment to indirectly affect carbon and nutrient cycling in soils [37,87], thus imposing a negative feedback on crop growth [40,48]. A comprehensive meta-analysis showed that the presence of microplastics could accelerate soil and crop evaporation, decrease germination rate and inhibit seedling growth [30]. On the Tibetan Plateau, crop growth is already constrained by low temperatures and arid environments. Under these climatic stressors, the high intensity of microplastic pollution might further exacerbate agricultural productivity. Moreover, Li et al. [40] observed that submicrometer- and micrometer-sized plastics could penetrate the lateral roots of wheat and translocate within xylem vessels. Highland barley and wheat are typical crops on the Tibetan Plateau, which might experience root uptake of microplastics, thereby threatening the food safety of local residents.

In cryospheric regions of the Tibetan Plateau, ice and snow harbor high levels of microplastics [77]. As the acceleration of melting ice shrinks the permafrost layer [84], microplastics in the snow/ice will penetrate into the affected soil layers of deteriorating permafrost regions. The soil ecological community of the permafrost layer is more fragile than that in the active layer. For instance, the microbial alpha diversity and community stability are lower in the permafrost layer versus the active layer [12,79]. Hence, microplastic intrusion into the permafrost might affect soil microbial activity and functions by altering soil density, pH and water holding capacity [31]. These changes would be expected to further impact microbial transformations of soil organic matter and greenhouse gas emissions, with possible feedbacks to climate warming [61].

Microplastic accumulation in various organisms has been widely reported in marine, freshwater and terrestrial systems [18,48,57]. Microplastics have been implicated in causing harmful impacts on biological organization/functions, such as oxidative stress, altered gene expression and growth inhibition [9,69]. However, studies concerning the direct impacts of microplastic pollution on organisms in the Tibetan Plateau are few. A single study reported the detection of microplastics in fish body tissue (*Gymnocypris przewalskii*) from Qinghai Lake [80]. Nylon, PE, PS and PP fibers were detected in the digestive tract of all fish samples ($n = 10$). Notably, this detection rate is significantly higher than that in commercial fish from coastal regions [74,78], suggesting that microplastics are already deeply incorporated into the local aquatic ecosystem. As a natural conservation area, fishing and shipping in Qinghai Lake have been strictly prohibited, hence few fisheries and shipping associated microplastics have been released since 2000. Thus, the microplastics found in the fish likely originate from local and tourist trash around the lake and/or from atmospheric deposition [80]. Although there is little evidence, we speculate that microplastics are widely distributed in aquatic organisms of the Tibetan Plateau. Additionally, there are thousands of lakes on the Tibetan Plateau that serve as an important habitat for migrating birds. Thus, microplastics in fish might be transferred through the foodweb to fish-eating birds. Similarly, important wildlife species, such as Tibetan antelopes and yaks, may inadvertently eat microplastics contained in soil and plant stems/leaves [7]. Therefore, widespread microplastic pollution might influence wildlife health through ingestion exposure, further increasing the extinction risk of endangered species in the Tibetan Plateau.

Although no assessment of the microplastic exposure on the peoples reside or travel in the Tibetan Plateau has been done, the ubiquitous of microplastics in this region implies potential health risk. Microplastics can be ingested during consumption of fishes and other foods [11,54]. Drinking water is considered another important exposure pathway of microplastics into the human body [38], especially for untreated natural water is the only water source of many Tibetans live in remote villages. Furthermore, the intake of atmospheric microplastics via inhalation is assumed to be much higher than those via other exposure pathways [14,90]. Since barometric pressure decreases with altitude, there is less oxygen per volume of gas than at sea level. Thus, supplying the same amount of oxygen for body requires the lungs take in a greater total volume of air [65], so that the airborne particles including microplastics are more likely to be inhaled. Therefore, although the microplastic pollution in this remote high mountain area is moderate, its health risks on residents and tourists cannot be ignored.

## 7. Future perspectives

Regardless of its remoteness, microplastics have infiltrated the biotic and abiotic components of ecosystems on the Tibetan Plateau. Based on this synthesis, a conceptual framework of the microplastic cycle was developed to better understand the sources and fate of microplastics within plateau ecosystems (Fig. 5). Despite several recent studies on microplastic distribution in this broad high mountain area, some areas remain conspicuously unexplored (e.g., Qiangtang). The Qiangtang region is home to the world's largest and highest-altitude lake group, as well as being a crucial habitat for many of the plateau's protected wildlife, such as Tibetan antelope [41]. However, the remoteness and harsh environmental conditions of the Qiangtang region make it extremely difficult for conducting rigorous scientific investigations. More spatial/temporal investigation of microplastic distribution in this remote and fragile ecosystem is crucial to establish a common database for deducing the sources, transport and fate of global microplastic pollution.

Identifying the sources and fate of microplastics on the Tibetan Plateau is of great importance, especially distinguishing allochthonous from autochthonous sources. As one of the largest high mountain ecosystems, the social (e.g., population density and intensity of agricultural/industrial production) and geographical conditions (e.g., radiation, temperature and atmospheric activities) vary dramatically with altitude. These differences further impact the sources and fate of microplastics in the environment. Currently, there is a paucity of information concerning the main factors regulating the microplastic cycle at different altitudes. The relative contributions of microplastic pollution from various sources are also unclear. Quantifying the microplastic loading from various sources is crucial for mitigating microplastic pollution in the Tibetan Plateau. Atmospheric transport is considered as one of the most important sources of microplastics in the Tibetan Plateau [20,77], but data for deposited and airborne microplastics are scarce and only available for a few locations across the plateau.

Weathering of plastics is another important factor driving the plastic aging/degradation process and production of micro- and nano-plastics [68]. However, studies of plastic weathering dynamics are markedly absence for the Tibetan Plateau. Although the high UV irradiation owing to the high altitude provides a strong weathering environment for photooxidation making it geographically unique, no field or simulation weathering experiment has been done. This lack of experimental data makes it difficult to estimate the amount of microplastics produced by various weathering pathways in the Tibetan Plateau. Owing to its vast area and low population density, waste collection and treatment has become extremely difficult and hence magnify the production of secondary microplastics. Hence, data on plastic production, use, recovery and dumping across the Tibetan Plateau are important for mass balance calculations to assess the relative magnitude of various anthropogenic activities to plastic weathering and microplastic production.

Furthermore, as global climate change continues to intensify, source-sink linkages of microplastic on the Tibetan Plateau are expected to strongly respond to climate warming. The acceleration of ice melting in exorheic basins will undoubtedly increase microplastic discharge from the Tibetan Plateau to downstream regions in the short term prior to glacial ice depletion. However, only a few studies have examined microplastic export in downstream rivers of the Tibetan Plateau, with data only available for the rivers of Jinsha (upstream of Yangtze River), the Brahmaputra and the Indus [73,94].

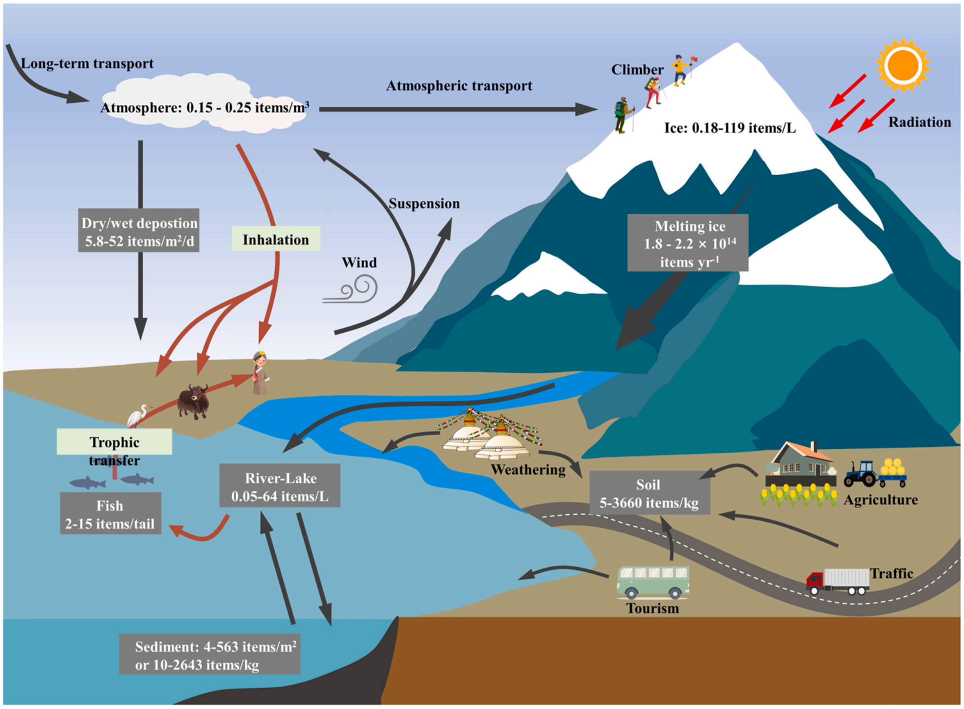

**Fig. 5.** Conceptual diagram of microplastic cycling on the Tibetan Plateau.

The lack of consistent methodologies among studies greatly hampers direct comparison and analysis of microplastic fate and transport processes between the Tibetan Plateau and downstream regions [27,73]. Thus, we strongly recommend the establishment of research/monitoring guidelines and databases for different ecological systems, such as those proposed by the Litter and Microplastics Monitoring Plan by the Arctic Monitoring and Assessment Programme (AMAP) [3]. Importantly, quantifying plastic pollution is not accomplished in a single spatial/temporal investigation, but rather requires the development of a long-term dataset to provide assessment of sources, fate and transport dynamics at meaningful regional scales. Moreover, microplastic pollution research requires a multidisciplinary approach, such as atmospheric science, environmental chemistry, geochemistry, soils, hydrology, geography and toxicology. Thus, long-term and comprehensive monitoring systems (e.g., chemical, biological, hydrological and atmospheric data) should be established through cross-sectoral and multidisciplinary collaborations. The advancement of studies on microplastic source and sink processes in the Tibetan Plateau will improve our understanding of the role of high mountain ecosystems on the global microplastic cycle.

Although current knowledge of microplastic pollution in biota of the Tibetan Plateau is limited to a single fish species [80], the intrusion of microplastics into the Tibetan Plateau food web is inevitable. The numerous lakes and rivers on the Tibetan Plateau provide an important source of drinking water for the local residents and wildlife. For instance, the presence of microplastics in both surface water and sediment was detected in the Naqu River, which is an important drinking water source for local residents [34]. However, legislative regulations on drinking water treatment for microplastics are lacking, and microplastic removal technologies for water purification are also underdeveloped [67]. Thus, local residents and wildlife may be exposed to microplastic pollution along with several toxicants adsorbed to the plastic polymers. Future studies should be focused on the entire ecosystem, and investigate the enrichment status (e.g., bioaccumulation/biomagnification) occurring across trophic levels to identify the most vulnerable species with respect to microplastic accumulation/toxicity. The risk of microplastic exposure to human and wildlife health is often linked to specific environmental conditions. Thus, site-specific investigations of microplastic contamination with organismal and ecological parameters are especially important for better assessing the ecological risks from microplastic pollution under the unique environmental conditions comprising the Tibetan Plateau.

Reducing the release of plastics into the environment is essential for microplastic pollution mitigation. The Chinese government has implemented plastic pollution-control policies, such as reducing the production of single-use plastic products, promoting plastic alternatives and standardizing plastic recycling [52]. However, microplastic pollution in the Tibetan Plateau appears to be a transboundary problem. The contribution of atmospheric microplastic transport from the South Asia continent might be an important source of microplastics to the Tibetan Plateau [77]. Thus, strengthening international cooperation is needed to promote the global regulation of microplastic pollution. On the other hand, awareness education is considered an important method that could lead to a rapid reduction in the use of plastic products. Education about the sources and dangers of microplastics can help to change the perception of local residents (especially students and tourists) about the use and recycling of plastic products. For example, replacing the plastic prayer flags with natural materials could greatly reduce plastic shedding into the environment. The development of degradable plastic substitutes should also be encouraged. Several degradable plastic materials, such as hydrolysable and bio-degradable plastics, have been recently developed and could become an important component of the circular economy [16,46]. Industrialization and societies' adoption of degradable plastics could greatly decrease microplastic generation from agricultural production and daily human activities. Overall, to preserve the integrity of Tibetan Plateau ecosystems and protect human/wildlife health, an effective microplastic pollution mitigation strategy, based on the best available science, is urgently required.

## 8. Conclusions

This study reviewed the current pollution characteristics of microplastics in the remote Third Pole - the Tibetan Plateau. Microplastics are widely distributed in rivers, lakes, sediments, soil, atmosphere and ice/snow environments throughout the Tibetan Plateau, highlighting that microplastics are a ubiquitous pollutant in this fragile high mountain environment. Microplastic concentrations in the Tibetan Plateau were higher than those found in the ocean system, but far lower than densely populated lowland areas. Plastic waste from transient tourist populations is a substantial source of anthropogenic input rather than local residents. In sparsely inhabited remote areas of the Tibetan Plateau, long-range atmospheric transport is the most important transport pathway for allochthonous microplastics. The robust environmental weathering/degradation of plastics on the Tibetan Plateau might play a key role in the production of secondary microplastics due to its ultrahigh altitude and UV radiation. Our estimate of microplastic export flux from melting glaciers was higher than that measured in most of the world's largest rivers, which might progressively increase with a warming climate. Given the fragile ecosystem of the Tibetan Plateau and it is sensitivity to global climate change and anthropogenic forcing, additional studies are urgently needed to assess the role of microplastics as an environmental pollutant in high mountain systems. In particular, assessing the impacts of microplastic pollution on local food webs is necessary to determine potential health risks for humans and wildlife before it causes irreparable harm.

## Environmental Implication

Microplastics are rising global concerns due to their threat to ecological systems. Recent studies showed the distribution of microplastics in different environmental media in the Tibetan Plateau, such as water, sediment, soil, even the snow/ice on Mt. Everest. However, a comprehensive synthesis of microplastic characteristics in this fragile high mountain ecosystem is still lacking. Our review presents a thoroughly summarization of the studies on the distribution, fate, and ecological risk of microplastics in the Tibetan Plateau up to date. The sources and potential mitigation strategies are also discussed and will be useful for future waste management in this area.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data Availability

Data will be made available on request.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2023.131711.

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