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Invisible travellers: a mini review on the presence and the ecological implications of microplastics in remote areas

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Microplastics (MPs) are becoming a cause for concern in the environment due to their potential to cause adverse effects. Microplastic studies have focused on environments that are in proximity to human activities, with the polar regions, remote wetlands, groundwater, mountain tops, and remote streams, and those draining protected catchments receiving little attention. The review aims to unpack evidence of microplastic occurrence in remote areas, the transport pathways, reasons for limited studies, potential ecological effects, and identify the research gaps, thereof. Microplastics reach remote areas primarily through an atmospheric pathway, whereas flowing rivers and migratory organisms are showing to contribute a considerable amount. Fibres were found to constitute >90% of the morphotypes in remote ecosystems, with particle size below 100 μm being more prominent. Microplastic research in remote areas received little attention due to perceptions that they are not affected by anthropogenic activities. Moreover, inaccessibility and the vague policy posture and implementation are among the reasons hindering microplastic studies in remote areas. Nevertheless, there is a need for microplastic studies in remote areas due to their potential ecological impacts. Effects on the physiology of organisms, nutrient cycling, climate, microbial communities, and sequestration capacity were observed in remote ecosystems. Nevertheless, the morphotype-related impacts and vertical distribution have been poorly studied. Moreover, nothing has been done on the projection and modelling of the cumulative effect of microplastics in remote ecosystems. Given the scale of the problem, international collaborations are also recommended for the sustainable protection of ecosystems and their ecological processes in a global context.

KEYWORDS
remote ecosystems, microplastics, soil pollution, atmospheric pathways, polar regions

1 Introduction

Microplastics, which are plastic particles <5 mm, have become a cause for concern due to their ubiquity and effects on the environment (Sarkar et al., 2023; Khanam et al., 2025). They have recently been categorised among emerging pollutants due to their notable effect on biota (Shehu et al., 2022). Microplastics are formed as a result of the disintegration of plastic bags, kitchen utensils, building coatings, fishing nets, abrasion of synthetic soles of footwear and tyres, clothes, etc. (Bhardwaj et al., 2024; Sharma et al., 2025). Nevertheless, microplastics were found in areas with limited human footprints such as mountain streams

TABLE 1 The abundance (MP/L) and sizes (μm unless specified) of microplastics reported in remote areas.

Area/ ecosystem	Environmental matrix	Processing reagents	Equipment for detection and characterisation	Abundance	Sizes (μm)	References
Antarctica	Water/snow	Fe_2SO_4 and H_2O_2	μFTIR	22.4 ± 4.0 MP/L	<1,000 (81%) <200 (28%)	Aves et al. (2022)
					<100 (98%)	
					<350 (95%)	
Arctic sea	Algae	H_2O_2	μ-Raman microscopy Fluorescence microscopy	5–66 MP/mg	<10 (95%)	Bergmann et al. (2023)
Forest	Soil	Na_4P_2O7	μFTIR	1,000–10,000 MP/m^2	<500–1,000 (85%)	Weber and Bigalke (2025)
Forest	Soil	H_2O_2 and $ZnCl_2$	Metallographic microscope	600–3858 MP/kg	0–0.1 (70%)	Hu et al. (2025)
River	Water	None	μ-Raman microscopy	1.6 MP/m^3	0.78–1.58 mm	Gündoğdu et al. (2023)
River	Water	None	ATR-FTIR	13 ± 7.34 MP/m^3	500–1,000 (27.8%) 1,001–5,000 (46.6%) >5,000 (25.7%)	Chifflard et al. (2024)
Mountain	Soil Water Atmosphere	H_2O_2 and $CaCl_2$	μ-Raman microscopy	4.9 MP/kg 1.9 MP/L 0.13 MP/m^2/d	1–20 (38.2%) 21–50 (24.8%) 51–100 (32.4%) 101–200 (4.6%)	Wang et al. (2025)

(Wei et al., 2024), caves (Mutshekwa et al., 2025a), remote springs (Nesterovschi et al., 2023), groundwater (Alvarado-Zambrano et al., 2023), Arctic (Collard et al., 2025), Antarctica (Aves et al., 2022), and the deepest and middle of the oceans (Barrett et al., 2020). Despite the transport mechanisms having been fairly studied, it is still to be seen how these mechanisms may assist in building predictive models to enhance understanding of the build-up kinetics and potential threats thereof. Moreover, particle sizes are known to influence microplastic transportation; however, the association with the potential distance to be travelled is worth a comprehensive exploration to allow robust modelling of pollution in remote areas.

There are uncertainties regarding the direct role of anthropogenic activities on microplastic pollution in remote areas. Studies reported atmospheric transport and migratory organisms' transport as the primary drivers for microplastic pollution in remote areas (Sherlock et al., 2022; Habibi et al., 2024). The density, types, shape, and sizes were reported to be the fundamental drivers influencing the distance for microplastic transport (Hee et al., 2023). Nevertheless, microplastic concentrations in remote areas were found to be very low compared to highly populated areas (Wright et al., 2020; Mutshekwa et al., 2025b). Despite low concentrations, the transport and atmospheric deposition processes are worthy of further investigation, as their vertical and horizontal distributions remain poorly understood. Moreover, their potential to convey other chemical pollutants makes their low concentrations in remote areas a cause for concern.

Remote areas are known for their unique biodiversity supported by unique landscapes and biogeological characteristics (Ficetola et al., 2013). Moreover, remote ecosystems are fragile due to having not experienced human induced impacts, hence, low adaptation capacity. Given the overwhelming evidence of the effect of microplastics in ecosystems, it is imperative to understand the scale of occurrence, their potential impacts and factors influencing their dynamics in remote areas. The present mini review aims to interrogate microplastic occurrence, transport pathways, research-hindering challenges and potential ecological impacts in remote areas. The mini-review further identifies potential research gaps for future studies.

2 Global reach: microplastics in remote environments

Although they were once considered pristine, Earth's most remote regions were found not to be immune to microplastic pollution. According to Lusher et al. (2015), the presence of microplastics in both surface and sub-surface Arctic waters provided some of the first indisputable proof that pollutants from lower latitudes are reaching this remote region. Studies reported a wide range of microplastics across various environmental matrices from remote ecosystems (Table 1). A high abundance of microplastics was observed in Arctic ice (Bergmann et al., 2016; Peeken et al., 2018; Kanhai et al., 2020; D'Angelo et al., 2023). Peeken et al. (2018) found an abundance of 1.2 × 10^7 MP/m^3, with particle size of ≤50 μm in Arctic ice. Similarly, Emberson-Marl et al. (2023) reported 0.007–0.015 MP/m^3 with a size range of 22–65 μm being dominant. In contrast, Kanhai et al. (2020) reported an abundance range of 0–18 MP/m^3, with particle size ranging from 0.10–4.66 mm, whereas Courtene-Jones et al. (2022) reported an abundance of 1.62 MP/m^3 for 0.02–0.0334 mm particles. Among the particles reported in the Arctic ice, fibre was found to be dominant, contributing between 80% and 97% of the total number of particles (Peeken et al., 2018; Kanhai et al., 2020; Emberson-Marl et al., 2023). According to Ross et al. (2021), the Arctic is a "dead end" for microplastics carried by ocean currents and atmospheric transport.

In Antarctica, Aves et al. (2022) confirmed the presence of microplastics for the first time, detecting an average of 29 MP/L across 19 sites near Ross Island. Moreover, Kelly et al. (2020) reported microplastic abundance ranging from 6 to 33.3 MP/L in the Antarctic sea ice. In contrast, Jones-Williams et al. (2025) reported a significantly high abundance of microplastics (73–3099 MP/L), with 98% being ≤50 µm. Moreover, an average atmospheric deposition of 1.7 MP/m^2/d was observed in Victoria Land, with fragments being the dominant morphotype (Illuminati et al., 2024). Antarctica's greater isolation, a surrounding ocean current barrier, and a lack of significant local industry suggest that its microplastic contamination could be linked to long-range atmospheric transport. However, it remains unclear how climate dynamics in the Arctic and Antarctic regions influence microplastic residence time, movements, and routes to endpoints. Moreover, the effect mechanisms of microplastics on the melting dynamics of ice are still worth further exploration.

Despite remote ice, microplastics were also reported in remote mountains, their rivers, and high-altitude alpine lakes. Wang et al. (2025) reported a considerable abundance of microplastics in water, soil, and atmosphere at the Mt. Everest (Table 1). Allen et al. (2019) reported a daily average of 249 fragments, 73 films, and 44 fibres per square meter in a remote, pristine mountain catchment in the French Pyrenees. Velasco et al. (2020) reported significant concentrations of microplastic fibres in the water column (2.6 MP/L) and sediments (40 MP/kg) in Lake Sassolo. However, Pastorino et al. (2021) showed the absence of microplastics <10 µm in the water and sediment at the mountain Dimon Lake, whereas the snow exhibited a mean of 0.11 MP/L. Similarly, Napper et al. (2020) reported an average of 30 MP/L in snow and 1 MP/L in the water at Mt. Everest. Emphasised that atmospheric transport has been identified as a critical pathway, carrying microplastics to high-altitude mountain peaks like Mount Everest, where they have been detected in snow and stream water, whereas large quantities of plastic debris and microplastics were observed at uninhabited islands such as Henderson Island and the Xisha Islands (Lavers and Bond, 2017; Wei et al., 2025). These findings highlight that no corner of the planet is truly safe from microplastic pollution, emphasising its status as a global environmental crisis. Despite considerable evidence of microplastic occurrence in remote mountain and river ecosystems, the data are still inadequate to model the roles of different receptors as sinks for airborne microplastics, as well as release and adsorption potential.

3 Transport pathways of microplastics in remote regions

Remote ecosystems are located miles away from anthropogenic activities; however, major microplastic sources still include urban and industrial activities, road traffic, wastewater effluents, and plastic manufacturing industries (Figure 1). The transport of MPs to remote regions may occur through atmospheric, hydrologic, and cryospheric processes (Wang et al., 2025). The atmospheric pathway has emerged as a crucial phenomenon for dispersing microplastics to remote areas (Figure 1). According to Sathyamohan et al. (2023) and Yang et al. (2023), small and lightweight MPs are dominant in remote areas, as they can be suspended in the air and carried by wind currents over long distances. Evangeliou et al. (2020) found tyre wear particles (TWPs) and brake wear particles (BWPs) miles away from roads. Moreover, Ryan et al. (2023) observed a substantial increase in airborne microplastics during the peak of Hurricane Larry.

Complementing atmospheric pathways, river flow is another pathway contributing to microplastic distribution, particularly larger particles (Wichmann et al., 2019; Pu et al., 2024). The transportation of microplastics by water flow was also observed in rivers, with some estimates suggesting that Arctic rivers alone convey approximately 8–48 tons/year, with a discharge flux of about 9.35×10^8 MP/s (Zhang et al., 2023). Yang et al. (2021) found a remote Koshi River in the Himalayas transporting microplastics, with 98% being fibres ranging from 0.1 to 1 mm in size. Similarly, the Ganges River was found to transport particles approximately 1.9 mm in size through water flow, with 96% being fibres (Napper et al., 2023). Moreover, the Mekong River was found to transport microplastics >2 mm dominated by fibres in Southeast Asia (Mendrik et al., 2025). The water flow pathway seems to be the primary contributor of larger microplastic particles in remote areas. Moreover, fibres are showing to be the dominant particles, which raises a concern due to the uncertainties around their impact on biota.

Besides the atmospheric pathway and river flow, migratory birds were reported to be potential transporters of microplastics to remote areas (Figure 1) (Mallory, 2008; Baak et al., 2020). Poon et al. (2017) investigated seabirds and found that the surface feeders exhibit a higher abundance of microplastics than the diving birds. Hamilton et al. (2021) found a significant abundance of microplastics (0.89 MP/individual) in the gastrointestinal tract (GIT) of migratory birds, fulmar, with fibres constituting 96% of the total number of particles. Moreover, Trevail et al. (2015) found an average of 15 MP/individual in the fulmar GIT. Microplastics ingestion by birds becomes a cause for concern due to potential ecological risks that could result in the food web.

There is overwhelming evidence proving that the atmospheric pathway, river flow and migratory birds transport microplastics to remote areas, with fibres constituting a high percentage of particles transported through these three modes. However, it remains unclear as to what drives this huge disparity of morphotypes with regard to transportation. Future studies may focus on quantification of the contributions of each pathway relative to the others to determine the one to be prioritised when establishing mitigation strategies. Moreover, there is little to no knowledge on the vertical distribution of microplastics, with size and morphotypes, and the partitioning between environmental matrices in remote areas. Therefore, future studies may also focus on this aspect to understand the potential of other morphotypes to increase in the soil, water, air and biota in remote areas.

4 Why the silence?

Microplastic research in remote areas has received limited attention (Figure 2), mainly due to methodological restrictions, limited accessibility, less interest as they are of no use to humans, and restrictions of human activities (Borriello, 2023; Kirschke et al., 2023). These limitations hinder comprehensive understanding and effective management of microplastic pollution in remote areas (Mihai et al., 2021). Accessibility and sampling challenges in remote

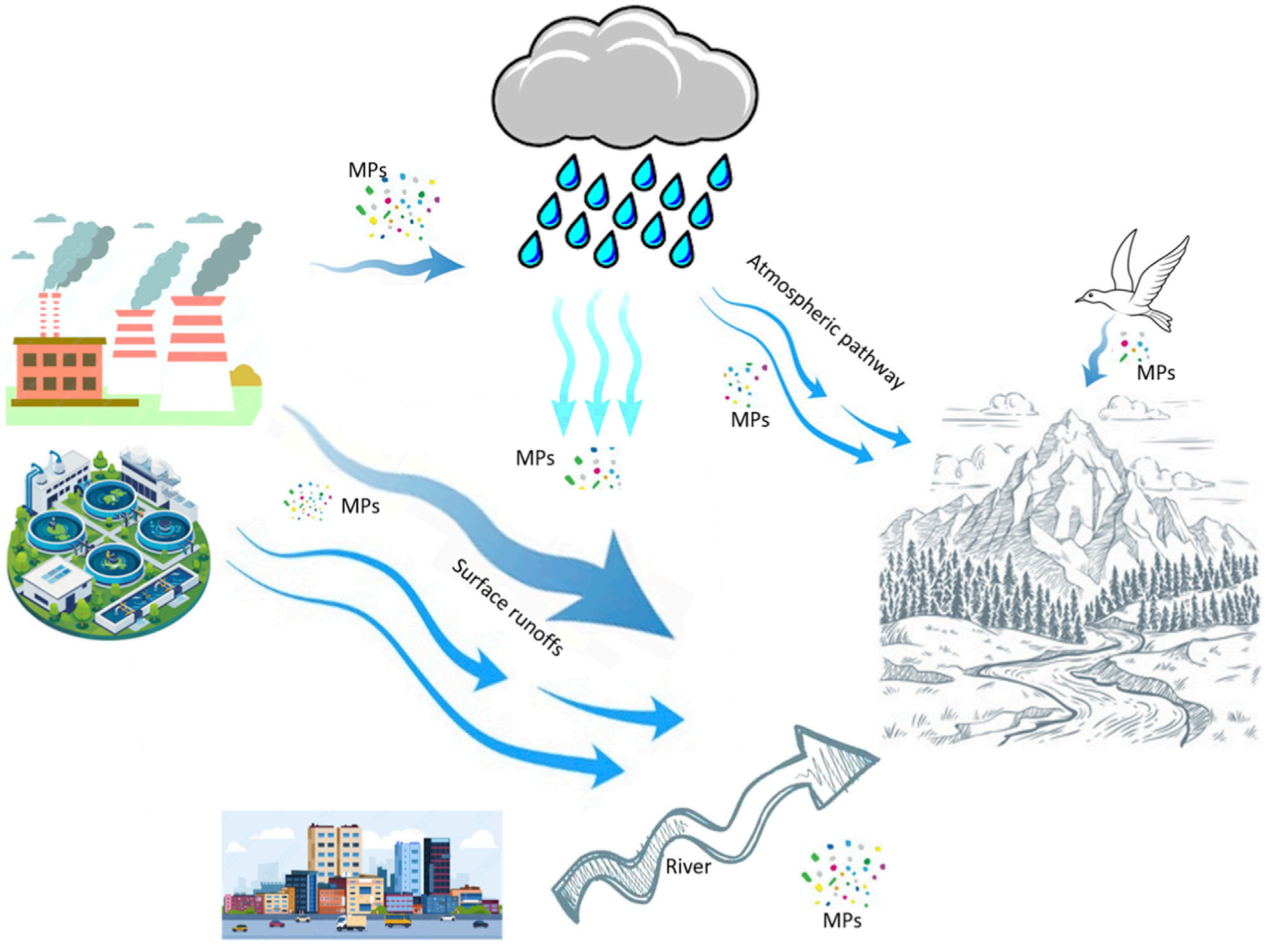

FIGURE 1
Pathways of microplastics to remote ecosystems.

areas, such as mountain terrains and polar regions, present significant difficulties for scientific research through restricted access to sites (Abdelmajeed and Juszczak, 2024). Geographical barriers such as steep slopes, streams, or ice cores and snow, harsh environmental conditions, and the need for specialized equipment and methodologies make data collection expensive, dangerous, and time-consuming (Borriello, 2023; Abdelmajeed and Juszczak, 2024).

According to Devriese et al. (2025), the vague policy posture and implementation is among the reasons hindering microplastic studies in remote areas. The absence of specific regulations and indices to measure the impact of existing policies further complicates the evaluation process (Deme et al., 2022). The challenge of translating the broader plastic pollution policies into actionable strategies is mainly pronounced in isolated communities, where unique socio-economic and environmental contexts must be considered (Devriese et al., 2025). Many policies aim to ban single-use plastics or promote recycling without addressing the systemic issues that contribute to plastic pollution, particularly in vulnerable areas (Kentin and Kaarto, 2018). For instance, the International Coral Reef Initiative and the Secretariat of the Antarctic Treaty (Vince et al., 2024) and the European Chemicals Agency (ECHA) endorsed the reduction of plastic microbeads (Kokalj et al., 2019). Furthermore, the Helsinki Commission (HELCOM) proposed a regional action plan to tackle microplastics, including recommendations on legal instruments to act upon it, encouraging microplastic-free formulas and replacing microplastics in personal care products (Munhoz et al., 2022).

5 Ecological implications

Despite little attention given to remote ecosystems, there is overwhelming evidence proving that no remote area is remote enough to escape microplastic pollution. Remote ecosystems exhibit unique characteristics, and their communities are sensitive to microplastic pollution (Wang et al., 2025). Various microplastic impacts have been observed on soil properties, ecosystem functioning, and physiology of organisms (Table 2). Microplastic particles in the soil may be blown from the soil back to the atmosphere, resulting in the atmospheric ecosystem comprising microplastics from two sources (Shinde et al., 2025). Peries et al. (2024) emphasised that microplastics in the atmosphere usually exhibit higher abundance due to multiple sources. The toxicity of microplastics may be influenced by their abundance, size, physical characteristics, and the sensitivity of the receptor (Jeong et al., 2024; Lebepe et al., 2025). Cheng et al. (2024) observed significant impacts on biochemical properties and ecosystem function in the soil, whereas Ju et al. (2025) emphasised that even at

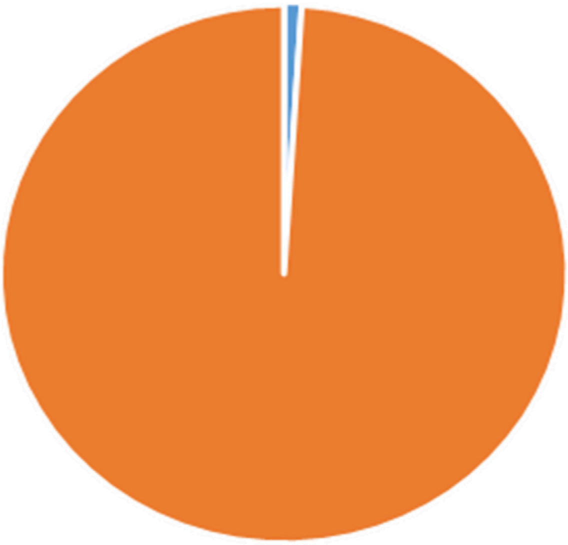

FIGURE 2
The proportion of microplastic studies in remote ecosystems relative to elsewhere.

emphasised the impact of rainwater-borne microplastics in blocking the pores of plant cells. Moreover, microplastics may land in Arctic ice, and form a cover, which may affect the climate system by absorbing the radiation and influencing the melting rate (Bergmann et al., 2016; Bergmann et al., 2023). Microplastics impact in remote areas have been fairly explored; however, there is still a research gap on the morphotypes-related impact, which will support modelling of cumulative effect in the soil, air, water, and biota.

6 Conclusion

Based on the evidence scrutinized in the review, it may not be ideal to assume the environment is pristine and free from microplastics based on its location relative to anthropogenic activities. Microplastics are showing footprints in remote areas, deeming the word "remote area" irrelevant in the context of microplastic pollution. Given the uniqueness and sensitivity of most remote areas, the ecological effects of microplastics are likely to be felt severely compared to areas closer to human activities. It is evident that even in the absence of direct sources, microplastics find their way to all regions through numerous pathways. The atmospheric pathway shows to be the primary driver for microplastic pollution in remote regions, whereas river flows and migratory organisms also play a role in microplastic transportation. Nevertheless, the mechanism driving the morphotype distribution on the three transport pathways remains unclear. Therefore, future studies may explore vertical distribution of different sizes and morphotypes, and the partitioning between different matrices to provide insight into the fate and potential effect through predictive models.

TABLE 2 The impact of microplastics in remote areas.

Impact	References
Reduced microbial diversity in soil, and impact on metabolic pathways related to carbon and nitrogen cycling in soil	Li et al. (2024)
Increase in soil pH	Zhang et al. (2025)
Absorb the radiation and affect the melting rate of ice in polar regions	Bergmann et al. (2023)
Cloud formation processes	Aeschlimann et al. (2022)
Mortality on caddisfly and reduced leaf litter decomposition, hence, ecosystem functioning	López-Rojo et al. (2020)
Cellular swelling and pyknotic nuclei in the liver and kidney of wading birds	Mehboob et al. (2025)
Oxidative stress in a terrestrial Japanese quail	de Souza et al. (2022)
Significant decrease in the number of emerged rice midge adults	Ziajahromi et al. (2018)

low abundance, microplastics affect soil aggregate stability and nutrient cycling due to their potential to block pores. Moreover, low abundance of microplastics was found to affect soil microbial community functioning (Yang et al., 2022). Iqbal et al. (2025) reported a significant reduction of plant growth, soil quality, and risk of global warming as a result of smaller microplastic particles, with a shift in soil microbial community structure being reported by Ma et al. (2023). Similarly, Hu et al. (2025) found smaller microplastic particles affecting the microbial communities and carbon metabolism in the forests, whereas Bergmann et al. (2023) found microplastics disturbing the metabolic activities in *Melosira arctica* algae at the deep seafloor in polar environments.

Besides impact on biota and ecological functions, microplastics in the atmosphere were found to influence cloud formation processes (Aeschlimann et al., 2022). According to Gaylarde et al. (2025), microplastics in the atmosphere may also be washed down to the Earth's surface by rainfall, whereas Ishfaq et al. (2025)

Author contributions

JL: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Visualization, Writing – original draft, Writing – review and editing. NB: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Writing – original draft, Writing – review and editing. MM: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Writing – original draft, Writing – review and editing.

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