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Microplastic sources and distribution dynamics across contrasting anthropogenic settings: implications for lake management

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Microplastic (MP) particles have emerged as a concerning pollutant that interferes with ecological processes and poses risks to human health. A comprehensive understanding of their source, distribution dynamics and controlling factors across diverse freshwater systems is essential for deciphering their environmental impacts. This study investigates the magnitude and spatial distribution of MP contamination in the water and sediment of two contrasting freshwater lakes, Mansar and Sukhna, and elucidates the key environmental drivers governing their variability, including TOC, TN, grain-size characteristics, and water depth. In Mansar Lake, an anthropogenically influenced and unregulated site, exhibited substantially higher microplastic levels, varying between 45–120 particles per L in the water and 390–5720 particles per kg in the sediment. In contrast, Sukhna Lake, which is relatively well managed, microplastic concentrations ranged from 5–75 particles per L in the surface water and 170–2320 particles per kg in the sediment. The markedly lower MPs abundance in Sukhna Lake can be attributed to its ongoing conservation and management interventions, including restrictions on construction activities and bans on single-use plastics within the catchment. The chemical composition of MPs identified in the water and sediment samples comprises polypropylene (PP), polyethylene (PE), polystyrene (PS), and polyethylene terephthalate (PET), predominantly occurring as pellets, fibres, and fragments. The coherent spatial patterns of TOC and TN, along with their strong positive covariance in Mansar Lake, indicate a common source of organic matter. In contrast, the decoupled distributions of TOC and TN in Sukhna Lake suggest multiple and compositionally distinct organic matter sources. The absence of statistically significant relationships between MP abundance and environmental variables, including grain size, water depth, TOC, and TN, implies that MP loading is largely driven by the proximity and intensity of local anthropogenic activities rather than in-lake physicochemical controls. These findings highlight the efficacy of targeted lake-management interventions, including restrictions on specific anthropogenic activities within the catchment, in reducing MP inputs to freshwater systems.

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Environmental significance

Microplastics (MPs) are emerging contaminants that pose growing risks to freshwater ecosystems and human health. This study provides new insights into the distribution and sources of MPs across two freshwater lakes with contrasting anthropogenic pressures and management regimes. The markedly lower MP abundance observed in the managed Sukhna Lake compared to the unmanaged Mansar Lake highlights the effectiveness of targeted conservation and catchment-level management interventions in reducing plastic pollution. These findings demonstrate that proactive environmental governance, including restrictions on single-use plastics and regulated land-use practices, can significantly limit MP inputs into freshwater systems. The results provide a scientific basis for policymakers and environmental managers to implement effective strategies for mitigating microplastic contamination in inland waters.

1 Introduction

Over the past several decades, the unprecedented rise in global plastic production and consumption has emerged as a major threat to environmental integrity and human health.[1] Commercial plastics were widely deployed across industrial sectors such as textiles, packaging, and personal care products in the 1950s, with current global annual consumption

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exceeding 450 million metric tons.[2] Alarmingly, only about 20% of this material is recycled or properly incinerated, whereas approximately 31.9 million metric tons of mismanaged plastic waste leak into the environment each year, accumulating in landfills and in terrestrial and marine environments, where it persists and continues to fragment.[3,4]

Microplastics (MPs), typically defined as plastic particles ranging from 1 μm to 5 mm and composed primarily of petroleum-derived organic polymers, have been widely reported across marine, riverine, and lacustrine environments worldwide.[5–7] They originate both from primary sources, such as microbeads and industrial abrasives intentionally manufactured at microscopic scales,[8,9] and secondary sources that arise from the fragmentation of larger plastic debris or the progressive degradation of plastics under various environmental stressors, including thermal fluctuations, mechanical abrasion, photochemical reactions, and microbially mediated processes.[10,11] MPs enter aquatic systems through multiple transport pathways, including atmospheric deposition, surface runoff, wastewater discharge, and fluvial connectivity, and persist for extended periods owing to their inherently slow degradation rates.[12,13] Their long environmental residence time allows them to accumulate across ecosystem compartments, resulting in significant ecological perturbations, habitat alterations, and potential risks to biota and human health.[14,15]

Freshwater ecosystems are vital ecological and socioeconomic systems, supplying water for drinking and agriculture while supporting diverse biological communities. However, the rapid increase in plastic pollution has rendered these environments particularly vulnerable, as their close interaction with human activities and semi-enclosed hydrological nature make them efficient sinks for MPs and associated pollutants.[16] The MPs can remain buoyant and interact with pelagic organisms, or sink and accumulate in sediments, where they come into contact with benthic communities, depending on their polymer density and surface properties.[17] Once introduced into aquatic food webs, MPs and their associated chemical additives can be transferred across trophic levels, ultimately entering the human body through ingestion, inhalation, or consumption of contaminated food resources.[18,19] Studies have proven that the physicochemical characteristics of MPs, including their size, shape, and polymer composition, play a critical role in mediating toxicological responses. These include endocrine disruption, impaired growth and development, hormonal imbalances, reduced fertility, and injuries to digestive and other vital organs.[20–22] Considering the severity of emerging contaminants, particularly plastics and microplastics, the United Nations adopted the Sustainable Development Goals (SDGs) in 2015, emphasized the need for comprehensive strategies for pollution management, mitigation, and adaptation.[23,24] Consequently, urgent and coordinated action from the scientific community, policymakers, and global environmental agencies is essential to curb the proliferation of MP contamination and safeguard ecosystem and human health.[25]

India is among the fastest-growing economies globally, marked by rapid industrialization, urban expansion, and population growth, all of which have contributed to a substantial rise in plastic production and consumption.[26,27] According to the Central Pollution Control Board (CPCB) report for 2018–2019, the country generates approximately 3.3 million tonnes of plastic waste annually.[28] Inefficient and often poorly enforced waste management practices prevalent across many regions of India have exacerbated plastic leakage into the environment, making plastic and MP pollution an escalating threat to freshwater systems.[29] MP research in India has predominantly focused on coastal and marine environments, with only a limited number of studies examining its fate and effects in freshwater lakes.[30,31] The fate and impacts of MPs vary across freshwater systems due to differences in source-to-sink pathways, hydrodynamic transport processes, and system-specific management practices. Consequently, comparative assessments that consider multiple environmental, management, and anthropogenic controls on MP distribution in lacustrine settings remain scarce. Existing evidence suggests that MP accumulation and spatial heterogeneity may be influenced by sediment grain size,[20] water depth,[32] land-use/land-cover patterns,[33] and organic matter content, including total organic carbon (TOC) and total nitrogen (TN), owing to the sorptive affinity of MPs for organic substrates.[34] However, these relationships are still poorly constrained in the Indian context. To address this research gap, the present study investigates MPs in surface water and sediment from two freshwater lakes, Mansar and Sukhna, that differ in terms of anthropogenic pressures, management regimes, and altitudinal variation. This comparative framework provides insights into the factors controlling MP distribution and accumulation in diverse lacustrine environments.

This study provides a framework to evaluate the effectiveness of lake management interventions in mitigating pollution by directly comparing a protected freshwater system with an unregulated water body. The specific objectives are to: (1) quantify the abundance, sources, and polymer composition of MPs and elucidate the relationships between MPs, key environmental parameters, and land-use/land-cover dynamics within the catchment; and (2) assess the interactions between MPs and sedimentary TOC and TN, including the underlying processes governing their affinity.

2 Study area

Mansar Lake (32.6966° N and 75.1443° E), a wetland of international importance located in the rural Himalayan foothills of Jammu and Kashmir, was designated a Ramsar site in November 2005. The lake is situated at an elevation of 666 m above sea level and is the largest and deepest lake in the Jammu region, with a maximum depth of 38.25 m and a surface area of 0.53 km^2. The lake is non-drainage in nature and is fed by catchment runoff, rainfall (annual average ~1500 mm), and underground springs. Geologically, the lake is situated on the folded lower Siwalik formation of tertiary age, composed of sandstone with alternating clay bands 1–2 m thick.[35] The northern and eastern peripheries of the lake are covered by human habitation; the western side has some agricultural fields; and the southern portion is covered by forest on a hill slope.[35] Mansar Lake is an unmanaged freshwater lake and a major regional and religious tourist site that is undergoing environmental deterioration primarily due to pollutant inputs from untreated domestic sewage, agricultural runoff, detergents, nutrients, and other catchment-derived contaminants.[36]

Sukhna Lake (30.7421°N and 76.8188°E) is an artificial freshwater lake created in 1958 by constructing an earthen dam that is approximately 3 km in length and 14 meters in height. The dam was built on the Sukhna Choe, a seasonal rivulet located in the northeast corner of Chandigarh City. The lake has a surface area of ~3 km^2 (1.52 km × 1.49 km) and lies at a mean elevation of ~356 m above sea level. It has a catchment area of ~42 km^2, with 33 km^2 falling within the region of the Siwalik Hills and the rest in a few villages of Punjab, Haryana, and the Union Territory of Chandigarh.[37] The area has a semi-arid climate with a temperature range of ~5.10 °C (January) to ~41.8 °C (June), which receives an annual rainfall of ~1120 mm. The lake is fed mainly by two hilly torrents, the Kansal and Nepli Choes, mostly during the monsoon season (July to September).[38] The Ministry of Environment (Government of India) declared Sukhna Lake a wetland of national importance in July 2019 under the Environment (Protection) Act, prompting the implementation of stringent conservation and management measures, including prohibitions on illegal construction, industrial expansion, and single-use plastics within the catchment.

3 Materials and methods

3.1 Sampling

The sediment and water samples were collected at twenty-three locations ($n = 23$) from Mansar Lake, Jammu and Kashmir, and at thirty locations ($n = 30$) from Sukhna Lake, Chandigarh (Fig. 1). The sampling of surface water and sediment was performed as outlined in Kumar *et al.*[31] The field sampling was designed to provide comprehensive spatial coverage of both lakes and to yield a representative analysis of their environmental conditions. At each sampling site, surface water samples were collected using pre-cleaned sterile glass bottles (1 L), and surface sediments (~1.5 kg) were collected using a Van Veen grab sampler and packed in aluminium foil. All sediment and water samples were stored in ice boxes and transported to the laboratory under controlled conditions to limit alterations in their physical, chemical, and biological properties. Comprehensive metadata, including GPS coordinates and *in situ* environmental observations, were recorded for each site to support spatial analysis and interpretation.

3.2 Extraction and analysis of microplastics

For microplastic extraction from the water sample, the collected samples were homogenized by shaking the container and then passed through a 5 mm sieve to remove larger debris and particles. The sieved samples were transferred to pre-cleaned glass bottles and subsequently filtered through glass fibre filter paper (Whatman CAT no. 1820–047, 47 mm, 1 μm pore size) using the motorised glass filtration assembly. The filter papers were dried and transferred to a glass Petri dish for further analysis. To extract MPs from sediment samples, approximately 100 g of oven-dried sediment was treated with H_2O_2 and Fenton's reagent to remove organic matter, and the resulting slurry was filtered through a 5 mm mesh. Digestion was performed for up to 2 weeks, depending on the organic matter content, at room temperature inside the fume hood,

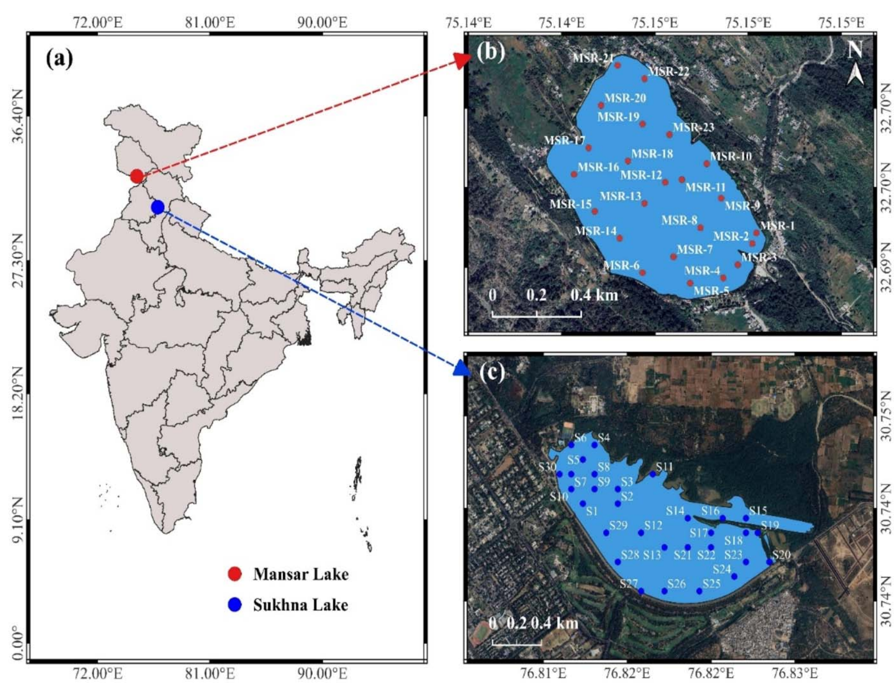

Fig. 1 (a) Map of India showing the locations of the study areas; (b) Mansar Lake map showing the sampling sites; (c) Sukhna Lake map showing the sampling sites.

ensuring complete decomposition of organic matter. A saturated $ZnCl_2$ (1.6 g cm^{-3}) solution, three times the volume of the filtrate, was added to a separate beaker for density separation. The supernatant was then decanted and filtered using a vacuum filtration assembly, and the glass fibre filter papers were retained for further analysis. Identification, counting, and morphological characterization of MPs in sediment and water samples were performed under a fluorescent microscope (Nikon SMZ18) equipped with an illuminator. The chemical composition of selected MP particles was determined using a Raman microscope (Renishaw InVia) equipped with three laser sources (514, 633, and 785 nm) at IISER Mohali. For this, two hundred ($n = 200$) MP particles were manually picked from water and sediment samples containing particles >0.4 mm in size, present as fibres, fragments, films, and foams. The obtained Raman spectra were verified against literature data reported in earlier studies.[39,40]

3.3 Grain size analysis

For grain-size measurement, the bulk sediments were treated with 30% H_2O_2 and 1 N HCl to remove organic matter and carbonate fractions, respectively, following the protocol described by Kumar *et al.*[31] This solution was centrifuged at 3500 rpm and washed with Milli-Q water ~3–4 times to remove the excess acid fraction. Dispersed samples were subsequently analyzed using a Malvern Mastersizer 3000 equipped with a Hydro EV wet-dispersion unit under standard operating conditions (dispersion velocity: 2500 rpm; measurement duration: 20 s). Each sample was measured in five replicates, and averaged particle-size distributions were classified into clay (<4 μm), silt (4–62.5 μm), and sand (>62.5–2000 μm) fractions. The De Brouckere mean diameter ($D[4, 3]$), reflecting the volumetrically dominant grain-size mode, was computed, and grain-size results are reported as volume percentages of clay, silt, and sand.[41]

3.4 Analysis of TOC and TN in the sediment

The bulk freeze-dried sediment powders were decarbonated using 0.5 N HCl to remove inorganic carbon, followed by repeated Milli-Q water rinsing and centrifugation to eliminate residual acid, according to the protocol published elsewhere.[42] The acid-treated residues were subsequently dried and homogenized with an agate mortar and pestle to ensure complete powdering and analytical uniformity. For measurement of TOC and TN concentration, decarbonated samples were accurately weighed into tin capsules, appropriately packed, and quantified using a UNICUBE Elemental Analyser at the IISER Mohali. Instrument calibration was performed by analyzing a standard of sulfanilamide ($C_6H_8N_2O_2S$), and analytical accuracy was maintained within ±5% ($n = 8$), confirming the reliability of the measurements.

3.5 Quality control

Field sampling and laboratory procedures were conducted under stringent contamination-control conditions, including the use of nitrile gloves, cotton face masks, and plastic-free cotton laboratory coats. Multiple quality-assurance steps were integrated throughout sampling and analysis to minimize the introduction of airborne MP particles contaminating the samples. All glassware was solvent-rinsed, thoroughly cleaned, and baked at 500 °C for 8 h in a muffle furnace and then wrapped in aluminium foil to prevent post-treatment contamination. Microplastic extraction was performed in a laminar-flow hood at controlled room temperature (27 °C), and filtered samples were stored exclusively in Milli-Q-rinsed glass Petri dishes. A saturated zinc chloride ($ZnCl_2$) solution was prepared at ambient temperature, with its density (1.6 kg L^{-1}) routinely verified using a specific-gravity hydrometer (OMSONS 1.00–2.00) to maintain flotation efficiency. Procedural blanks accompanied each extraction batch to identify potential laboratory-derived background contamination. Additionally, duplicate analyses were performed for all samples across both matrices to minimize analytical noise and ensure reproducibility of MP counts and characterization.

3.6 Statistical analysis

The number of MPs detected in the water and sediment samples is reported as particles per litre (particles per L) and particles per kilogram (particles per kg), respectively. A Pearson correlation matrix was generated to examine the interrelationships among the measured parameters using OriginLab software. Furthermore, an unpaired Student's *t*-test was performed to determine significant differences in the mean abundance of MPs between water and sediment samples within the study area, as well as other study areas using GraphPad QuickCalcs (https://www.graphpad.com/quickcalcs/). For correlation analysis and *t*-test, a p-value <0.05 is considered significant throughout the manuscript.

4 Results and discussion

4.1 Abundance and distribution of microplastics

The MP abundance quantified in surface water and sediment from Mansar and Sukhna Lakes are presented in Tables S1 and S2. In Mansar Lake, MP concentrations ranged from 45 to 120 particles per L in surface waters and 390 to 5720 particles per kg (dw) in sediments. In contrast, Sukhna Lake exhibited MP concentrations of 5–75 particles per L in surface waters and 170–2320 particles per kg (dw) in sediments. Across both lakes, sedimentary MP loads were consistently higher than those observed in the water samples, reflecting longer residence times, enhanced deposition, and sustained accumulation of buoyant and neutrally buoyant particles within benthic environments.[31,43] A statistically significant difference in MP abundance was observed between the two systems, with Mansar Lake exhibiting markedly higher concentrations than Sukhna Lake, as confirmed by an unpaired Student's *t*-test ($p < 0.05$). This disparity likely reflects the effectiveness of conservation and management interventions implemented at Sukhna Lake, including stringent restrictions on the use and disposal of single-use plastics within its catchment, which collectively mitigate MP inputs and subsequent accumulation.

Fig. 2 illustrates the spatial variability in MP abundances across surface water and sediment in Mansar and Sukhna Lakes. In Mansar Lake (Fig. 2a and b), surface-water MP concentrations ranged from 45 particles per L at MSR14 to a maximum of 120 particles per L at MSR19, whereas sediment-associated MPs varied from 390 particles per kg (dw) at MSR23 to 5720 particles per kg (dw) at MSR3. No coherent spatial trend was evident in the surface water; however, sediment samples showed a pronounced enrichment toward the southeastern sector of Mansar Lake. However, in Sukhna Lake (Fig. 2c and d), the highest surface-water MP abundance occurred at site S13 (75 particles per L) in the central zone, while the lowest was recorded at S8 (5 particles per L) in the western region. Meanwhile, in the sediment samples, the highest MPs were found at S7 (2320 particles per kg dw) in the northwest, and the lowest at S11 (170 particles per kg dw). The absence of a consistent MP spatial distribution pattern in Sukhna Lake likely reflects the interplay of multiple factors, including heterogeneous source inputs, variable hydrodynamic regimes, differential transport and deposition processes, and polymer-specific physical properties. The irregular and site-specific distribution observed in both lakes may also be driven by localized anthropogenic pressure, such as tourism, recreational boating, small-scale industries, fisheries, and agricultural activities, which influence the magnitude and spatial heterogeneity of MP loading.[44,45]

4.2 Origins and chemical composition of microplastics

The heterogeneous nature of plastic polymers results in markedly different ecological and human-health risks, owing to their variable toxicity, sorptive capacities, and degradation behaviours.[46,47] Consequently, characterizing the sources and chemical composition of MPs in freshwater ecosystems is essential for identifying dominant polluters, forecasting ecological responses associated with specific polymer types, and developing targeted mitigation and management strategies. In Mansar and Sukhna Lakes, MPs detected in both water and sediment matrices were categorized into five morphological classes: fragments, films, foams, fibres, and pellets/beads (Fig. 3).

In the surface water samples of Mansar and Sukhna Lakes, pellets/beads overwhelmingly dominated the MP assemblage, constituting 82.3% and 91.9% of total particles, respectively, followed by fragments (17.9% and 3.7%), fibres (6.4% and 3.0%), foams (1.7% and 0.3%), and films (0.8% and 1.1%).

A similar distribution pattern was observed in lake sediments, where pellets/beads again represented the dominant fraction (78.6% and 83.0% in Mansar and Sukhna, respectively), followed by fragments (17.9% and 12.8%), fibres (1.7% and 2.7%), films (1.0% and 1.0%), and foams (1.0% and 0.5%) (Fig. 4). The predominance of pellets/beads likely reflects their widespread usage in cosmetics and personal care products, such as exfoliating scrubs, hand cleansers, soaps, toothpastes, shaving foams, and various beauty and household cleaning agents, and their small size, which facilitates transport through atmospheric pathways and surface runoff.[48,49] The relatively high resistance of beads/pellets to physical abrasion further enhances their persistence in aquatic environments.[31,50] Fragments, the second-most-abundant category in both lakes, are indicative of *in situ* degradation of larger plastic debris, consistent with secondary MP formation pathways. Fibres are generally attributed to the release of synthetic textiles, fishing nets, and rope materials, reflecting both domestic and recreational sources.[51] In contrast, the comparatively lower proportions of films and foams point to limited inputs or to faster degradation of plastic bags, packaging materials, agricultural films, and construction-derived foamed polymers in these systems.[52,53]

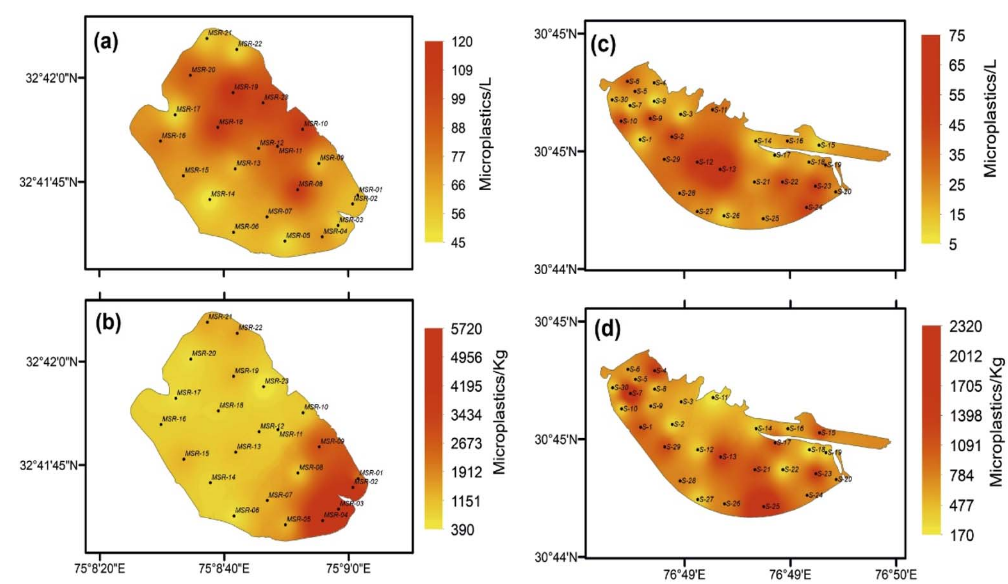

Fig. 2 Spatial variability of microplastic abundance in water and sediment samples of Mansar Lake (a and b) and Sukhna Lake (c and d).

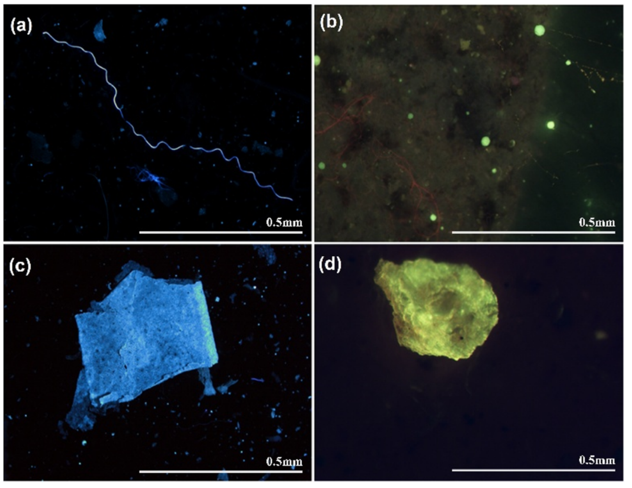

Fig. 3 Photographs of detected microplastic shapes in the study area: (a) fibre and fragment, (b) pellet/bead, (c) film and (d) foam.

Raman spectroscopic analysis of water and sediment samples from both lakes identified four major polymer types: polypropylene (PP), polyethylene (PE), polystyrene (PS), and polyethylene terephthalate (PET). Polymer assignments were confirmed by characteristic vibrational bands consistent with previously reported reference spectra.[31,39] Across both lakes, PE and PS emerged as the dominant polymers in surface water and the sedimentary matrix, indicating their pervasive input and environmental persistence. In Sukhna Lake, the filtered samples were primarily composed of PE, PS, and PP, whereas in Mansar Lake, a broader polymeric diversity was observed, with PET detected alongside PE, PS, and PP. Notably, PET occurred at substantially higher concentrations in sediment samples from Mansar Lake, suggesting enhanced depositional flux or stronger particle–sediment interactions for this polymer type. The predominance of PE and PS is consistent with their widespread utilization in single-use consumables, including food packaging, carry bags, disposable containers, and takeaway materials.[54,55]

Furthermore, PS represents a principal constituent of microbeads incorporated into personal care and cosmetic formulations, providing a plausible pathway for their introduction into freshwater systems.[56] PET, extensively used in beverage bottles and fruit/food packaging, reflects the increasing reliance on this material in the global packaging sector. In 2021, global PET production exceeded 55 million tonnes, underscoring its large-scale environmental footprint and growing contribution to aquatic plastic contamination.[57]

4.3 Grain size distribution of sediments and its relationship with microplastics

The accumulation and spatial distribution of MPs in lacustrine sediments are governed not only by land-use and land-cover characteristics but also by a suite of hydro-sedimentary controls, including sediment particle-size composition and water depth.[20,40] As shown in Fig. 5, the sediments comprise clay, silt, and sand fractions, reflecting the textural variability of

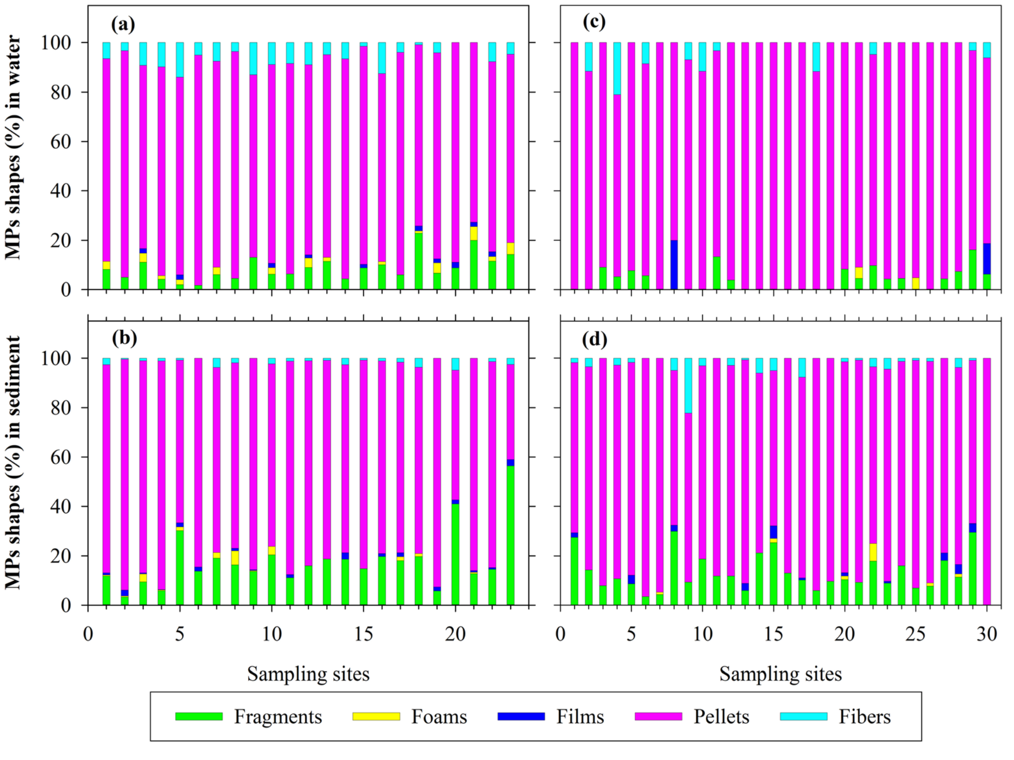

Fig. 4 Stacked bar plot of representative microplastic particle type (%) in water and sediment of Mansar Lake (a and b) and Sukhna Lake (c and d) across sampling locations.

the depositional environment. The mean grain size (De Brouckere mean diameter) of sediments ranged from 12.5 to 231 μm in Mansar Lake and from 4.68 to 41.30 μm in Sukhna Lake (Tables S1 and S2), reflecting contrasting depositional regimes between the two systems. In Mansar Lake, the sand fraction varied between 3.2 and 88.2%, silt between 10.5 and 77.0%, and clay between 1.3 and 41.2%, indicating pronounced spatial heterogeneity in sediment texture. In contrast, sediments from Sukhna Lake were dominated by finer fractions, with sand ranging from 0 to 13.2%, silt from 42.6 to 78.5%, and clay from 14.5 to 57.4%, consistent with relatively low-energy depositional conditions.

Pearson correlation heatmap analysis revealed a statistically significant negative relationship between MP abundance and water-column depth ($r = -0.45$, $p < 0.05$) in Mansar Lake, indicating a progressive decline in MP concentrations with increasing depth (Fig. 7a). This trend suggests preferential accumulation of MPs in shallower zones, likely driven by enhanced nearshore inputs, resuspension, and hydrodynamic sorting. Additionally, a substantial positive correlation was observed between water depth and finer sediment fractions (clay and silt), implying a relative enrichment of finer material in deeper parts of the Mansar Lake (Fig. 7a). Despite these depth-related patterns, no statistically significant relationship was observed between sediment grain-size fractions and MP abundance in Mansar Lake, suggesting that particle-size sorting alone does not exert dominant control on MP retention in the sediments. In Sukhna Lake, neither sediment grain size nor water-column depth exhibited any significant correlation with MP concentrations (Fig. 7b), indicating that hydro-sedimentary factors play a comparatively minor role in regulating MP distribution within this system. The absence of clear grain-size or depth dependency highlights the overriding influence of anthropogenic pressures, lake management practices, and

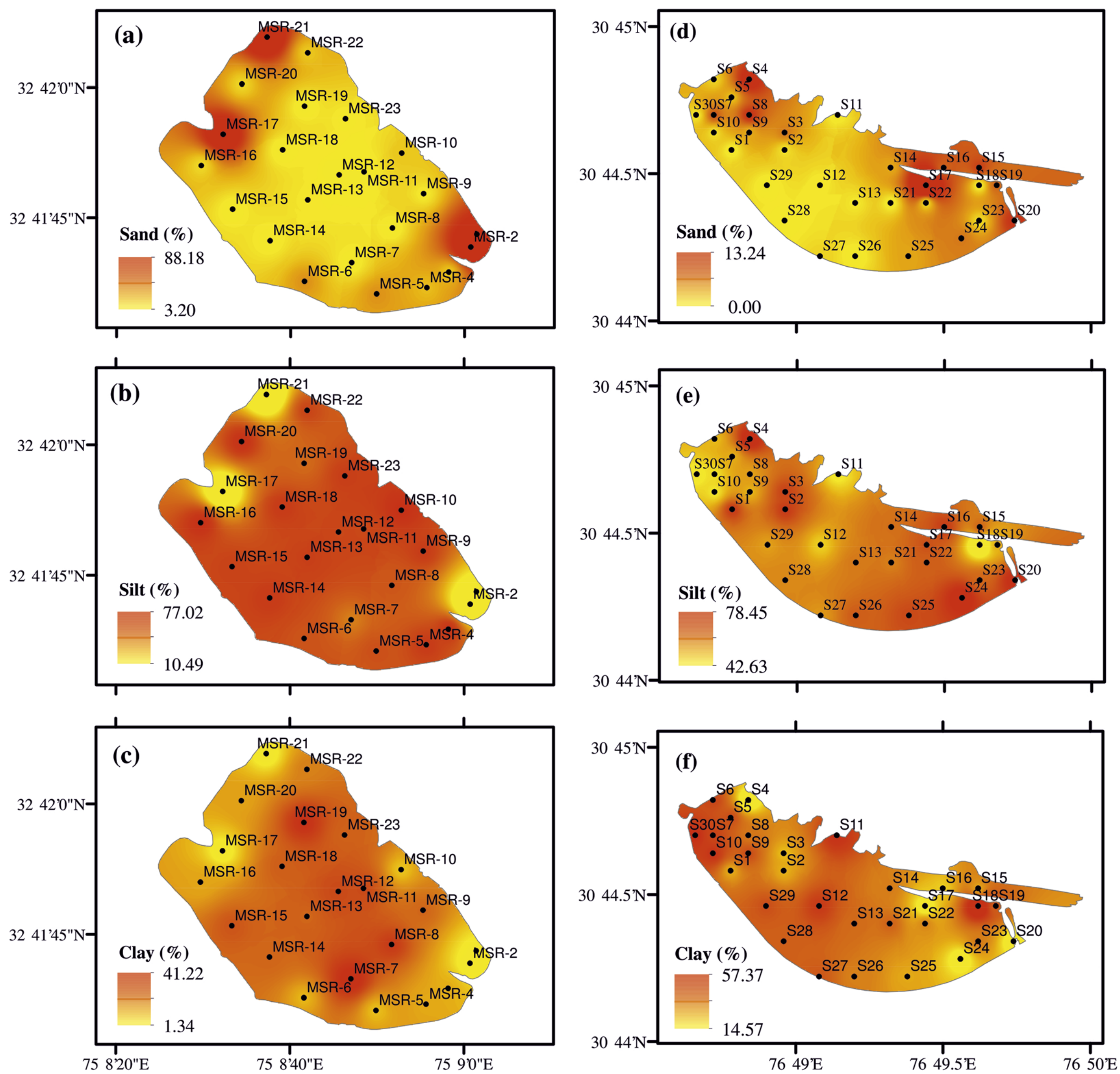

Fig. 5 Spatial variability in sand, silt and clay measured in sediments of Mansar Lake (a–c) and Sukhna Lake (d–f).

catchment-scale controls on MP inputs and accumulation. Overall, these findings underscore that while sedimentological and bathymetric factors may locally modulate MP distribution, particularly in structurally heterogeneous systems such as Mansar Lake, the primary drivers of MP contamination in both lakes are linked to human activities within the lakes and their catchments. This emphasizes the need to integrate sedimentological analyses with land-use and source-based assessments to robustly constrain MP dynamics in freshwater environments.

4.4 Organic matter distribution and its affinity with microplastics in the sediment

Variations in TOC and TN are widely used to assess the quantity, sources, nutrient cycling, and diagenetic fate of organic matter in lacustrine sediments.[58,59] In Mansar Lake, TOC concentrations ranged from 0.4 to 4.8% (mean: 3.3%), while TN varied between 0.1 and 0.7% (mean: 0.5%). In contrast, Sukhna Lake exhibited comparatively lower organic matter content, with TOC ranging from 0.5 to 1.3% (mean: 0.7%) and TN from 0.1 to 0.4% (mean: 0.3%). Statistical evaluation using an unpaired Student's t-test confirmed that mean TOC and TN concentrations in Mansar Lake are significantly higher than those in Sukhna Lake at the 95% confidence interval, indicating a greater degree of organic enrichment in Mansar sediments. The elevated TOC and TN levels in Mansar Lake reflect enhanced organic loading, likely driven by relatively uncontrolled anthropogenic inputs, including domestic effluents, surface runoff, and agricultural activities in the catchment. The organic matter pool in both lakes is derived from a combination of autochthonous sources, primarily phytoplankton and microbial biomass, and allochthonous inputs from catchment soils, fertilizers, and surface runoff.[60] The spatial distributions of TOC and TN across Mansar and Sukhna lakes are presented in Fig. 6, revealing pronounced variability in organic matter accumulation patterns between the two systems.

In Mansar Lake, TOC and TN display similar spatial trends and are strongly and positively correlated ($r = 0.97$, $p < 0.001$, $n = 23$), suggesting a common, relatively uniform source of organic matter input, likely driven by coupled nutrient enrichment and in-lake primary productivity. Conversely, TOC and TN in Sukhna Lake exhibit an irregular spatial distribution and a weak, statistically insignificant correlation ($r = 0.05$, $p > 0.05$), indicative of multiple and spatially variable organic matter sources influenced by lake management practices and heterogeneous catchment inputs.

Fig. 7 illustrates the Pearson correlation matrix between MP abundance and measured sedimentary parameters in both lakes. TOC exhibited weak, statistically insignificant correlations with MPs in Mansar Lake ($r = 0.18$, $p > 0.05$) and in Sukhna Lake ($r = -0.15$, $p > 0.05$). Similarly, TN showed no significant relationship with MP abundance in either Mansar ($r = 0.21$, $p > 0.05$) or Sukhna Lake ($r = -0.27$, $p > 0.05$). The absence of a strong association between MPs and TOC/TN suggests that organic matter content alone does not exert primary control on MP accumulation in these sediments. Instead, MP distribution is likely governed by a combination of physicochemical properties and sedimentological factors, including polymer type, particle size and shape, density-driven settling behaviour, and local sediment characteristics such as grain-size composition. Additionally, microbial degradation and biogeochemical transformation of organic matter may further decouple the relationship between MPs and bulk organic proxies such as TOC and TN. Notably, these findings contrast with several previous studies that reported strong positive correlations between MPs and organic matter parameters in sediments,[61,62] underscoring the site-specific nature of

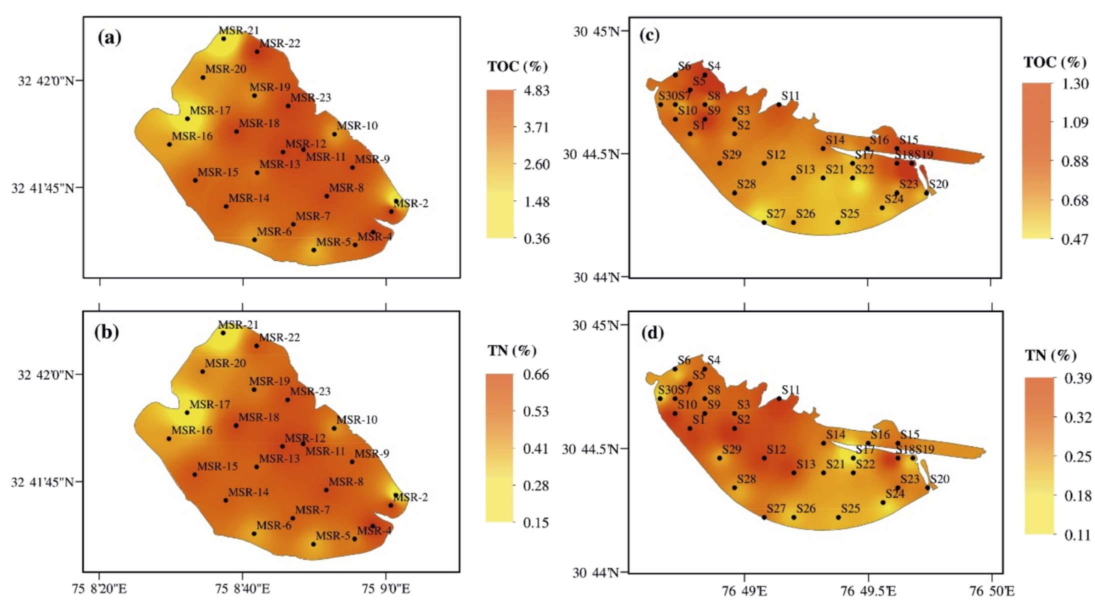

Fig. 6 Spatial distribution of total organic carbon (TOC) and total nitrogen (TN) measured in sediments of Mansar Lake (a and b) and Sukhna Lake (c and d).

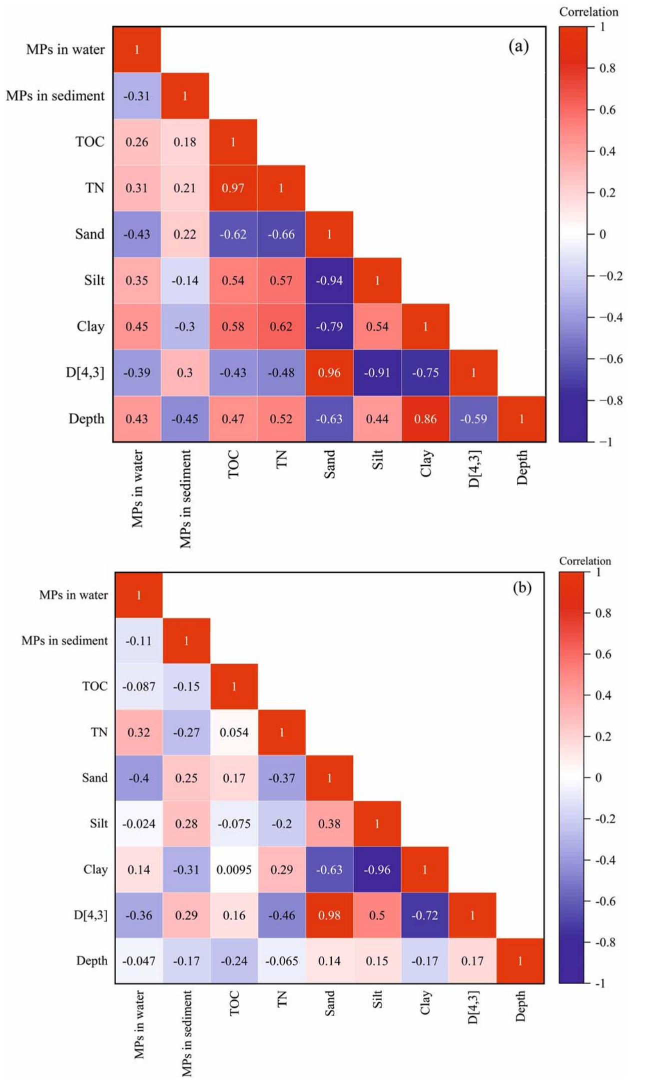

Fig. 7 Pearson correlation analysis of microplastics and measured environmental parameters in Mansar Lake (a) and Sukhna Lake (b).

MP–organic matter interactions and the need to consider local depositional and anthropogenic contexts when interpreting such relationships.

4.5 A comparison of microplastics with regional and global freshwater lakes

Comparison of MP data with those reported in regional and global studies is challenging because their abundance varies due to several factors, including land-use changes, climate, temperature, location, and altitude, as well as differences in sampling strategies, processing methods, and analytical methods. Here, we summarised a limited number of studies that share similarities in sample collection and reporting units across different Indian and global freshwater lakes (Table S3 and Fig. 8). The occurrence of MPs in the water and sediment of freshwater lakes from India and around the world is shown in Fig. 8 and Table S3. The MPs in the surface water of Mansar Lake are several orders of magnitude higher than those in several Indian lakes, such as Manipal Lake,[48] Red Hill Lake,[63] Vellayani Lake,[64] Renuka Lake,[39] Nainital Lake,[65] Mansbal Lake,[31] and Dal Lake[66] and global lakes such as Dzhulukul Lake,[67] Talmen Lake,[67] Taihu Lake,[68] Mohamaya Lake,[69] and Ulungur Lake.[70] In Sukhna Lake, water samples showed relatively lower MP abundance than in Mansar and other regional and global lakes, due to conservation practices. In the sediment of Mansar Lake, significantly higher MPs were found than in many regional and global lakes, as shown in Fig. 8, and were lower than those in Nainital Lake,[65] Mansbal Lake,[31] Dal Lake,[66] Taihu Lake,[68] and Lake Tollense.[71] In the Sukhna Lake sediment, MP abundance was significantly lower than in these lakes but higher than in other lakes, as shown in Fig. 8a. These results indicate that Mansar Lake is among the most polluted lakes in regional and global freshwater lakes, and Sukhna is comparatively less polluted. The significant MPs in freshwater lakes highlight the need for strict policy implementation globally to safeguard freshwater bodies from growing MP contamination.

4.6 Implications and policy making

Owing to their pervasive occurrence and persistence, MPs have emerged as a global stressor threatening aquatic ecosystems and long-term environmental sustainability. To date, most MP studies have primarily focused on their occurrence, spatial distribution, sources, and potential ecological and human health risks. In contrast, the present study provides a novel perspective by explicitly demonstrating the role of lake conservation and management strategies in regulating microplastic contamination, through a comparative assessment of a protected (Sukhna Lake) and a relatively unmanaged (Mansar Lake) aquatic system. The substantially lower abundance of MPs in the conserved and actively managed Sukhna Lake underscores the effectiveness of targeted management interventions, such as restrictions on anthropogenic activities, regulated land use, and catchment-scale controls, in mitigating plastic pollution. These findings provide compelling evidence that proactive lake conservation measures can significantly reduce MP accumulation in sediments and, by extension, lower ecological exposure risks. Conversely, the elevated MP concentrations observed in the less-protected system underscore the severity of plastic pollution and its potential implications for ecosystem integrity and human health.

The contrasting MP distributions across the two lakes strongly support the broader adoption of integrated lake management and conservation frameworks as a viable strategy for controlling plastic pollution in freshwater environments. From a policy perspective, the results emphasize the urgent need for stricter regulations on plastic use, improved waste management practices, and effective enforcement mechanisms to safeguard inland water bodies. Finally, this study underscores the necessity for broader, multi-regional investigations to systematically evaluate the effectiveness of lake management practices, thereby enabling the development of globally applicable strategies to combat microplastic pollution in freshwater ecosystems.

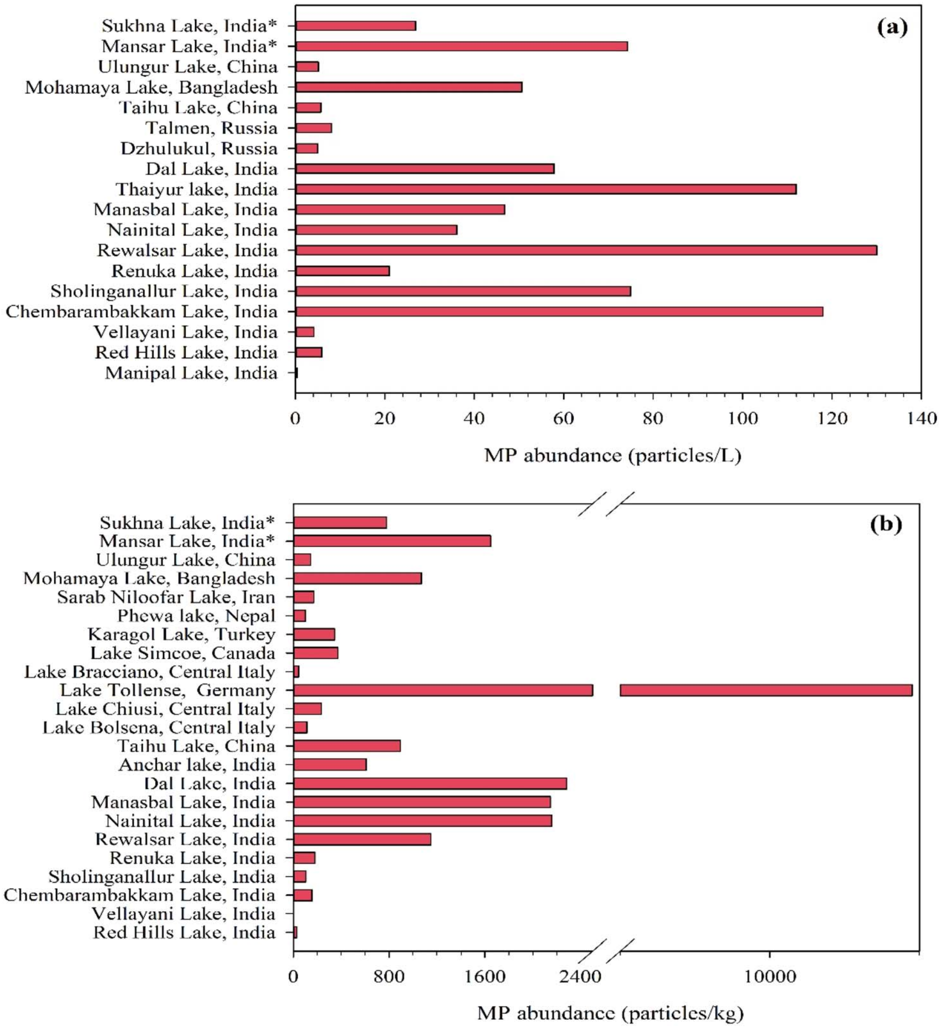

Fig. 8 Concentration of MPs in water (a) and sediment (b) samples from the freshwater lakes from regional and global freshwater lake ecosystems.

5 Conclusions

This study delineates the occurrence, distribution and sources of MPs in two freshwater lakes of contrasting anthropogenic settings, Mansar Lake (a Ramsar site) and Sukhna Lake (a managed and protected site) situated along the altitudinal gradient of the Siwalik Mountain Range of the Himalaya. A higher abundance of MPs was found in the water and sediment of Mansar Lake than in Sukhna Lake. The detected morphologies of MPs were pellets/beads, fibres, fragments, films, and foams, with chemical compositions of PE, PP, PVC, and PET. These MPs are widely used in personal care products, food packaging, water bottles, grocery bags, and garbage bags. The MP distribution is mainly influenced by anthropogenic activities, including land use/land cover in and around the lake, as evidenced by the negligible correlation with environmental factors such as grain size, depth, TOC, and TN. The reduced MP abundance in Sukhna Lake appears to be due to lake management practices adopted to safeguard the lake and to a ban on several anthropogenic activities in the catchment area, including construction work and single-use plastics. However, Mansar Lake receives anthropogenic inputs from agricultural activities, boating, sewage from the surrounding area, and waste from temples and tourism. This study highlights the importance of lake management in controlling the MP inputs to the aquatic body. The findings of this study are beneficial for assessing the role of lake management practices and bans on certain anthropogenic activities in the catchment area in controlling MP pollution and for highlighting the importance of such practices in other water bodies.

Author contributions

Kumar Ajay: writing – original draft, visualization, validation, software, methodology, investigation, formal analysis, data curation, and conceptualization. Nafees Ahmad: writing – original draft, investigation, data curation, writing – review & editing, visualization, validation, and conceptualization. Sunil Kumar: writing – review & editing, visualization, validation, data curation, and conceptualization. Aayush: writing – review &

editing, visualization, validation, and investigation. Praveen K Mishra: writing – review & editing, visualization, validation, and investigation. Ambili Anoop: writing – review & editing, visualization, validation, supervision, resources, project administration, investigation, funding acquisition, formal analysis, and conceptualization.

Conflicts of interest

There are no conflicts to declare.

Data availability

All the data generated and analyzed for this study are included in this manuscript and its supplementary information (SI). Supplementary information is available. See DOI: https://doi.org/10.1039/d5va00475f.

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References

1 R. U. Halden, C. Rolsky and F. R. Khan, Time: A Key Driver of Uncertainty When Assessing the Risk of Environmental Plastics to Human Health, *Environ. Sci. Technol.*, 2021, **55**, 12766–12769.
2 S. K. Joshi and A. Vashishth, in *Advanced Strategies for Biodegradation of Plastic Polymers*, ed. R. Soni, P. Debbarma, D. C. Suyal and R. Goel, Springer Nature Switzerland, Cham, 2024, pp. 405–420.
3 O. Alabi, K. Ologbonjaye, O. Awosolu and O. Alalade, Public and Environmental Health Effects of Plastic Wastes Disposal: A Review, *J. Toxicol. Stud.*, 2019, **5**, 021.
4 I. Ahmad, A. Ali and K. Shabbir, in *Combating Plastic Pollution in Terrestrial Environment: Challenges and Strategies for a Sustainable Future*, ed. S. Suriyanarayanan, S. H. P and K. Pakeerathan, Springer Nature Singapore, Singapore, 2025, pp. 209–235.
5 R. C. Hale, M. E. Seeley, M. J. La Guardia, L. Mai and E. Y. Zeng, A Global Perspective on Microplastics, *J. Geophys. Res., Oceans*, 2020, **125**, e2018JC014719.
6 B. He, B. Wijesiri, G. A. Ayoko, P. Egodawatta, L. Rintoul and A. Goonetilleke, Influential factors on microplastics occurrence in river sediments, *Sci. Total Environ.*, 2020, **738**, 139901.
7 B. S. Mayoma, C. Sørensen, Y. Shashoua and F. R. Khan, Microplastics in beach sediments and cockles (Anadara antiquata) along the Tanzanian coastline, *Bull. Environ. Contam. Toxicol.*, 2020, **105**, 513–521.
8 T. Stanton, M. Johnson, P. Nathanail, W. MacNaughtan and R. L. Gomes, Freshwater microplastic concentrations vary through both space and time, *Environ. Pollut.*, 2020, **263**, 114481.
9 P. Yadav, M. Rani and S. Chaudhary, Identification, characterisation and implication of releasing microplastics from personal care and cosmetic products in India, *J. Toxicol. Environ. Health Sci.*, 2025, **17**, 275–289.
10 F. Haque and C. Fan, Fate of microplastics under the influence of climate change, *iScience*, 2023, **26**, 107649.
11 H. Shi, J. Frias, A. El-Din, H. Sayed, G. E. De-la-Torre, M.-C. Jong, S. A. Uddin, R. Rajaram, S. Chavanich, A. Najii, M. D. Fernández-Severini, Y. S. Ibrahim and L. Su, Small plastic fragments: A bridge between large plastic debris and micro- & nano-plastics, *TrAC, Trends Anal. Chem.*, 2023, **168**, 117308.
12 A. T. Williams and S. L. Simmons, The degradation of plastic litter in rivers: Implications for beaches, *J. Coast Conserv.*, 1996, **2**, 63–72.
13 M. A. Browne, P. Crump, S. J. Niven, E. Teuten, A. Tonkin, T. Galloway and R. Thompson, Accumulation of Microplastic on Shorelines Woldwide: Sources and Sinks, *Environ. Sci. Technol.*, 2011, **45**, 9175–9179.
14 E. Ezeh and P. Agu, Environmental risk and human health impact of microplastic pollution, in *Microplastics in African and Asian Environments: The Influencers, Challenges, and Solutions*, Springer, 2024, pp. 375–394.
15 A. R. Sunny, S. A. Sazzad, M. A. Islam, M. H. Mithun, M. Hussain, A. Raposo and M. K. A. Bhuiyan, Microplastics in Aquatic Ecosystems: A Global Review of Distribution, Ecotoxicological Impacts, and Human Health Risks, *Water*, 2025, **17**, 1741.
16 V. M. Azevedo-Santos, M. F. G. Brito, P. S. Manoel, J. F. Perroca, J. L. Rodrigues-Filho, L. R. P. Paschoal, G. R. L. Gonçalves, M. R. Wolf, M. C. M. Blettler, M. C. Andrade, A. B. Nobile, F. P. Lima, A. M. C. Ruocco, C. V. Silva, G. Perbiche-Neves, J. L. Portinho, T. Giarrizzo, M. S. Arcifa and F. M. Pelicice, Plastic pollution: A focus on freshwater biodiversity, *Ambio*, 2021, **50**, 1313–1324.
17 A. Ockenden, L. A. Tremblay, N. Dikareva and K. S. Simon, Towards more ecologically relevant investigations of the impacts of microplastic pollution in freshwater ecosystems, *Sci. Total Environ.*, 2021, **792**, 148507.
18 A. A. Mamun, T. A. E. Prasetya, I. R. Dewi and M. Ahmad, Microplastics in human food chains: Food becoming a threat to health safety, *Sci. Total Environ.*, 2023, **858**, 159834.
19 P. I. Dikobe, M. Tekere, B. Nguegang and V. Masindi, in *Customized Technologies for Sustainable Management of Industrial Wastewater*, 2025, pp. 135–191.

20 X. Sun, T. Wang, B. Chen, A. M. Booth, S. Liu, R. Wang, L. Zhu, X. Zhao, K. Qu and X. Bin, Factors influencing the occurrence and distribution of microplastics in coastal sediments: From source to sink, *J. Hazard. Mater.*, 2021, **410**, 124982.
21 L. Jia, L. Liu, Y. Zhang, W. Fu, X. Liu, Q. Wang, M. Tanveer and L. Huang, Microplastic stress in plants: effects on plant growth and their remediations, *Front. Plant Sci.*, 2023, **14**, 1226484.
22 E. Jeong, J.-Y. Lee and M. Redwan, Animal exposure to microplastics and health effects: A review, *Emerging Contam.*, 2024, **10**, 100369.
23 T. R. Walker, (Micro)plastics and the UN Sustainable Development Goals, *Curr. Opin. Green Sustainable Chem.*, 2021, **30**, 100497.
24 K. Chouchene, J. P. da Costa, M. Chamkha, M. Ksibi and S. Sayadi, Effects of microplastics' physical and chemical properties on aquatic organisms: State-of-the-art and future research trends, *TrAC, Trends Anal. Chem.*, 2023, **166**, 117192.
25 M. A. Fayshal, Current practices of plastic waste management, environmental impacts, and potential alternatives for reducing pollution and improving management, *Heliyon*, 2024, **10**, e40838.
26 S. Padgelwar, A. Nandan and A. K. Mishra, Plastic waste management and current scenario in India: a review, *Int. J. Environ. Anal. Chem.*, 2021, **101**, 1894–1906.
27 A. Rafey and F. Z. Siddiqui, A review of plastic waste management in India – challenges and opportunities, *Int. J. Environ. Anal. Chem.*, 2023, **103**, 3971–3987.
28 S. K. Mallick, M. Pramanik, B. Maity, P. Das and M. Sahana, Plastic waste footprint in the context of COVID-19: Reduction challenges and policy recommendations towards sustainable development goals, *Sci. Total Environ.*, 2021, **796**, 148951.
29 M. G. Kibria, N. I. Masuk, R. Safayet, H. Q. Nguyen and M. Mourshed, Plastic Waste: Challenges and Opportunities to Mitigate Pollution and Effective Management, *Int. J. Environ. Res.*, 2023, **17**, 20.
30 K. Neelavannan and I. S. Sen, Microplastics in Freshwater Ecosystems of India: Current Trends and Future Perspectives, *ACS Omega*, 2023, **8**, 34235–34248.
31 S. Kumar, K. Ajay, D. Behera, A. Yaseen, B. Karthick, S. Prasad, S. U. Bhat, A. Jehangir and A. Anoop, Co-occurrence of microplastics and heavy metals in a freshwater lake system in Indian Himalaya: Distribution and influencing factors, *Emerging Contam.*, 2025, **11**, 100394.
32 S. Zhao, K. F. Kvale, L. Zhu, E. R. Zettler, M. Egger, T. J. Mincer, L. A. Amaral-Zettler, L. Lebreton, H. Niemann, R. Nakajima, M. Thiel, R. P. Bos, L. Galgani and A. Stubbins, The distribution of subsurface microplastics in the ocean, *Nature*, 2025, **641**, 51–61.
33 F. Corradini, F. Casado, V. Leiva, E. Huerta-Lwanga and V. Geissen, Microplastics occurrence and frequency in soils under different land uses on a regional scale, *Sci. Total Environ.*, 2021, **752**, 141917.
34 W. Mei, G. Chen, J. Bao, M. Song, Y. Li and C. Luo, Interactions between microplastics and organic compounds in aquatic environments: A mini review, *Sci. Total Environ.*, 2020, **736**, 139472.
35 V. Kumar, S. P. Rai and O. Singh, Water Quantity and Quality of Mansar Lake Located in the Himalayan Foothills, India, *Lake Reserv. Manag.*, 2006, **22**, 191–198.
36 M. K. Goyal, V. Jain and U. Yadav, in *Monitoring India's Ramsar Wetlands: Water Quality and Ecosystem Health via Remote Sensing and AI*, Springer, 2025, pp. 47–81.
37 P. Semwal, S. Khobragarde, S. K. Joshi and S. Kumar, Variation in δ18O and δ2H values of rainfall, surface water, and groundwater in the Sukhna Lake basin in northwest India, *Environ. Earth Sci.*, 2020, **79**, 535.
38 P. Chardhry, M. P. Sharma, R. Bhargava, S. Kumar and P. J. S. Dadhwal, Water Quality Assessment of Sukhna Lake of Chandigarh City of India, *Hydro Nepal J. Water, Energy Environ.*, 2013, **12**, 26–31.
39 K. Ajay, D. Behera, S. Bhattacharya, P. K. Mishra, Y. Ankit and A. Anoop, Distribution and characteristics of microplastics and phthalate esters from a freshwater lake system in Lesser Himalayas, *Chemosphere*, 2021, **283**, 131132.
40 S. Kumar, D. Behera, K. Ajay, B. Karthick, C. Dharia and A. Anoop, Microplastics and heavy metal contamination along a land-use gradient in a Himalayan foothill river: Prevalence and controlling factors, *J. Contam. Hydrol.*, 2024, **266**, 104411.
41 M. Bulbul, Y. Ankit, S. Basu and A. Anoop, Characterization of sedimentary organic matter and depositional processes in the Mandovi estuary, western India: An integrated lipid biomarker, sedimentological and stable isotope approach, *Appl. Geochem.*, 2021, **131**, 105041.
42 N. Ahmad, S. P. Singh, A. M. Lone, A. Qasim, R. Bhushan, G. R. Tripathy and C. Shah, Historical variations in autochthonous and allochthonous sediment supplies to the largest freshwater lake in Central India, *Int. J. Sediment Res.*, 2022, **37**, 563–575.
43 I. Dimante-Deimantovica, S. Saarni, M. Barone, N. Buhhalko, N. Stivrins, N. Suhareva, W. Tylmann, A. Vianello and J. Vollertsen, Downward migrating microplastics in lake sediments are a tricky indicator for the onset of the Anthropocene, *Sci. Adv.*, 2024, **10**, eadi8136.
44 Y. Zheng, J. Li, W. Cao, F. Jiang, C. Zhao, H. Ding, M. Wang, F. Gao and C. Sun, Vertical distribution of microplastics in bay sediment reflecting effects of sedimentation dynamics and anthropogenic activities, *Mar. Pollut. Bull.*, 2020, **152**, 110885.
45 M. Bulbul, S. Kumar, K. Ajay and A. Anoop, Spatial distribution and characteristics of microplastics and associated contaminants from mid-altitude lake in NW Himalaya, *Chemosphere*, 2023, **326**, 138415.
46 F. Cássio, D. Batista and A. Pradhan, Plastic Interactions with Pollutants and Consequences to Aquatic Ecosystems: What We Know and What We Do Not Know, *Biomolecules*, 2022, **12**, 798.

47 Z. Yuan, R. Nag and E. Cummins, Human health concerns regarding microplastics in the aquatic environment - From marine to food systems, *Sci. Total Environ.*, 2022, **823**, 153730.

48 A. K. Warrier, B. Kulkarni, K. Amrutha, D. Jayaram, G. Valsan and P. Agarwal, Seasonal variations in the abundance and distribution of microplastic particles in the surface waters of a Southern Indian Lake, *Chemosphere*, 2022, **300**, 134556.

49 C. Not, K. Chan, M. W. K. So, W. Lau, L. T.-W. Tang and C. K. H. Cheung, State of microbeads in facial scrubs: persistence and the need for broader regulation, *Environ. Sci. Pollut. Res.*, 2025, **32**, 11063–11071.

50 C. Abisha, R. Kutty, U. R. Gurjar, A. K. Jaiswar, G. Deshmuke, A. Sasidharan and K. A. M. Xavier, Microplastic prevalence, diversity and characteristics in commercially important edible bivalves and gastropods in relation to environmental matrices, *J. Hazard. Mater. Adv.*, 2024, **13**, 100392.

51 S. T. L. Sait, L. Sørensen, S. Kubowicz, K. Vike-Jonas, S. V. Gonzalez, A. G. Asimakopoulos and A. M. Booth, Microplastic fibres from synthetic textiles: Environmental degradation and additive chemical content, *Environ. Pollut.*, 2021, **268**, 115745.

52 J. J. Kurki-Fox, B. A. Doll, B. Monteleone, K. West, G. Putnam, L. Kelleher, S. Krause and U. Schneidewind, Microplastic distribution and characteristics across a large river basin: Insights from the Neuse River in North Carolina, USA, *Sci. Total Environ.*, 2023, **878**, 162940.

53 T. L. Jolaosho, M. F. Rasaq, E. V. Omotoye, O. V. Araomo, O. S. Adekoya, O. Y. Abolaji and J. J. Hungbo, Microplastics in freshwater and marine ecosystems: Occurrence, characterization, sources, distribution dynamics, fate, transport processes, potential mitigation strategies, and policy interventions, *Ecotoxicol. Environ. Saf.*, 2025, **294**, 118036.

54 T. K. Dey, M. E. Uddin and M. Jamal, Detection and removal of microplastics in wastewater: evolution and impact, *Environ. Sci. Pollut. Res.*, 2021, **28**, 16925–16947.

55 X. Guo, H. Dai and L. He, Migration testing of microplastics from selected water and food containers by Raman microscopy, *J. Hazard. Mater.*, 2024, **462**, 132798.

56 V. Prakash Ranjan, A. Joseph, S. Srivastava, H. Bhakta Sharma, B. Biswas, S. Goel and S. Kumar, From cosmetics to Contamination: Microplastics in personal care products as vectors for chromium in aquatic environments, *Waste Manag. Bull.*, 2024, **2**, 229–240.

57 D. Pamucar, V. Simic, S. Dabic-Miletic, A. A. Zaidan, N. Petrović and S. Narayanamoorthy, Sustainable management of polyethylene terephthalate waste flow using a fuzzy frank weighted assessment model, *Eng. Appl. Artif. Intell.*, 2024, **138**, 109254.

58 N. Ahmad, S. P. Singh, S. Sahu, R. Bhattacharyya, A. S. Maurya, N. Kumar, R. K. Rout and G. R. Tripathy, Isotopic evidence of autochthonous organic matter acting as a major sink of anthropogenic heavy metals in modern lacustrine sediments, *Environ. Pollut.*, 2024, **349**, 123964.

59 K. Yu, Y. Zhang, X. He, Z. Zhao, M. Zhang, Y. Chen, X. Lang and Y. Wang, Characteristics and environmental significance of organic carbon in sediments from Taihu Lake, China, *Ecol. Indic.*, 2022, **138**, 108796.

60 K. L. Reinl, T. D. Harris, I. Elfferich, A. Coker, Q. Zhan, L. N. De Senerpont Domis, A. M. Morales-Williams, R. Bhattacharya, H.-P. Grossart, R. L. North and J. N. Sweetman, The role of organic nutrients in structuring freshwater phytoplankton communities in a rapidly changing world, *Water Res.*, 2022, **219**, 118573.

61 L. Duan, L. Luo, L. Zhang, D. Li, H. Li, T. Xu, J. Xu and H. Zhang, The Occurrence of Microplastics Pollution in the Surface Water and Sediment of Lake Chenghai in Southwestern China, *Water*, 2024, **16**, 2672.

62 S. Sajad, B. K. Allam, A. Debnath, P. Bangotra and S. Banerjee, Pollution status of microplastics in the sediments of warm monomictic Dal lake, India: Abundance, composition, and risk assessment, *Environ. Pollut.*, 2024, **363**, 125247.

63 K. Gopinath, S. Seshachalam, K. Neelavannan, V. Anburaj, M. Rachel, S. Ravi, M. Bharath and H. Achyuthan, Quantification of microplastic in Red Hills Lake of Chennai city, Tamil Nadu, India, *Environ. Sci. Pollut. Res.*, 2020, **27**, 33297–33306.

64 T. Immanuvel David, M. S. Sheela, S. Krishnakumar, A. Muhammed Siyad, A. Abimanyu, V. K. Vikasini, T. Monisha and S. Dineshbabu, Distribution and characterization of microplastics and ecological risks in Vellayani Lake, Kerala, India, *Total Environ. Res. Themes.*, 2023, **7**, 100065.

65 Y. Jain, H. Govindasamy, G. Kaur, N. Ajith, K. Ramasamy, R. R. S and P. Ramachandran, Microplastic pollution in high-altitude Nainital lake, Uttarakhand, India, *Environ. Pollut.*, 2024, **346**, 123598.

66 A. Yaseen, S. ul Islam, K. Ajay, S. U. Bhat, A. Jehangir and A. Ambili, Microplastic contamination in environmental matrices of multi-basin Dal Lake, Kashmir, *Sci. Total Environ.*, 2025, **1005**, 180825.

67 N. Malygina, E. Mitrofanova, N. Kuryatnikova, R. Biryukov, D. Zolotov, D. Pershin and D. Chernykh, Microplastic Pollution in the Surface Waters from Plain and Mountainous Lakes in Siberia, Russia, *Water*, 2021, **13**, 2287.

68 Q. Zhang, T. Liu, L. Liu, Y. Fan, W. Rao, J. Zheng and X. Qian, Distribution and sedimentation of microplastics in Taihu Lake, *Sci. Total Environ.*, 2021, **795**, 148745.

69 M. Manik, M. T. Hossain and P. Pastorino, Characterization and risk assessment of microplastics pollution in Mohamaya Lake, Bangladesh, *J. Contam. Hydrol.*, 2025, **269**, 104487.

70 B. Wang, J. Lu, L. Wang, J. Xiao, G. Liu, Y. Chai and X. Li, Distribution characteristics, source analysis, and ecological risk assessment of microplastics in Ulungur Lake, China, *J. Contam. Hydrol.*, 2026, **276**, 104747.

71 E. Hengstmann, E. Weil, P. C. Wallbott, M. Tamminga and E. K. Fischer, Microplastics in lakeshore and lakebed sediments – External influences and temporal and spatial variabilities of concentrations, *Environ. Res.*, 2021, **197**, 111141.