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Microplastic occurrence and densities in small subtropical reservoirs of Southern Africa

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Abstract

Microplastics (MPs) pollution is now a global concern and particles have been detected in various aquatic environments and their associated biota including in humans. Its only recent that research in MPs have gain a better understanding of MPs sources, transportation and sink including potential impacts. To further contribute to the growing body of literature, this study aims to quantify and enumerate seasonal MPs densities and characteristics in sediments and surface water samples in small subtropical reservoirs associated with different landscape and human activities. Moreover, the study not only quantified and characterised MPs but further assessed the risk of MPs contamination using pollution load indices. High MPs densities were found during the dry season in sediments (84.74–374.76 particles/kg^{-1} dwt) and surface water (6.07–21.77 particles/100^{-1} L), in comparison with low densities in the wet season i.e. sediments (68.72–260.87 particles/kg^{-1} dwt) and surface water (7.33–19.27 particles/100^{-1} L). White (43.1%) and transparent (38.4%) colours were the most dominant in sediments and surface water samples, respectively. In terms of MPs shapes and polymer types, fibres and polyethylene (PE) were the most dominate for sediments and surface water. Moreover, no correlative relationships were observed for tested water quality parameters and MPs densities within and between reservoirs and seasons. MPs pollution indices indicated high pollution levels in reservoirs associated with high human activities, indicating a source-driven effect of anthropogenic activities on MPs contamination. This study contributes to understanding the seasonal variations in MPs occurrence and characteristics in small subtropical reservoirs. Additionally, the study establishes a benchmark for future plastic pollution control and management efforts in South African small reservoirs, since if left unattended MPs pollution could escalate and pose significant environmental risks in the future.

Keywords Standing water bodies · Microplastic contamination · Source-sink · Anthropogenic activities · Plastic debris

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1 Introduction

Microplastics (MPs), defined as plastic particles smaller than 5 mm, have emerged as a significant environmental concern globally, particularly in aquatic ecosystems [26]. As an emerging pollutant, MPs have attracted much attention in recent years [3, 29], since the first discovery of MPs by Carpenter and Smith [9]. The poor management of plastic waste and domestic wastewater in general has led to the widespread and release of plastics into the environment, which further degrades into smaller particles, forming MPs contamination [8, 72]. These particles originate from various sources, including the degradation of larger plastic debris, industrial processes, and consumer products such as cosmetics and clothing [7, 65]. Once introduced into the environment, these particles can be transported to aquatic ecosystems [42, 62], especially freshwater systems, through various pathways, including stormwater runoff and treated and untreated domestic wastewater [37, 38] from urban and rural areas [20, 41], agricultural activities [49], and atmospheric deposition [55].

In freshwater environments, depending on physical characteristics including season, river flow and available habitats, MPs accumulate in the water column and later settle on the sediments, which act as temporary sinks depending on MPs specific characteristics [1, 17, 61]. Rivers in most cases transport MPs further down rivers and MPs will start to build-up in dams, reservoirs, lakes including the marine environments with both the former and the latter well known as MPs sink [24]. Their presence in water and sediments disrupts aquatic habitats, by altering species composition, reduces biodiversity and become transport agents for harmful metals and other contaminants [5, 48]. In sediments, MPs can alter the physical properties of the substrate, affecting the development of phytoplankton and periphyton communities and thus affecting important ecosystem processes including photosynthesis, nutrient cycling and herbivory by aquatic invertebrates [4, 21]. In water, these particles can be ingested by various aquatic species, potentially leading to physical harm, reduced physiological fitness, growth and leading to mortality [18, 64]. Through the food chain, these MPs can accumulate in higher trophic level organisms, ultimately posing risks to human health by exposing consumers to toxic chemicals associated with these particles [44, 67].

Freshwater ecosystems are mostly associated with high population density and intensive human activities and there is a growing body of literature contributing to the better understanding of MPs pollution in different landscapes and aquatic ecosystems [56]. MPs levels in these ecosystems can also be seasonally influenced by various factors such as rainfall, runoff, and water flow dynamics [51, 68]. Although global research on MPs in freshwater systems is increasing, there remains a substantial gap in data regarding their detection, quantification and standardised methodologies across studies and regions. More studies are required in order to develop standardized models to advance understanding, improve risk assessments, and inform management strategies for mitigating the effects of MPs in freshwater ecosystems. Dalu et al. [16] made an attempt to assess the risk of MPs in South Africa, however, further studies are needed to support local municipalities and stakeholders in developing effective management strategies to address MPs pollution.

MPs in freshwater reservoirs are primarily influenced by local sources. These pollutants significantly impact aquatic ecosystems, disrupting biodiversity and ecological balance. Additionally, they pose potential risks to human health through water contamination [54]. As such, the current study is among the few studies to investigate MPs pollution in small subtropical reservoirs associated with different levels of human activities in South Africa [14, 36]. Specifically, we (*i*) investigated MPs occurrence, characteristics (colours, shapes, and polymer types), (*ii*) assessed the level of MPs pollution using the pollution load indices and (*iii*) tested seasonal variation (dry and wet) in MPs densities. Specifically, we hypothesised that reservoirs associated with high human activity would exhibit greater MPs densities, particularly during the dry season when there is reduced water flow and MPs settled from different sources and pathways [23]. Additionally, we anticipate a diversity of MPs characteristics due to differences in anthropogenic activities, with reservoirs experiencing high human activity expected to show greater MPs pollution loads. Additionally, we predict that water quality parameters would have minimal influence on MPs densities and that seasonality will be main driver. This study will contribute insight on the existing body of literature on MPs occurrence and dynamics in South Africa in support of more advance models i.e. machine learning that could be developed in the future to trace and track MPs pollution in freshwater systems with associated land use activities and thus develop mitigation strategies and increasing public awareness to reduce plastic pollution.

2 Material and methods

2.1 Study area

The study was conducted in four reservoirs across two sampling seasons i.e., dry (October 2023) and wet (April 2024). Two reservoirs, Reservoir 1: 22° 59′ 24.8" S, 30°25′ 15.2" E and Reservoir 2: 23° 00′ 26.8" S, 30° 24′ 34.6" E (hereafter referred to as H1–H2) were associated with high human activities (i.e. irrigation, fishing, and domestic activities including laundry, swimming, bathing), which were located in densely populated formal and informal settlements in Shayandima village, Limpopo Province (Fig. 1). In contrast, the other two reservoirs Reservoir 3: 23° 03′ 45.5″ S, 30° 20′ 06.1″ E and Reservoir 4: 23° 06′ 54.7″ S, 30°15′ 46.7″ E (also hereafter referred to as L1–L2), were located within agricultural area (rural setting) with low population density and only exposed to activities such as irrigation and fishing near Tshakhuma village, also in Limpopo Province, South Africa. All four reservoirs are impounded freshwater streams, within the Vhembe District Municipality, which includes Thohoyandou. The region has annual rainfall range of approximately 400–800 mm, with the highest precipitation occurring between November and April. Daily maximum temperatures frequently exceed 35 °C in summer (October–March) and the average annual temperature is 26 °C [10].

At each sampling occasion (wet and dry season), all sampling equipment were washed and rinsed with distilled water five times and immediately wrapped with an aluminium foil to prevent contamination. Prior sediments and surface water sample collection, selected water quality parameters were first measured including water temperature (°C), pH, conductivity ($\mu S \cdot cm^{-1}$) and total dissolved solids ($mg \cdot L^{-1}$) using a multi-parameter handheld waterproof Cyber Scan 300 (EuTech Instruments, Singapore). Thereafter, sediment samples were collected along five demarcated plots using a steel hand shovel around the reservoir's shoreline, between depth of 5–10 cm (see [77]), making up ~ 1 kg sample × 5 replicates = 5 kg total sediment sample for each sampling season. After collection, large debris (stones, plant or waste material of > 2 mm size) were manually removed from the sediments samples to allow efficient MPs processing and

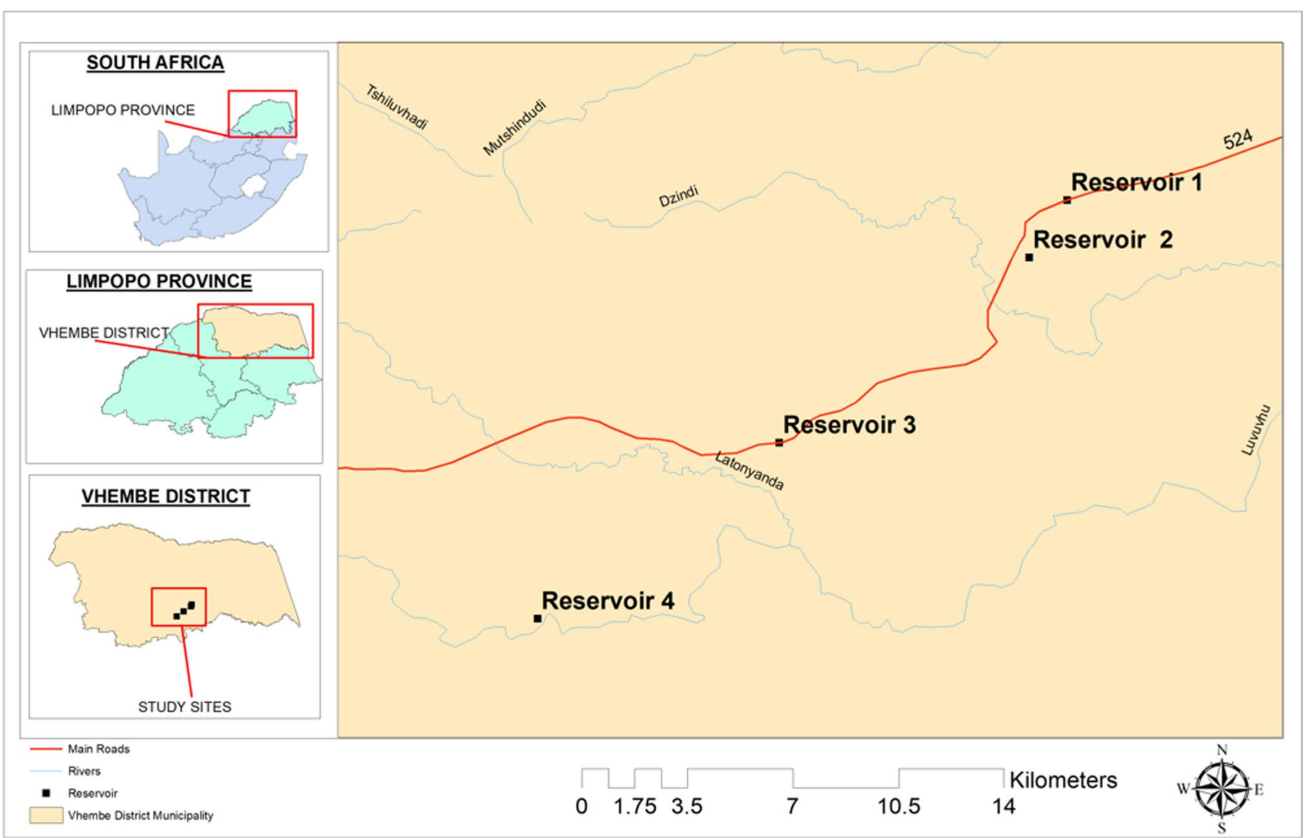

Fig. 1 Location of four study sites where MPs samples were collected. Reservoirs 1 and 2 – high human activities (H1–H2); Reservoirs 3 and 4 – low human activities (L1–L2) in Limpopo province, South Africa

treatment in the laboratory [34]. Thereafter, sediment samples (in replicates) were placed in aluminium foil and transported to the laboratory for further analysis.

Surface water samples (100 L) were collected following a bulk method by Prata et al. [43], where a 25 L stainless bucket was used to collect surface water at a depth of 0–5 cm from the water surface and the water sample passed through two stainless-steel sieves (Whatman®, Sigma-Aldrich, St. Louis, MO, USA) with a mesh size of 5 mm and 63 µm, respectively. The material remaining on the 5 mm sieve were discarded, and only samples on the 63 µm mesh sieve were rinsed and transferred into a 500 ml glass beaker for further analysis in the laboratory.

2.2 Sample extraction

In the laboratory, sediments were left to dry for 24 hrs and then homogenized, thereafter, divided into 500 g sub-sample (n = 3 per site per season) which were then oven dried at 50 °C for 48 hrs for sediment dry weight determination and MPs analysis. Each subsample was treated by adding 500 ml of a hypersaline solution (700 g L^{-1}, density 1.6 g cm^{-3}) for density separation following Mbedzi et al. [35]'s procedure. Thereafter, the solution was stirred for six minutes and left to settle for 1 hr. The resulting supernatant was collected and kept in a glass beaker. For each replicate, the process was repeated 6 times to effectively remove and sample available MPs on sediments samples and avoid under representation [35]. The resulting "extracted MPs samples" were further treated with 30% H_2O_2 to eliminate available organic material in the sample over a 24 hrs period, and the sample passed through a 63 µm mesh sieve. The material on the sieve was covered with aluminium foil to prevent contamination where the samples were left to oven dry at 50 °C for 48 hrs followed by MPs identification, classification and enumeration.

For the surface water samples, 40 ml of 30% H_2O_2 was added to the sample, and then homogenised by stirring and allowed to react and settle overnight to digest natural organic materials prior MPs analysis. Treated surface water samples were thereafter treated with 100 ml of NaCl solution and again homogenised by stirring for 6 min to separate plastic and non-plastic materials. The sample was then left for 24 hrs, and similar to the sediment samples, the surface water supernatant after NaCl solution treatment was then filtered through a 63 µm mesh sieve. The mesh sieve containing MPs was stored in labelled petri dishes, oven dried at 50 °C for 48 hrs and later MPs identification, classification and enumeration was done in the laboratory.

2.3 MP identification, classification and enumeration

The retained MPs for sediments and surface waters were classified and enumerated using a dissecting microscope at X50 magnifications following Ribeiro et al. [50]. The current study considered MPs particles between 5 mm and 63 µm sizes, with shape i.e. identified and classified as fibre (fibre/filament), pellet, film, fragment and foam [13] together with colour [25] were observed and noted during identifications. The colours, shapes, and polymer types of MPs found were combined across reservoirs and seasons and presented as an overall proportion (%).

To identify MPs polymer types, a representative sample (30–40%) of MPs particles > 500 µm size were selected on each sample and season. Selected MPs particles were manually isolated and analysed by using a vibrational Platinum-ATR Fourier-transform infrared spectroscopy (FT-IR) (Bruker Alpha model, Germany). The technique covered a wide spectral range of 400–3200 cm^{-1}, with a resolution of 8 cm^{-1}, and conducted 16 scans per analysis. Prior to each sample analysis, background scans were performed, and the ATR crystal was cleaned with 70% propanol solution [11]. MPs particles spectra were compared to the polymer data banks i.e. Hummel Polymer Sample Library, HR polymer Additives and Plasticizers, HR Hummel Polymers and Additives, and Synthetic Fibres by Microscope and a matching degree of > 75% between the samples and standard spectra were considered acceptable [12].

2.4 Quality control

To prevent the samples from being contaminated by plastic products in the laboratory [22], the following measures were followed. To minimize contamination with airborne MPs, nitrile glover, nontextile lab coats, stainless steel buckets, glass and aluminium were used during samples collection, pre-treatment and laboratory processes. All solutions used during the extraction process were prepared with ultrapure water. In the laboratory, a lamina-flow controlled unit was used when treating collected samples and when filtering. Additionally, wet filters with distilled water were placed at every station in the laboratory during the sample analysis including next to the microscope, inside the oven and on the bench. Filters were then examined under a microscope and no MPs contamination was found.

3 Data analysis

To evaluate the MPs pollution level, contamination factor (CF) and pollution load index (PLI) were calculated. The CF and PLI indices were determined following Eqs. (1) and (2) respectively, as described by Tomlinson et al. [59] and Xu et al. [70] and recently applied by [27].

$$CF_i = \frac{C_i}{C_{oi}} \tag{1}$$

Here, CF_i denotes the MPs contamination factor, which is calculated as the ratio of C_i (MPs abundance at a specific site) to Co_i (lowest MPs abundance observed, used as the background concentration in this study). Were, CF values of < 1 denotes low contamination, between 1 and 3 moderate contamination and 3–6 high and > 6 very high [46]. On the other hand, the PLI is derived from CF and is defined as follows:

$$PLI = \sqrt{CF_i} \tag{2}$$

Where PLI represents the pollution load index for each site and as described above, Cf_i – MPs contamination factor. A PLI value of greater than 1 indicates a MPs contaminate and polluted site, and with an increase is PLV value denotes the degree of contamination.

To test for significant difference between water quality parameters, MPs densities and other indices, a two-way analysis of variance (ANOVA) was used, were reservoirs and seasons were factors. This was after the variances were homogeneity (Levene's test, $p < 0.05$) and the data normally distributed (Shapiro–Wilk test, $p > 0.05$). Additionally, a post-hoc Tukey multiple comparison test was performed to identify which season and site were significant. Pearson rank correlation was used to investigate the relationships between different water quality parameters, sediment and surface water MPs particles.

4 Results

4.1 Water quality parameters

Pearson correlation analysis revealed no significant relationship between temperature, pH, conductivity, TDS, and MPs densities found in sediment and surface water samples ($p > 0.05$). This further supports the null hypothesis, indicating that water quality parameters were not correlated to MPs density, but seasonality was more important. Majority of the water quality parameters were found to be similar between the two seasons, with pH ($F = 1.050$; df = 1; $p = 0.014$) showing significance difference (Table 1). However, Temperature ($F = 14.109$; df = 3; $p < 0.001$), pH ($F = 5.894$; df = 3; $p = 0.007$), and conductivity ($F = 5.698$; df = 3; $p = 0.008$) were found to be significantly different between the study reservoirs, whereas TDS was not different ($F = 0.812$; df = 3; $p = 0.506$). In general, high temperature (28.93 °C), conductivity (393.93 μS·cm $^{-1}$) and TDS (176.0 mg·L^{-1}) were observed in reservoirs associated with low human activities during the wet season, same goes for pH (8.0) during the dry season. The interaction between Reservoir x Season was not significant for all water quality parameters (Table 1).

Table 1 Two-way analysis of variance (ANOVA) based on water quality parameters measured across reservoirs and seasons

Variables	Reservoir		Season		Reservoir x Season	
	F	*P*	F	*P*	F	*P*
Temperature	**14.109**	**< 0.000**	3.461	0.081	2.906	0.067
pH	**5.894**	**0.007**	**1.050**	**0.014**	2.392	0.107
Conductivity	**5.698**	**0.008**	7.634	0.679	0.156	0.924
TDS	0.812	0.506	0.177	0.321	1.020	0.410

Bold values indicate significant differences at $p < 0.05$. *TDS* total dissolved solids

4.2 MP in sediments and surface waters

MPs were found in all sediment samples across reservoirs and seasons, with an average range of 68.72 ± 4.52 (wet season) to 374.76 ± 130.40 (dry season) particles/kg^{-1} dwt and an overall average of 182.03 ± 24.76 particles/kg^{-1} dwt (Fig. 2a, c). The highest MPs densities of 374.76 ± 130.40 particles/kg^{-1} dwt were found in Reservoir 1 (H1) during the dry season, whilst the lowest densities of 68.72 ± 4.52 particles/kg^{-1} dwt were found in Reservoir 4 (L2) during the wet season (Fig. 2). According to ANOVA, significant differences were observed between MPs across reservoirs (ANOVA: $F = 8.055$; $df = 3$; $p = 0.002$), and the pairwise multiple comparison test highlighted significant differences in MPs densities between H1 *vs* L4 ($F = 8.055$; $df = 3$; $p = 0.009$), H2 *vs* L3 ($F = 8.055$; $df = 3$; $p = 0.031$), and H2 *vs* L4 ($F = 8.055$; $df = 3$; $p < 0.001$).

Similarly, MPs were also found in all surface water samples across reservoirs and seasons with an overall average of 13.97 ± 1.30 particles/100^{-1} L, ranging between 6.07 ± 0.50 (wet season) to 21.77 ± 2.02 particles/100^{-1} L (Fig. 2b, d). When comparing all reservoirs, the highest MPs densities 21.77 ± 2.02 particles/100^{-1} L were found at Reservoir 2 (H2) during the dry season, whilst the lowest MPs densities 6.07 ± 0.50 particles/100^{-1} L were found at Reservoir 4 (L2) during the wet season (Fig. 2). According to ANOVA, there were significant differences in MPs between reservoirs (ANOVA: $F = 11.362$; $df = 3$; $p < 0.001$), whilst seasons indicated no significant differences (ANOVA: $F = 0.001$; $df = 1$; $p = 0.989$). Pairwise multiple comparison tests highlighted significance differences in MPs densities between H1 *vs* L3 ($F = 11.362$; $df = 3$; $p = 0.017$), H1 *vs* L4 ($F = 11.362$; $df = 3$; $p = 0.002$) and H2 *vs* L4 ($F = 11.362$; $df = 3$; $p = 0.026$).

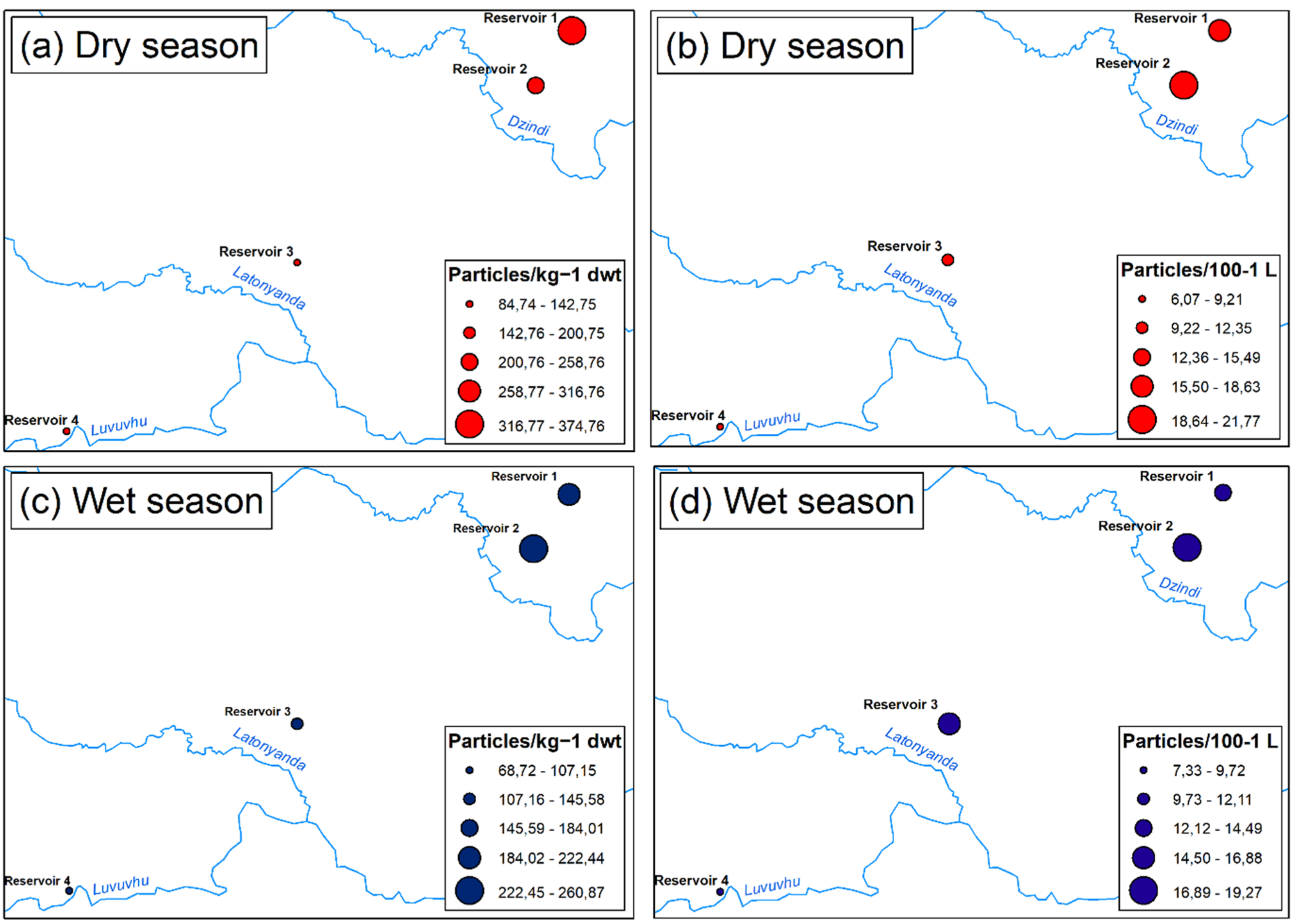

Fig. 2 Distribution map of MPs densities in sediments (**a**, **c**) and surface waters (**b**, **d**) across four reservoirs in Limpopo, South Africa. Reservoirs 1 and 2 – high human activities (H1–H2); Reservoirs 3 and 4 – low human activities (L1–L2)

4.3 MP classification and type

In terms of colours, white and transparent were found to be the most dominant colours in sediments and water, respectively (Fig. 3). In sediment samples, white colour accounted for 43.1% of the total MPs count across the two seasons, followed by transparent (20.1%), blue (19.0%), black (9.2%), red (5.2%), yellow (2.1%) and green (1.3%) (Fig. 3a). In contrast, for surface water samples, transparent accounted for 38.4% of the total MPs count, followed by blue (27.9%), white (21.3%), black (5.2%), green (4.3%), others (1.7%) and red (1.2%) (Fig. 3b).

MPs particles found during the study also exhibited diverse shapes and polymer types (Fig. 4a). The most representative shapes were fibres and fragments, with fibres predominating across reservoirs and seasons (70.4% sediment and 91.2% water) (Fig. 4a, b). Fragment was the second most abundant shape found, 22.7% in sediment and 6.4% in surface water, followed by pellet with 4% in sediment and 0.4% in surface water, then foam which was only recorded in sediments (2%), and film with only 0.9% in sediment and 2% in surface water (Fig. 4). Following the ATF-FTIR analysis, MPs particles from sediment were made up of polyethylene (47.3%; PE) and polypropylene (27.2%; PP) (Fig. 4c). The other ~ 25% were made up of polystyrene (12.2%; PS), polyethylene terephthalate (6%; PET), polydimethylsiloxane (5.7%; PDMS), and high-density polyethylene (1.6%; HDPE) (Fig. 4). Surface water MPs particles were less diverse when compared to sediments samples and only made up of PE (61.2%), PP (27%), PS (10.1%), and PET (1.7%) (Fig. 4d).

5 MP pollution and contamination indices

The MPs contamination factor (CF) values ranged from 1 (risk category – low) for Reservoir 4 (L2) to 5.4 (risk category – high) for Reservoir 1 (H1) for sediments samples, then 1 (risk category – low) at Reservoir 4 (L2) to 3.59 (risk category – high) at Reservoir 2 (H2) for surface waters (Fig. 5). On the other hand, the pollution load index (PLI) values ranged from < 1 indicating no pollution for Reservoir 4 (L2) to 2.3 which was > 1, indicating pollution at Reservoir 1 (H1) for sediments, this was the same as in sediments samples were Reservoir 4 (L2) for surface water showed no pollution (< 1) but different for Reservoir 2 (H2) which was > 1 indicating pollution for surface waters (Fig. 5). Overall, while most reservoirs showed moderate levels of pollution, Reservoir 1 (H1) and 2 (H2) are the most impacted, with seasonal variations in contamination levels ($p < 0.05$), thus in agreement with our hypothesis.

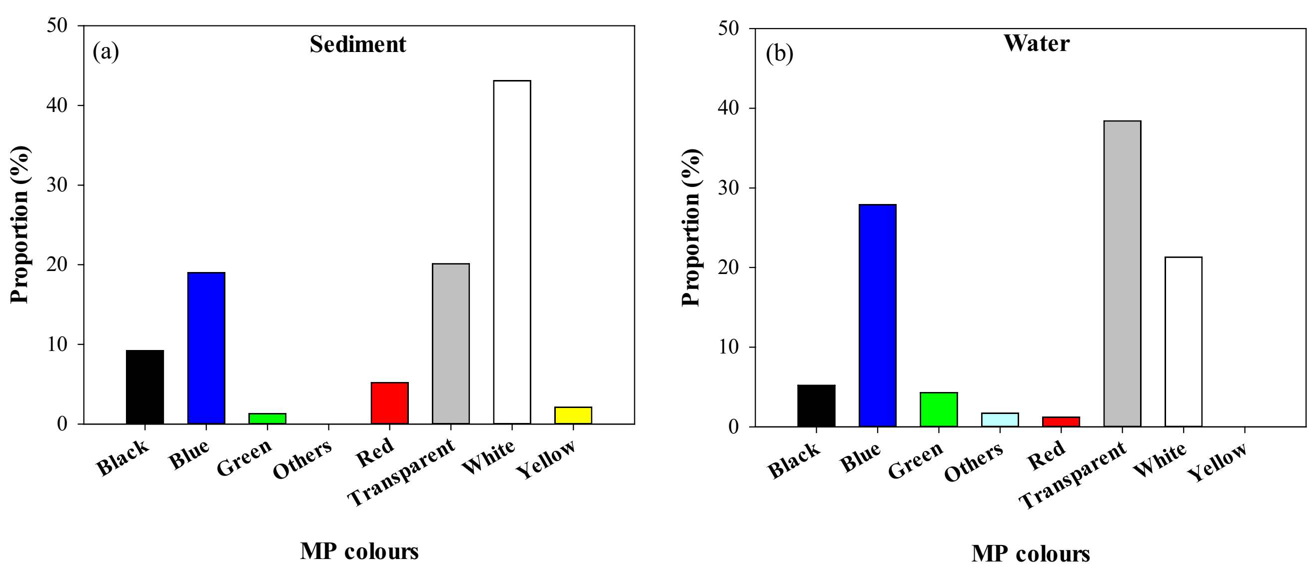

Fig. 3 The overall proportion (%) of MPs colours found in **a** sediments and **b** surface waters from four small reservoirs in Limpopo, South Africa

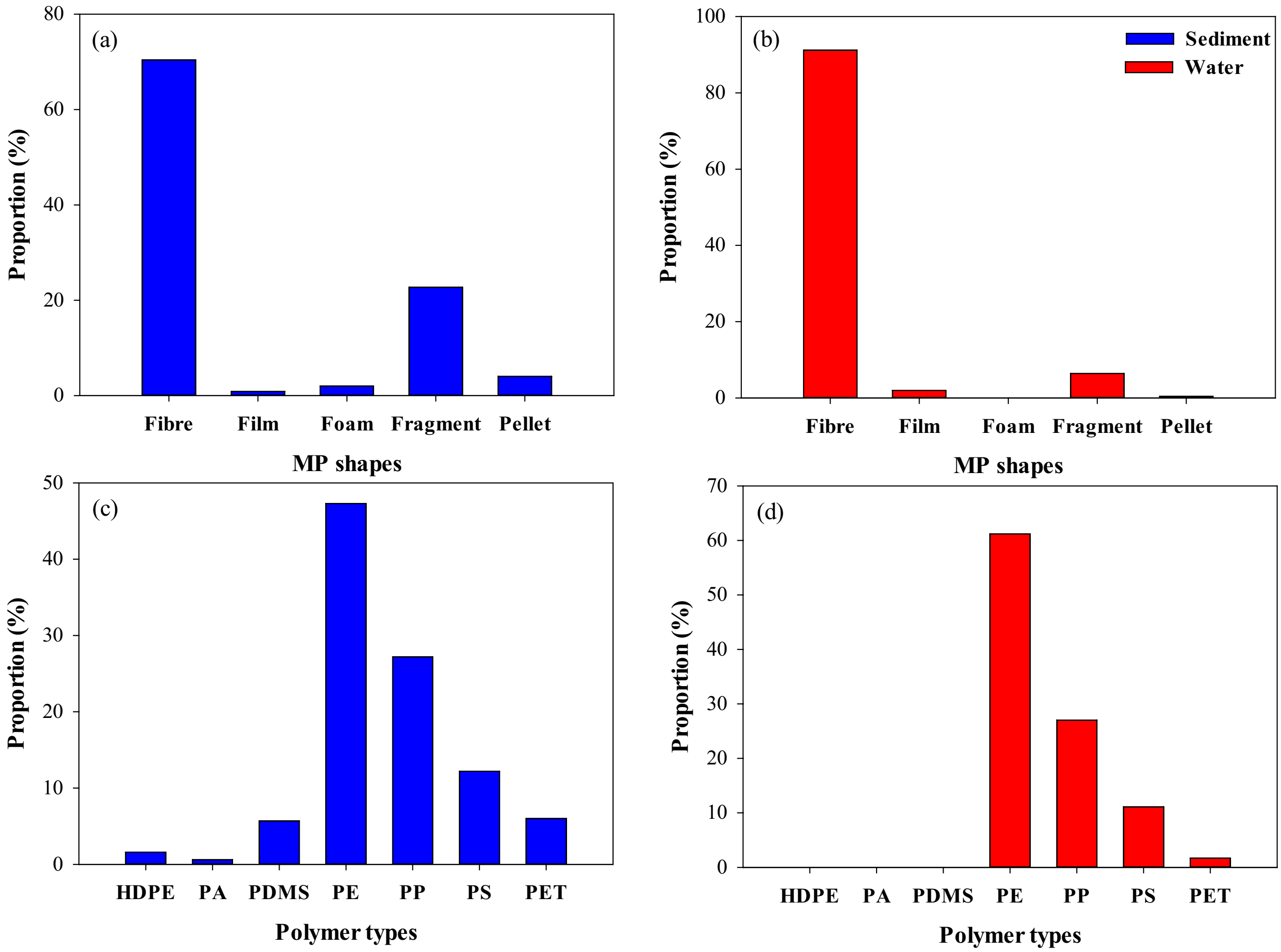

Fig. 4 The overall proportion (%) of MPs shapes and polymer types found in sediments (**a**, **c**) and surface waters (**b**, **d**) from four small reservoirs in Limpopo, South Africa.

6 Discussion

The study aimed to investigate MPs occurrence and characteristics in small subtropical reservoirs associated with low and high human activities, using MPs pollution and contamination indices between seasons. Despite the growing global focus on MPs pollution, there remains a significant research gap concerning the occurrence, characteristics, and ecological implications of MPs in freshwater environments in the Global South, including South Africa, particularly in the rural settling where freshwater systems are heavily used for domestic purposes and for local economic opportunities [36]. In the present study, we found MPs in both sediments and surface waters and our findings supported our hypothesis that high human activities and season will be the main driver of MPs densities and pollution indices. Reservoirs with high human activities were found to be vulnerable to MPs contamination as further indicated by MPs pollution load indices and that seasons influenced MPs densities. MPs classification in terms of colours, shapes and polymer types, highlighted diverse sources and complex pathways of MPs pollution within our study areas, thus emphasising that even in rural setting MPs will remain a biggest challenge when it comes to freshwater contamination and management. Most abiotic variables differed significantly across reservoirs, and we also observed no significant correlations between MPs densities and measured water quality parameters. This lack of correlation suggests that MPs pollution is prevalent and not influenced by the immediate environmental factors commonly used to assess water quality health. But MPs are mostly driven by land-use, anthropogenic activities and seasonal differences. However, reservoirs with largely modified water quality parameters i.e. high TDS and EC also were observed to have high MPs and thus indicative of high human activities. Such results indicate that MPs are entering these ecosystems through

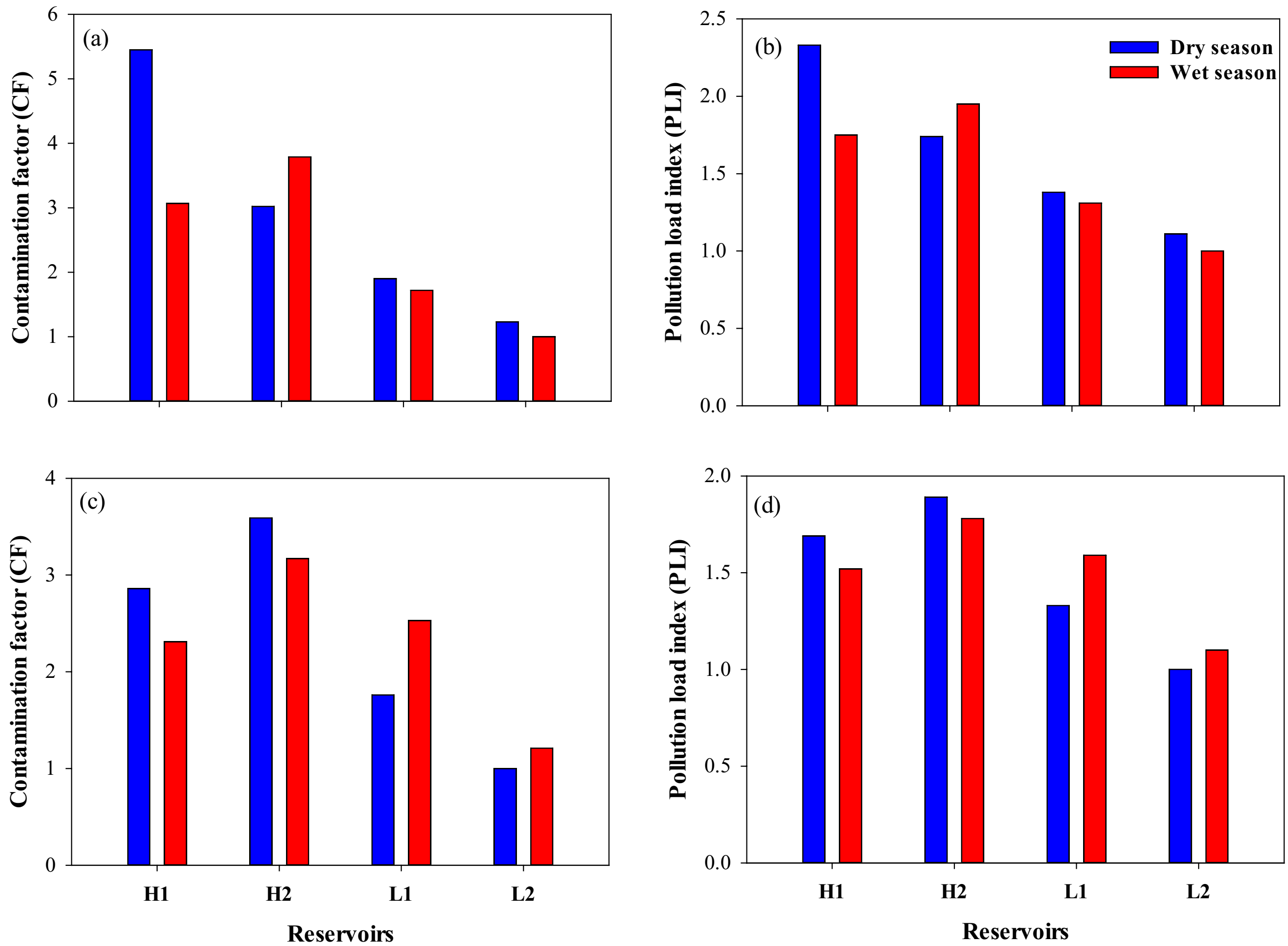

Fig. 5 The contamination factor (CF) and Pollution load index (PLI) values for sediments (**a**, **c**) and surface waters (**b**, **d**) across reservoirs and seasons in Limpopo, South Africa

Table 2 Literature on the seasonal densities of MPs in reservoirs sediments and surface waters samples

Location	Sample type	Season	Separation method	MP Found	References
Nandoni Reservoir, South Africa	Sediment	Hot-dry Hot-wet	Density separation	224.1 ± 151.5 particles/kg^{-1} 189 ± 135.5 particles/kg^{-1}	[57]
Nandoni Reservoir, South Africa	Sediment	Hot-dry Hot-wet	Density separation	120–6417 particles/kg^{-1} dwt 5–94 particles/kg^{-1} dwt	[35]
Recreational reservoirs, South Africa	Sediment	Dry Wet	Density separation	3.1–140.6 particles/kg^{-1} dwt 22.6–97.8 particles/kg^{-1} dwt	[39]
Subtropical reservoirs, South Africa	Sediment	Dry Wet	Density separation	84.74–374.76 particles/kg^{-1} dwt 68.72–260.87 particles/kg^{-1} dwt	Current study
Dau Tieng Reservoir, Vietnam	Water	Dry Wet	Sieving and filtration	4.36 ± 1.71 items m^{-3} 3.57 ± 0.95 items m^{-3}	[60]
Subtropical reservoirs, South Africa	Water	Dry Wet	Density separation	6.07–21.77 particles/100^{-1} L 7.33–19.27 particles/100^{-1} L	Current study
Tri An Reservoir, Vietnam	Water	Dry Wet	Sieving and filtration	6.42 items m^{-3} 2.36 items m^{-3}	[60]

a variety of sources and some source may not be associated with poor water quality but seasonal weather/climate difference and accumulation.

MPs densities found in the current study showed a seasonal variation, with the highest MPs for both sediments and surface waters being observed during the dry season. According to Xu et al. [71] and Klein et al. [30], MPs tend to accumulate more during drier seasons after the rainy season which is associated with storm water drainage and landscape transporting and degrading MPs from terrestrial into aquatic systems, particularly from rivers to dams and reservoirs. During dry season, with less flow and increased evaporation rates, MPs now settles and accumulate in the sediments but some still found on the surface water [33]. As a result, dry season are also regarded as a temporary sink for MPs due to reduced water flow, which limits MPs transport, and increased sedimentation rates, allowing MPs to settle and accumulate in the sediment layers [69]. This accumulation further explains the higher densities of MPs in surface waters during the dry season in the current study, as MPs tend to behave differently under varying physical conditions, in wet seasons, higher water flow disperses and flushes MPs downstream, reducing local concentrations [69]. Compared with findings from other studies, our findings were consistent with Mbedzi et al. [35], Mutshekwa et al. [39], and Themba et al. [57] who also found the highest MPs in sediment during drier season in South African subtropical reservoirs (Table S1). MPs densities found in surface waters across reservoirs and seasons were also consistent with findings by Truong et al. [60] in the Dau Tieng and Tri An reservoir (see Table 2). We also observed, human activities such as recreation and domestic water use near reservoirs often intensify during the dry season, thus contributing to higher MPs inputs. This was further supported by pollution load indices, were CF and PLI revealed that reservoirs with high human activity were heavily polluted and contaminated with MPs for on both the sediment and surface water, with a clear seasonal variation. Additionally, seasonality further influenced pollution levels, with the dry season showing higher pollution load and contamination as compared to the wet season, which was expected and consistent with other findings including that of Huang et al. [27] recently. The human influence and seasonal trends emphasize the need for targeted monitoring and mitigation strategies that will help address the heightened accumulation of MPs, bearing in mind the different MPs sources i.e. primary versus secondary sources.

MPs particles from the current study showed diverse characteristics including colours, shapes and polymer types. As indicated by Rodríguez-Seijo and Pereira [52], MPs characteristics are essential for identifying potential origins/sources of MPs. White MPs particles, fibres, and PE were the most dominant in sediment samples, consistent with findings from other studies assessing MPs in sediments (see [53, 63, 66]). From the surface water samples, transparent particles, fibres and PE were dominant. These materials are lightweight, durable, and resistant to environmental degradation, leading to their persistence in the water column and transported widely within the aquatic environment far away from their sources and accumulate over time [73, 75].

White MPs particles found on sediments are normally derived from consumer products such as personal care items, packaging, and synthetic textiles thus are persisted throughout aquatic systems particularly near areas associated with human settlement [6]. Transparent particles, as noted by Mvovo [40], are likely derived from MPs products including plastic containers, beverage packaging, and bags, which typically have a shorter lifespan. However, it is worth noting that some plastic products may change colour to white and transparent due to degradation processes overtime, thus making colourless and transparent MPs particles overlooked during identification and mistakenly classified as white [52]. Fibres found in the current study could have originated from synthetic textiles such as clothing, nets, and agricultural equipment [15]. For instance, the reservoirs associated with high human activities are mostly used for laundry (or washing) and fishing. Moreover, these reservoirs are subjected to runoff, waste disposal and direct contamination from the landscape. Whereas reservoirs exposed to low human activities were subjected to fibres from agricultural fabrics like shade nets or crop covers [19]. MPs particles like fragments found in this study are likely a result of degradation of larger plastic items, such as plastic bags, bottles, packaging materials, and other debris [15, 74]. Polyethylene MPs particles are widely used in everyday products including packaging, plastic bottles, bags, and fishing gear and thus their presence in this study and area could have arisen from these activities [2].

The lack of significant relationships between water quality parameters and MPs particles in sediment and surface water is not surprising and may indicate that MPs distribution is influenced more by external and physical factors and less chemical characteristics, such as proximity to pollution sources, land use, and hydrodynamic conditions, rather than by intrinsic water quality characteristics [58]. Similar findings have been reported by Zhou et al. [76], Mbedzi et al. [35] and Mutshekwa et al. [39], where MPs abundance showed weak or no correlations with water quality parameters like pH, conductivity, TDS and temperature. This suggests that MPs, being physical contaminants, behave independently of chemical parameters, emphasizing the need to consider human activities and physical transport mechanisms in MPs studies and mitigation.

Like other ecological studies, this research faced several limitations. We acknowledge that there is no uniform and standardised sampling, processing, analysis and reporting MPs abundance from sediments and surface waters, which means that not all published studies can be compared. Additionally, the mesh size used in this study may not have captured all MPs, since we understand that MPs sizes range from 1 micron to < 5 micron particles, potentially underrepresenting the overall MPs particles. Even though this might be the case, it is challenging to sampling, treat and validate MPs particles that are very small with contamination or human errors, as such modern and effective technology is needed to help deal with this drawback. Moreover, we used hydrogen peroxide (H_2O_2) to remove organic material from our samples, however, a variety of other solutions have also been suggested such as H_2O_2 + Fe and KOH [32]. We believe that the use of FTIR analysis have assisted in the verification of MPs particles extracted from our study samples which have provided us with an ideal outcome and conclusion on MPs in small subtropic reservoirs. Furthermore, given that there is no standardised threshold (or an official accepted density mark) to assess MPs risk assessment, the current study considered the lowest MPs densities using those reported by Isobe et al. [28], and Ranjani et al. [47]. Nevertheless, our results contribute to enhancing the understanding on MPs occurrence, characteristics, potential impacts in inland subtropical reservoirs and the need for management strategies.

While the present study highlights MPs pollution in small subtropical reservoirs and examines the influence of various human activities, the impact of pollution levels to natural environments and seasonal variation, this provide a baseline data on MPs in the region which is critical for future follow-up studies and/or any aquatic biodiversity studies to be undertaken to considered MPs pollution as a factor. Future research should focus on the ecological implications of MPs pollution, particularly how it affects local species and ecosystems and the transportation and accumulations dynamics of MPs. Long-term exposure to MPs if left unattended or continued contamination may disrupt aquatic biodiversity, alter food webs, and impact the health of aquatic organisms and humans depending on the use of reservoirs. MPs can pose risks to human health through the consumption of contaminated water and biota. Given these concerns, future studies could explore the transport pathways of MPs across trophic levels and assess the role of reservoirs as both sinks and sources of MPs within larger watershed systems. To enhance the practical relevance of these findings, it is essential to include actionable recommendations for the development of mitigating MPs pollution. Local stakeholders, including municipalities and conservation groups, could benefit from our results when implementing strategies aimed at reducing human impacts on aquatic ecosystems, such as improved waste management, public awareness campaigns, and stricter regulations on plastic use, to effectively protect small reservoirs and public health.

7 Conclusion

Our study showed that small subtropical reservoirs associated with high human activity were polluted and MPs densities were seasonally influenced for both sediments and surface waters. MPs densities and pollution levels were higher in the dry season. The variability of MPs densities was mainly due to local human activities associated with each reservoir, supporting our hypothesis of high human activities as a major source of MPs. Considering that these reservoirs host diverse aquatic ecosystems and provide critical ecosystem services such as water supply, fisheries, and recreation, further studies are essential to understand the dynamics of MPs pollution, including its sources, distribution, and potential impacts on aquatic organisms and ecosystem functionality. Moreover, increased MPs pollution in small subtropical reservoirs and the associated human health risks underscore the urgency of implementing effective monitoring and management strategies. It is crucial to address MPs pollution by addressing sewerage spillage, developing landscapes sustainably and control physical pollution within catchments areas to prevent long-term ecological damage and safeguard public health, particularly as the influence of human activity continues to rise in these vulnerable environments.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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