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Spatial patterns and short-term deposition of atmospheric microplastics in an urban environment / Mutshekwa, T., Mkhencele, S., Lebepe, J., Balestra, V., Mofu, L., Motitsoe, S.N.. - In: SCIENTIFIC REPORTS. - ISSN 2045-2322. - ELETTRONICO. - 16:1(2026). [10.1038/s41598-026-60015-w]

Availability:

This version is available at: 11583/3016415 since: 2026-10-07T19:35:14Z

Publisher:

Springer Nature

Published

DOI:10.1038/s41598-026-60015-w

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OPEN Spatial patterns and short-term deposition of atmospheric microplastics in an urban environment

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Atmospheric deposition is an important and newly recognised pathway for microplastics (MPs), influencing their transportation and distribution both on land and in aquatic environments. However, MP pollution in the air remains relatively understudied compared to aquatic environments, particularly in developing regions such as Southern Africa. Despite the growing body of literature on MPs in Southern Africa, studies investigating atmospheric MP deposition, short-term variability, and links with meteorological conditions remain limited. This study investigates the occurrence and characteristics of atmospheric MP deposition and their relationship with meteorological factors within an urban town in the Albany thicket biome of South Africa, using weekly sampling over a six-week period across three sites associated with different land-use types. MP deposition fluxes were found to be significantly different between study sites, with an average of 86.5 ± 10.4 particles/m²/day. The highest deposition fluxes were recorded at S2, located in a peri-urban area (178.1 ± 69.2 particles/m²/day) ~4.5 km from the town center, while the lowest were observed at S3, ~10 km outside the town in a semi-natural area (24.7 ± 8.2 particles/m²/day). Around 30.2% of MPs identified had particle sizes between ≥ 250 and < 500 μm . The dominant colour was transparent/clear (46.6%) and the prevalent shape was fibre/filament (95.5%). FTIR-ATR analysis revealed that polyethylene terephthalate (PET) was the predominant polymer type (42.5%). Microplastic deposition fluxes at S1 (urban area) showed a positive correlation with rainfall, suggesting that rainfall likely influences local MP deposition dynamics at this site. Microplastic deposition fluxes in the town are likely influenced by a combination of local pollution sources, including sewage seepage, poor waste disposal, wastewater management, and textile-related activities. These findings demonstrate clear spatial variation in atmospheric MP deposition linked to land use and local anthropogenic activities, emphasising the importance of atmospheric pathways in regional plastic pollution cycling. The study highlights an urgent need to incorporate atmospheric MPs into environmental monitoring and waste management policies, particularly in urbanising regions of Southern Africa where regulatory frameworks and baseline datasets are still emerging.

Keywords Airborne pollution, Rainfall, Deposition flux, Plastic debris

Microplastics (MPs) are pervasive contaminants occurring globally in diverse environmental compartments, ranging in size from 1 to < 5000 μm ^{1,2}. They are capable of adsorbing environmental pollutants and contain endogenous chemical additives^{3–5}, and furthermore, they may harm organisms through direct or indirect ingestion and subsequent transfer across trophic levels^{6,7}. Microplastics can be categorised into primary, which are those intentionally manufactured at microscopic sizes, and secondary resulting from the environmental

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degradation of larger plastics^{8,9}. Airborne MPs originate from different sources, such as synthetic textiles, tyre wear, industrial emissions, and poorly managed waste, and pose environmental and human health risks. Due especially to their persistence and high mobility, MPs can be transported over long distances, increasing their potential to spread across environmental compartments and contribute to ecological and human exposure risks^{10,11}. While extensive research has focused on MPs in water, sediments and biota, atmospheric MP deposition remains poorly studied, despite their role as a crucial pathway linking source and sink¹².

Atmospheric MP deposition was first investigated by Dris et al.¹³, although MPs had already been reported decades earlier in aquatic ecosystems¹⁴. Atmospheric deposition is the process by which substances are transferred from their source through the atmosphere¹⁵. This process can occur under both dry and wet conditions and collectively these are referred to as bulk MP deposition¹⁶. Through this process, atmospheric MPs can settle onto terrestrial¹⁷ and aquatic surfaces¹⁸ and they may also be re-suspended into the atmosphere through wind action and surface disturbances¹⁷. Atmospheric MP studies have reported their occurrence across a wide range of environments, from heavily polluted urban areas [e.g.^{19–21}] to remote and relatively pristine regions [e.g.^{22–24}]. Atmospheric MPs are also influenced by meteorological factors, particularly wind speed and rainfall. For instance, the influence of meteorological factors on atmospheric deposition of MP has been assessed using passive deposition sample sampling over short [e.g.²¹] and long periods [e.g.²⁵], and factors such as rainfall and wind speed were found to influence the deposition of MPs. Previous studies by Szewc et al.²⁵ and Jia et al.²⁶ demonstrated that in densely populated and industrial areas, rainfall and wind patterns can affect the distribution and abundance of airborne MPs, while in more remote settings, precipitation and wind-driven transport facilitate their movement over long distances from urban sources²⁵.

Through atmospheric deposition, these MP particles can settle onto a variety of environments, including soils [e.g.^{27,28}], freshwater bodies [e.g.^{29,30}], and vegetation [e.g.³¹], thereby contributing to the spread of plastic contamination beyond their original sources¹³. In addition to environmental exposure, airborne MPs present a potential risk to human health because they can be inhaled, raising concerns about their possible association with respiratory irritation, inflammation, and other physiological impacts³². Wildlife may also be affected when these particles accumulate in habitats and are directly or indirectly ingested or assimilated by organisms, exposing them to both the physical presence of MPs and the chemical contaminants that may adhere to their surfaces³³.

Despite the growing research on MP pollution in Africa, studies on atmospheric MPs deposition remain limited³⁴. To the best of our knowledge, this will be one of two case studies in addition to Mutshekwa et al.²¹ to contribute to our understanding of MPs deposition, and it is among the first studies to specifically focus on the Albany Thicket biome part of the Eastern Cape Province, South Africa. The Albany Thicket biome is scientifically relevant for this study because it represents a semi-arid to sub-humid landscape with a mosaic of urban, peri-urban, and semi-natural environments, allowing assessment of atmospheric MP deposition across different land-use types. In addition, the region experiences variable meteorological conditions, such as wind and episodic rainfall, which may influence the transport and deposition of airborne MPs. As such, the present study was initiated to expand on the understanding of atmospheric MPs deposition in Southern Africa. Specifically, the study aims to: (1) investigate the short-term occurrence and characteristics of MPs in an urban town, in the Albany Thicket biome of the Eastern Cape Province of South Africa; (2) examine the relationship between MP deposition fluxes and meteorological variables such as humidity, air temperature, wind speed, and rainfall; and (3) infer likely sources of atmospheric MPs based on polymer composition, particle morphology, and land-use context. Findings are expected to enhance our current knowledge of MPs in South Africa, their source-sink dynamics, distribution, characteristics, and fluxes.

Methods and materials

Sampling locations

The study was conducted in Makhanda (formerly known as Grahamstown; 33.3094° S, 26.5284° E), situated in the Albany Thicket biome within the Eastern Cape Province of South Africa (Fig. 1; Table S1). The town is estimated to have a population of about 97,815³⁵. The town is located within a subtropical climate zone, characterized by warm, wet summers (November–March) and cool, dry winters (May–August). Average annual rainfall is approximately 450–600 mm, predominantly occurring during the summer months, while mean temperatures range from 7 °C in winter to 28 °C in summer as reported by the South African Weather Service and supported by Mutshekwa et al.³⁶. The town is situated on undulating hills and plateaus with intervening valleys and small rivers, forming a heterogeneous landscape that includes urban, peri-urban, and natural land-use types³⁷. The average elevation of the town is approximately 507 m above sea level and is characterised by mixed land uses, including formal and informal residential areas, urban centers, commercial agriculture and game farming³⁶. The surrounding natural vegetation is dominated by grasslands and riparian forests, with patches of indigenous thicket and scattered exotic tree species³⁶.

Three sampling sites were selected within and around the town of Makhanda (Fig. 1). Site 1 (hereafter referred to as S1) was located within the urban center, encompassing the central business district and residential areas representing an urban area. Site 2 (hereafter referred to as S2) was situated in high-density formal and informal settlement areas ~4.5 km away from urban center, with limited waste management and a high concentration of household and commercial factories in the vicinity, thus representing a peri-urban area. Site 3 (hereafter referred to as S3) was located ~10 km southeast from the urban center towards the coast, within Kubusi Safaris/Tuskers Lodge, characterized by game farming and agricultural lands with low human disturbance and largely natural vegetation, representing a semi-natural area.

Microplastic sampling and processing

Atmospheric MP deposition samples were passively collected over a six-week sampling period (W1 – W6), from 29 January to 06 March 2026, using a 20 L stainless steel bucket (diameter 305 mm; height 400 mm),

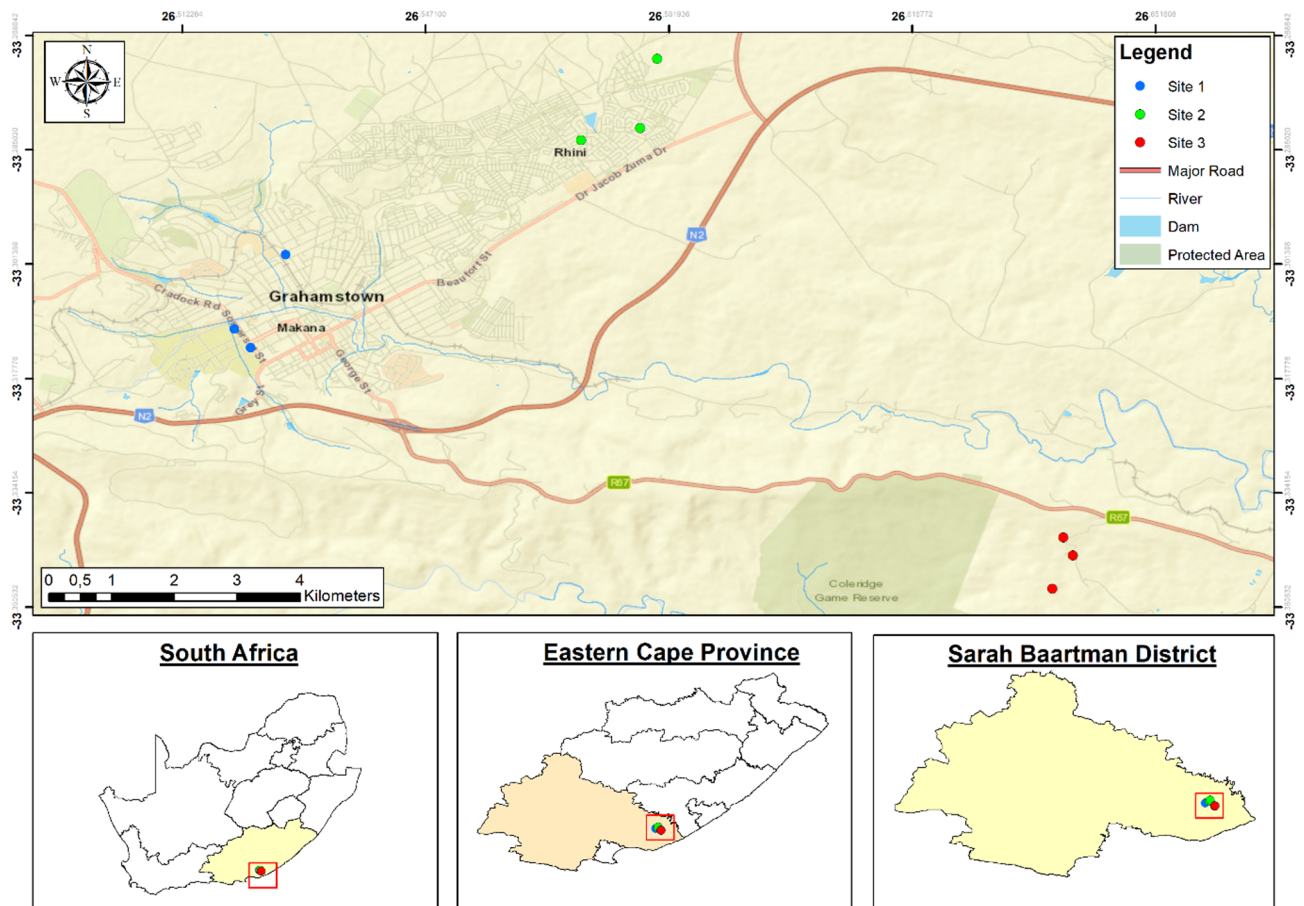


Fig. 1. Map of the study area in Makhanda town (formerly known as Grahamstown), located in the Makana Municipality, Eastern Cape, South Africa, showing the locations of the three sampling sites (S1 - S3): Site 1 within the town center (urban area), Site 2 in high-density settlement areas outside the town center (peri-urban area), and Site 3 approximately 10 km outside the town within Kubusi Safaris/Tuskers Lodge (semi-natural area). The map was created using ArcGIS Desktop (version 10.8; <https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview>) with tools from the Data Management Toolbox ("Calculate Field"), and QGIS (version 3.28; <https://qgis.org/>), using the dataset "MDB District Municipal Boundary 2018" obtained from the Municipal Demarcation Board of South Africa (<https://www.demarcation.org.za/>).

deployed on Thursdays and retrieved on Fridays, following Adediran et al.³⁸ and Mutshekwa et al.²¹ protocols. Each sampling event represented a 24-hour deposition period per week, rather than continuous weekly (7-day) integration²¹. A total of 54 deposition samples were collected during the study period (3 sites × 3 replicates × 6 weeks), including both wet and dry deposition. The sampling points at S1 (urban area) included rooftops at the National Research Foundation-South African Institute for Aquatic Biodiversity (NRF-SAIAB), the Albany Museum Natural Science building, and a private residential house in Park Road Street. The sampling points at S2 (peri-urban area), included rooftops of residential houses in the Joza location, those at S3 (semi-natural area), were all located within a private property (i.e., Kubusi Safaris/Tuskers Lodge), approximately 10 km outside Makhanda town, with sampling points positioned ~5m apart on rooftops. All sampling points were approximately 3 m above ground level depending on building height, to minimise ground-level resuspension effects and ensure consistency across sites.

Prior to sample collection, buckets were pre-cleaned with deionised water and covered with aluminium foil. At each site, the buckets were deployed between 9:00 am and 10:00 am, each week and left open to the atmosphere for 24 h to collect airborne particles. Meteorological conditions were considered prior to deployment; during rainfall events, buckets were exposed directly to wet deposition without any modification. During dry-weather conditions, 500 mL of distilled water was added prior to deployment to retain deposited particles and minimise loss through resuspension. Meteorological data (humidity, air temperature, wind speed, and rainfall) were obtained from the South African Weather Service³⁹ at 4-hour intervals during each 24-hour sampling day. After exposure, buckets were carefully retrieved from each site, immediately closed with aluminium foil, and transported back to the laboratory for processing. In the laboratory, samples were treated with 30% H₂O₂ to digest organic matter and subsequently filtered through stacked sieves with different mesh sizes i.e., 1000 µm, 500 µm, 250 µm, and 100 µm. To recover particles adhering to the bucket walls, each bucket was rinsed three times with milli-Q distilled water, and the resulting sample was sieved as mentioned above. The sieves were then

oven dried overnight at 30 °C before MP identification. All liquid reagents used during this study were first pre-filtered through Whatman membrane filters (2 µm pore size, 47 mm diameter).

To minimise laboratory contamination, the use of plastic equipment was avoided wherever possible. Prior to MP identification, laboratory benches were cleaned with a filtered 70% ethanol solution. Cotton laboratory coats and nitrile gloves were worn throughout laboratory procedures^{40,41}, and no more than two individuals were allowed in the sterile, controlled laboratory space at any given time. Although nitrile gloves may contribute minimal synthetic particle contamination, they were used as they are widely recommended in MP laboratory protocols due to their relatively low shedding compared to other glove types and their effectiveness in reducing direct sample contamination from handling⁴¹. Microplastic particles were identified using a stereomicroscope (Olympus SZX7, Olympus Optical, Japan) fitted with a KL 1600 LED light source and an integrated Olympus Cam-SC50 camera, controlled via Stream Essential 2.3 software. Particles were counted and categorised based on their colour and shape, following the criteria described by Rodríguez-Seijo and Pereira⁴². Particles were classified as MPs if they exhibited unnatural colouration (e.g., bright or multicoloured) and/or unnatural shapes (e.g., sharp edges or perfectly spherical forms)⁴². To evaluate potential contamination during sample processing, blank glass microfiber filters were placed at three locations: inside the laminar flow cabinet, in the drying oven, and on the laboratory bench near the microscope, following Bhat et al.⁴³. If any MP particles were detected in the blanks, these were considered indicative of laboratory contamination and were subsequently used to correct the corresponding sample counts by subtraction⁴⁴.

Fourier transform infrared spectroscopy analyses

Fourier Transform Infrared Spectroscopy (FTIR) was used to validate the visual identification of MP particles⁴⁵. A pragmatic subsample comprising 50–60% of visually identified MP particles was selected for polymer characterisation using a Platinum-ATR FTIR spectrometer (Bruker Alpha, Germany) at the University of Venda, South Africa. This approach was adopted to balance analytical resource constraints while maintaining representation across particle shapes, colours, and size classes. To minimise selection bias, particles were stratified according to shape, colour, and size classes before random selection. Analyses were performed over a spectral range of 650–4000 cm⁻¹, with a resolution of 8 cm⁻¹ and 16 scans per sample. Before each measurement, background scans were conducted, and the ATR crystal was cleaned with 70% propanol to avoid contamination. The resulting spectra were compared and validated against reference databases, including the Hummel Polymer Sample Library, HR Polymer Additives and Plasticizers, HR Hummel Polymers and Additives, and Synthetic Fibres by Microscope, using a spectral match threshold of ≥ 70% similarity for polymer identification⁴⁶.

Statistical analysis

The deposition flux of MPs was calculated by taking into account the number of MP particles found, the surface area of the sampling unit (bucket opening in m²), and the duration of sampling (in days). Fluxes were expressed as particles/m²/day, representing the number of MPs deposited per square meter per day.

A two-way analysis of variance (ANOVA) was performed to examine differences in MP deposition fluxes between sites (S1–S3) and weeks (W1–W6), after confirming the assumptions of homogeneity of variances using Levene's test ($p > 0.05$) and normality using the Shapiro–Wilk test ($p > 0.05$). Significant differences were further explored using Tukey's post hoc test for pairwise comparisons. Differences in MP colours and shapes were analysed using the non-parametric Kruskal–Wallis test due to non-normal data. To explore potential relationships between selected meteorological variables and MP deposition fluxes, Pearson correlation analyses were performed. However, due to the restricted temporal coverage and sample size, these analyses are exploratory in nature and should not be interpreted as evidence of causal relationships between meteorological variables and atmospheric MP deposition. Statistical significance was set at $p < 0.05$, and all analyses were carried out using IBM SPSS version 25.

To visualise short-term variation in MP shapes, a non-metric multidimensional scaling (nMDS) based on Bray–Curtis similarity was performed using PAST version 4.03. Although only a limited number of shape categories were recorded, this multivariate approach was used to assess overall compositional differences in MP shape assemblages across sites and weeks. Differences in MP shapes were further tested for statistical significance using a distance-based Permutational Analysis of Variance (PERMANOVA) with PERMANOVA+ PRIMER version 6.

Results

Microplastic deposition fluxes

No MP particles were found in our control blanks but were found in all samples across the three different sites, indicating the presence of atmospheric MPs in the study area. Microplastic deposition fluxes had an overall average of 86.5 ± 10.4 particles/m²/day, ranging from 24.7 ± 8.2 particles/m²/day to 178.1 ± 69.2 particles/m²/day (Fig. 2; Table 1; Table S2). The highest MP deposition flux (178.1 ± 69.2 particles/m²/day; W3) was found in S2 (peri-urban area) ranging from 84.0 ± 21.0 to 178.1 ± 69.2 particles/m²/day, whereas the lowest MP deposition flux (24.7 ± 8.2 particles/m²/day; W3) was found in S3 (semi-natural area) ranging from 24.7 ± 8.2 to 66.7 ± 20.2 particles/m²/day (Fig. 2B & C). Site 1 (urban area) was found to have MP deposition flux ranging from 34.2 ± 6.9 to 123.1 ± 8.6 particles/m²/day, with an average of 86.7 ± 50.1 particles/m²/day (Fig. 2A & D). According to two-way ANOVA results, there was a significant difference between sites ($df = 2$; $F = 11.181$; $p < 0.005$) and weeks ($df = 5$; $F = 2.575$; $p = 0.048$), but no significant difference in the interaction between site $\times$ weeks ($df = 10$; $F = 0.413$; $p = 0.931$).

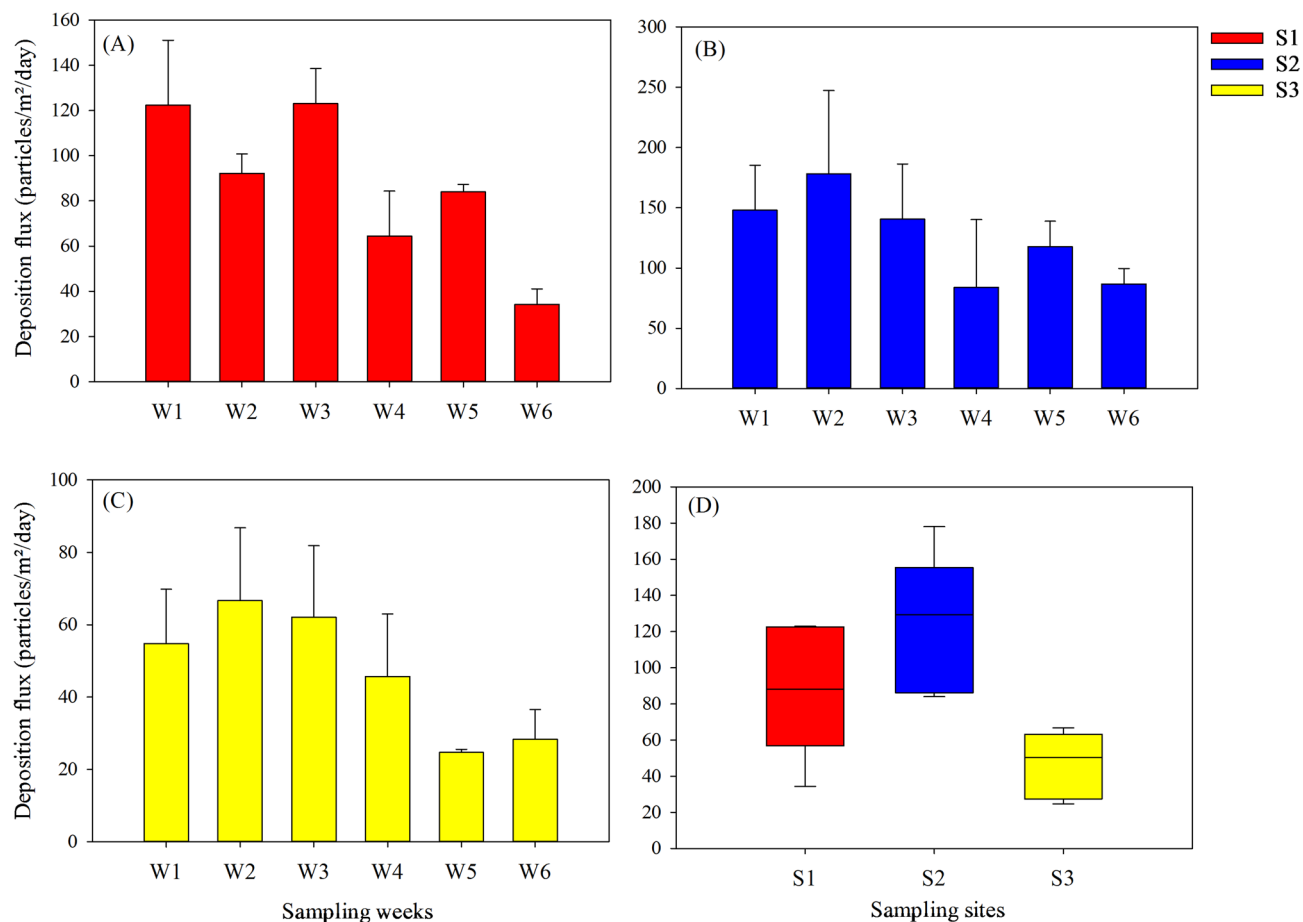


Fig. 2. Microplastic deposition fluxes (Mean $\pm$ SD) collected in (A) S1 (urban area) (B) S2 (peri-urban area), and (C) S3 (semi-natural area) over time (6 weeks); (D) Boxplot highlight significance analysis across sampling sites in Makhanda town, Eastern Cape, South Africa. Abbreviation: S – site; W – week.

Sampling weeks	MP items/m ² /day		
	Site 1 (urban area)	Site 2 (peri-urban area)	Site 3 (semi-natural area)
Week 1	82.2–178.1	104.1–221.9	27.4–93.2
Week 2	76.7–123.3	93.2–315.1	43.8–106.8
Week 3	106.2–134.2	79.5–230.1	35.6–87.7
Week 4	35.6–102.7	63.0–126.0	21.9–79.5
Week 5	79.5–90.4	57.5–230.1	16.4–41.1
Week 6	27.4–47.9	63.0–106.8	27.4–30.1

Table 1. Range of MP deposition fluxes (items/m²/day) across three sampling sites over a 6-week period. Values represent the range of replicate measurements (individual weekly deposition collectors) recorded within each site per week.

Microplastic amounts and characteristics

A variety of colours, shapes and sizes were found during the study (Fig. 3). Overall, a total of nine colours were observed, with transparent (46.6%), and black (21.2%) being the dominant colours (Fig. 3A). Of the nine colours observed, yellow was not found in S3, and occurred in low proportion at other sites (Fig. 3). Across sites, transparent was the most dominant, accounting for 41.1% (S1), 48.3% (S2) and 53.4% (S3) (Fig. 3A). Additionally, three shapes were identified during the study, with fibre/filament (95.5%) being the most dominant overall (Fig. 3B). Fragments and films were also observed, accounting for 4.0% and 0.5%, respectively (Fig. 3B), and between sites, fragments accounted for 6.5% (S1), 2.8% (S2) and 2.1% (S3). Films were only found in S1 (0.4%) and S2 (0.6%) (Fig. 3B). Following the Kruskal Wallis test, fibre/filament ($H=61.97$; $p<0.001$) and fragment ($H=8.38$; $p=0.015$) shapes were significantly different across sites, whereas films were not statistically significant ($H=2.00$; $p=0.368$). Across weeks, significant differences were only found for fibres/filaments

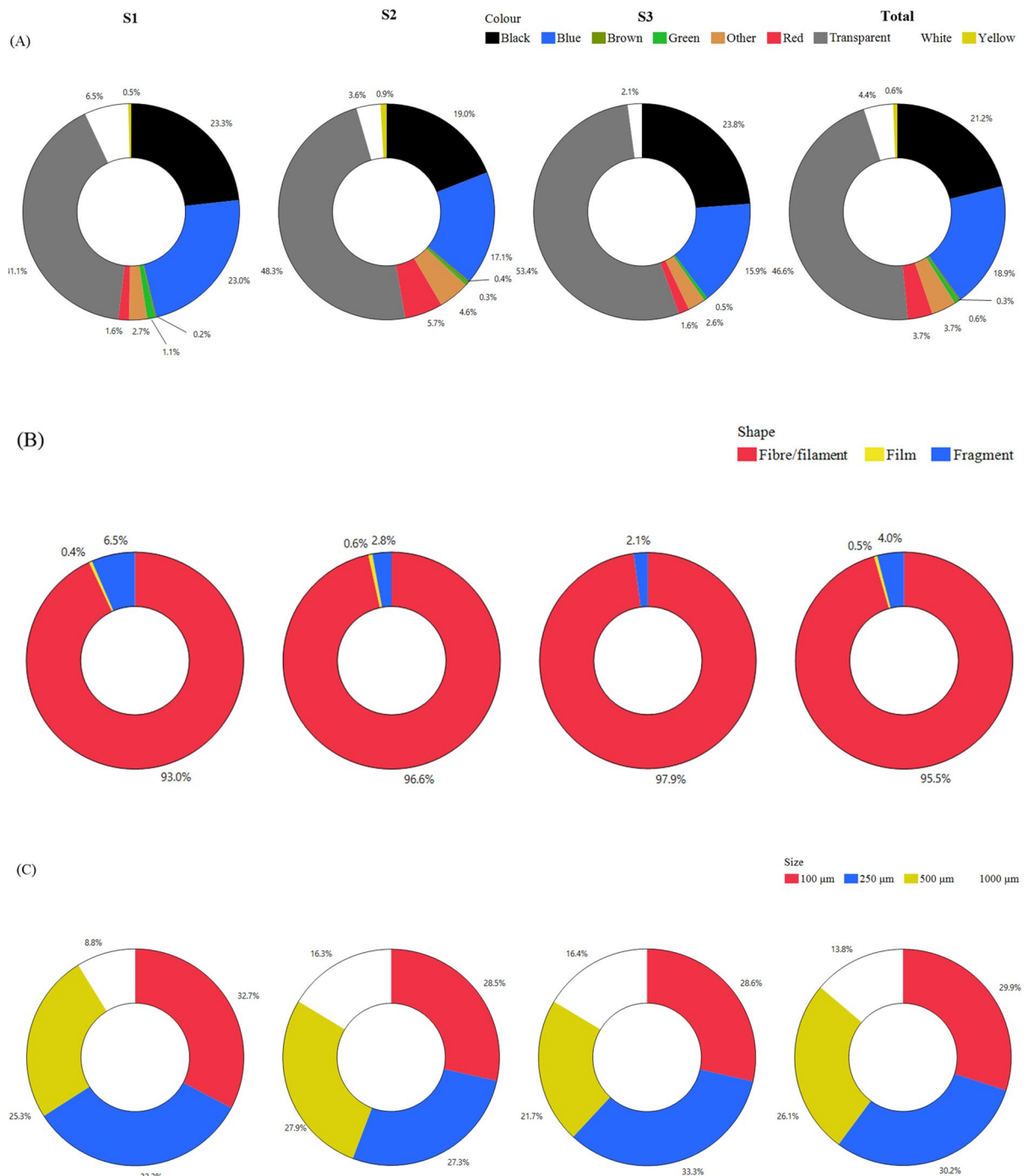


Fig. 3. Characteristics of MPs at each sampling site: (A) colour, (B) shape, and (C) size. Abbreviation: S – Site.

($H = 14.47$; $p = 0.013$) and films ($H = 15.14$; $p = 0.009$) shapes, whereas fragments ($H = 10.55$; $p = 0.061$) were not significant. Based on sieve retentions, MP were mostly found in the 250 µm sieve size (30.2%), followed by 100 µm (29.9%), 500 µm (26.1%) and 1000 µm (13.8%) showing the least densities (Fig. 3C).

After FTIR-ATR analysis of 50–60% of the total MP particles, seven polymer types were identified: polyethylene terephthalate (PET), polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyamide (PA), and polyvinyl alcohol (PVA) (Fig. 4). Polymers that were present in very low abundances or could not be confidently matched to reference spectra due to low-quality or ambiguous FTIR signals were categorized as “Others”. PET was the most prevalent polymer, representing 42.5% of the total MP, followed by PE (21.5%) and PP (13.6%). Polystyrene (PS), PVC, PA, and PVA occurred at lower abundances (12.8%, 4.0%, 2.8%, and 0.5%, respectively), while the least abundant category, “Others” accounted for 2.4% of the total.

The nMDS ordination plots revealed significant overlaps in MP abundance across the different study sites and across the six-week study period, indicating high similarities in MP shapes throughout the duration of the

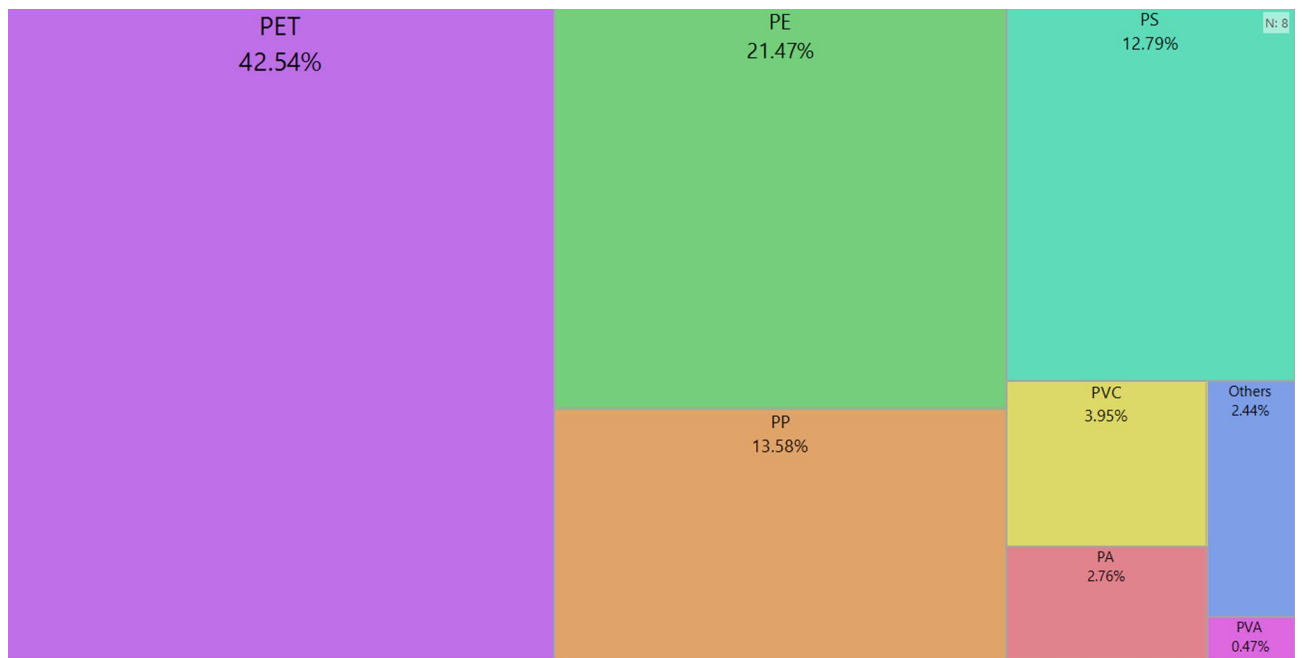


Fig. 4. Treemap showing proportional distribution of polymer types found across sites (S1 – S3) and week (W1 – W6). The area of each block represents the relative percentage of the total polymer composition. Abbreviation: S – Site; W – Week; PET – Polyethylene Terephthalate; PE – Polyethylene; PS – Polystyrene; PP – Polypropylene; PVC – Polyvinyl Chloride; PA – Polyamide; PVA – Polyvinyl Acetate.

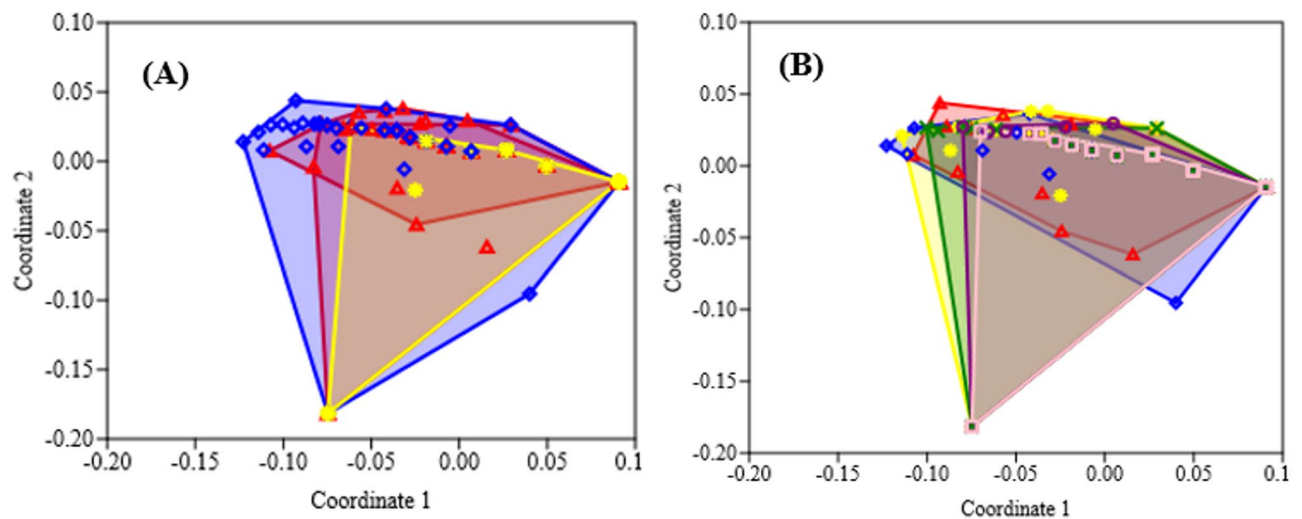


Fig. 5. Non-metric multidimensional scaling (*n*-MDS) illustrating variations in MP particle abundances across (A) sites (red = S1, blue = S2, yellow = S3), (B) weeks. (W1 = red, W2 = blue, W3 = yellow, W4 = green, W5 = purple, W6 = pink). Abbreviation: S – site; W – week.

study (Fig. 5). These observations were statistically supported by the PERMANOVA results, which confirmed no significant difference in MP shapes across the different study sites (Pseudo- $F = 1.104$, $p = 0.334$) and weeks (Pseudo- $F = 0.842$, $p = 0.581$), suggesting that although some individual shape categories differed significantly based on Kruskal Wallis, the overall MP shape assemblage remained relatively similar across sites and sampling weeks.

Relationship between meteorological variables and MPs deposition

Table S3 indicates the range of meteorological variables measured over six weeks period. Based on Pearson correlation analysis revealed a strong and positive relationship between MP fluxes and rainfall ($r = 0.683$; $p = 0.0018$) for S1, however this was not the case for S2 ($r = 0.012$; $p = 0.963$) with a moderate relationship but

Country	City/Town	Sampling method	Sampling height	MPs shapes found	MP found (particles/m ² /day)	References
China	Dongguan	Passive	~ 15	Fibres	36.7	47
China	Guangzhou	Passive	~ 10	Fibers, fragments, films and microbead	51–178	20
China	Nonjing	Passive	1.5	Fragment, fibre	134.18–500.94	48
Indonesia	Ancol, North Jakarta	Passive	28	Fibre (86.36%), fragment (10.61%), foam (3.03%)	3–40	49
Malaysia	Koula Nerus Bangi	Passive	-	Fibre, fragment	114–689 280–394	50
Northern Germany	Hamburg	Passive	2	Fragment, fibre	147	51
South Africa	Makhanda	Passive	~ 3	Fibres/filament (95.5%), fragment (4.0%), film (0.5%)	24.7 ± 8.2–178.1 ± 69.2	Current study
South Africa	Thohoyandou	Passive	2	Fibres (89.2%), fragment (8.7%), films (1.6%) and foams (0.5%)	355.64 ± 47.65	21
United Kingdom	London north	Passive	~ 50	Fibrous, non-fibrous	575 to 1008	19

Table 2. Microplastic deposition fluxes from the atmosphere in the current study and in cities/towns around the world. .

not significant at S3 ($r=0.397$; $p=0.102$) (Figure S1; Table S3–5). Other meteorological variables indicated no significant correlations across all sites ($p>0.05$) (Figure S1; Table S4–6). These results suggest that rainfall may have influenced MP deposition at S1 during the sampling period. However, given the relatively short sampling duration, the absence of significant relationships for temperature, wind speed, and humidity should be interpreted cautiously, as the study design may not have been sufficient to fully capture their potential influence on atmospheric MP deposition.

Discussion

This study investigated atmospheric MPs deposition in the urban, peri-urban and semi-natural areas of a town in the Eastern Cape Province of South Africa. The results confirmed the presence of atmospheric MPs across the study areas, with an overall mean deposition flux of 86.5 ± 10.4 particles/m²/day. Spatial variation was evident, with the highest deposition fluxes recorded at the site associated with high-density residential areas (peri-urban area; 125.9 ± 15.0 particles/m²/day), followed by the site located within the urban centre of Makhanda (urban area; 86.7 ± 14.0 particles/m²/day) and the site located 10 km outside town (semi-natural area; 47.0 ± 7.1 particles/m²/day). This spatial gradient likely reflects site-level variability arising from a combination of local emission intensity, resuspension processes, and differences in sampling exposure characteristics. Although the sites were selected to represent contrasting land-use settings, factors such as rooftop exposure, building height, surrounding structures, and the degree of micro-environmental shielding may also have influenced deposition rates. Therefore, the observed differences should be interpreted as reflecting both land-use context and exposure heterogeneity rather than land use alone. Elevated fluxes in the peri-urban area may nevertheless be associated with domestic plastic use, waste handling practices, and local atmospheric conditions (Figure S2). Microplastics were also observed in a range of colours, shapes, sizes, and polymer types, with transparent fibers/filaments, PET, and small-sized particles ($\geq 250 - < 500$ μm) representing the largest proportions, suggesting strong contributions from textile-related sources and secondary fragmentation of larger plastic debris. Short-term variability in MP deposition fluxes was observed among sampling weeks during the six-week study period, which may reflect changing local meteorological conditions and emission dynamics during the sampling window. This was partially supported by rainfall, which demonstrated a positive correlation with MP deposition fluxes at a site located in the centre of Makhanda, likely due to variability in rainfall during the study period.

The present study showed short-term week-to-week variability in atmospheric MP deposition across the three sampling sites during the six-week monitoring period in Makhanda, with the highest MP fluxes observed in the densely populated settlement area located outside the urban center (S2: 125.9 ± 15.0 particles/m²/day), followed by the urban center (S1: 86.72 ± 14.0 particles/m²/day), and the lowest deposition recorded away from anthropogenic activities at the semi-natural area 10 km outside town (S3: 47.03 ± 7.1 particles/m²/day). Our findings are consistent with a study conducted in Thohoyandou Town, South Africa, where atmospheric MP deposition was sampled approximately 2 m above ground level using a protocol comparable to the present study, including similar mesh sizes, sampling duration, and dry/wet deposition separation. In that study, MP deposition fluxes were significantly higher in the urban area (335.6 ± 47.6 particles/m²/day) compared to the less populated rural area (189 ± 20.0 particles/m²/day) and the remote forested area (52.70 ± 13.94 particles/m²/day)²¹ (Table 2). Similarly, Klein et al.⁵¹ reported deposition rates from Hamburg, Northern Germany, collected biweekly at ~ 2 m above ground level, with an average of 147 particles/m²/day. These values fall within the range observed at S2 in the present study (84.1 ± 48.5 – 178.1 ± 102.8 particles/m²/day) (Table 2). However, several studies have reported substantially higher MP deposition fluxes than those observed in the present study. For instance, Central London recorded deposition rates ranging from 575 to 1008 particles/m²/day, sampled twice per week at ~ 50 m above ground level¹⁹. Similarly, elevated fluxes have been reported in urban centres in China, including Nanjing City (134.18 – 500.94 particles/m²/day), where sampling was conducted at ~ 1.5 m above ground level⁴⁸. In Malaysia, higher deposition rates were also recorded in Koula Nerus town (up to 689 particles/m²/day) and Bangi town (280 – 394 particles/m²/day)⁵⁰. Overall, these values exceed those recorded in Makhanda (24.7 ± 14.2 – 178.1 ± 102.8 particles/m²/day) (Table 2), highlighting strong spatial variability in

atmospheric MP deposition across different urbanization gradients and study settings. These differences may be due to urbanization, industrial activity, meteorological conditions, and sampling height across the studies. Conversely, lower deposition fluxes have also been reported in some other cities/towns, including Dongguan city (36.7 particles/m²/day)⁴⁷ and Jakarta city (3–40 particles/m²/day)⁴⁹ (Table 2), indicating that atmospheric MP deposition can vary greatly between locations, depending on local sources, human activities, and meteorological conditions¹².

Microplastic colours and shapes can provide important information on their origin, and it may be associated with ingestion by certain species⁵². For instance, dyed plastics are often associated with packaging materials, while coloured fibres and fragments typically originate from textile sources and the fragmentation of larger plastic items⁸. In the present study, transparent fibres/filaments constituted most MP particles across all study sites. Nevertheless, a wide variety of colours was recorded, and multiple particle types, including fragments, and films. Several atmospheric studies have similarly reported transparent fibres/filaments as the most dominant MP shape (Table 2). The prevalence of transparent particles in the current study may be attributed to weathering and prolonged environmental exposure, which can lead to colour fading and degradation of originally coloured plastics⁵². The dominance of fibres/filaments observed in this study is consistent with patterns reported in atmospheric MP studies (Table 2); however, the present dataset does not include atmospheric transport modelling, and therefore interpretations regarding suspension time are based on literature evidence rather than site-specific measurement⁵³. FTIR-ATR analysis revealed that PET, PE, and PP were the most common polymers found, all of which are widely used in packaging materials, plastic bags, bottles, and textiles in South Africa³³. The most abundant MP particles observed in this study were within the size range of $\geq 250 - < 500 \mu\text{m}$, suggesting that MPs in the atmosphere in Makhanda are predominantly small, lightweight particles that can be easily transported and deposited, posing a potential risk of inhalation and environmental redistribution. The transport and deposition of MPs in the atmosphere is often influenced by meteorological conditions⁵⁴. Rainfall was positively correlated with MP deposition fluxes at one study site, suggesting that wet deposition may contribute to the removal of suspended particles from the atmosphere. However, given the short study duration and observational nature of the dataset, this relationship should be interpreted cautiously and does not establish a causal mechanism.

While the present study highlights atmospheric MP pollution in Makhanda, the relatively high MP deposition fluxes compared to global studies highlight the urgent need for further research on atmospheric MP deposition in South Africa. Future studies should prioritise a broader spatial coverage, including megacities and remote areas, to better understand the transport dynamics and regional distribution of MPs. The observed MP characteristics and site contexts suggest that multiple anthropogenic activities, including poor wastewater and material management, sewage discharge, foot and vehicle traffic, and commercial activities associated with shopping centres and small-scale industries, may represent potential contributors to atmospheric MP emissions in Makhanda¹². However, these proposed sources remain hypothetical because the present study did not incorporate wind-direction measurements, atmospheric transport modelling, back-trajectory analyses, or direct emission assessments required for robust source attribution. This is supported by the presence of MP fluxes at S3 located in a relatively less disturbed, semi-natural area approximately 10 km from the urban centre. Although Makhanda is a relatively small town, it hosts a major academic institution, Rhodes University, as well as prominent tourist attractions such as the Albany Museum and the 820 Settlers National Monument, which increase human activity. Additionally, the town is experiencing rapid population growth and expanding settlement development, contributing to increased pressure on waste management systems and plastic pollution (Fig S2). We thus recommend the Makana Municipality to prioritise the improvement of wastewater treatment infrastructure, enhance sewage management systems, and increase the availability of waste disposal facilities throughout the town^{55,56}.

Like other atmospheric studies, this study faced several limitations. The sampling differed from those used in some other studies due to the lack of a standardised sampling protocol for atmospheric MP deposition, which may limit the comparability of our results with other studies. Nevertheless, the results confirmed the presence and deposition of MPs within the study area. Furthermore, the mesh size used in this study may not have captured all MP particles, particularly smaller particles ($< 100 \mu\text{m}$), potentially leading to an underestimation of the total MP load when considering the smaller size class. Furthermore, FTIR analyses covered only 50–60% of visually identified particles due to a pragmatic subsampling approach, which introduces some uncertainty in polymer distribution. While efficient, this may affect the representativeness of polymer characterisation, and future studies should consider more comprehensive or fully stratified FTIR verification to improve robustness.

The study carries several inherent design constraints that should be considered when interpreting the results. First, the relatively short temporal coverage (six weeks of 24-hour deposition events) may not adequately capture seasonal or longer-term variability in atmospheric MP deposition. Second, the passive sampling approach provides valuable estimates of deposition fluxes but offers limited resolution regarding atmospheric transport pathways, particle dynamics, and deposition mechanisms compared with active monitoring approaches. Third, although potential MP sources were hypothesised from land-use context, particle morphology, and polymer composition, the study did not include wind-direction measurements, atmospheric back-trajectory analyses, source-apportionment approaches, emission inventories, or detailed environmental covariates. Consequently, the ability to identify specific emission sources and establish causal relationships was limited, and all source-related interpretations should be regarded as exploratory hypotheses rather than definitive evidence of origin. Furthermore, although sampling heights were broadly comparable across sites, differences in rooftop exposure, surrounding structures, and local shielding effects may have influenced particle capture efficiency. Consequently, differences among sites should be interpreted as indicators of site-level variability rather than direct effects of land-use categories alone. These limitations do not invalidate the reported spatial patterns and particle characteristics but appropriately constrain the strength of mechanistic and causal interpretations. Future

studies in South Africa should therefore adopt standardised sampling approaches, incorporate smaller mesh sizes or advanced analytical techniques capable of detecting finer particles, and separately quantify dry and wet deposition processes to improve understanding of the mechanisms driving atmospheric MP fluxes. In addition, the use of active air samplers and other complementary sampling methods alongside passive collectors is recommended to validate observed particle compositions, particularly the predominance of fibres, and to assess the extent of potential sampler-related biases. Additionally, future research should integrate meteorological variables, including wind direction, together with atmospheric back-trajectory modelling, emission inventories, traffic density, land-use characteristics, and waste management assessments to improve source apportionment and identify the drivers of atmospheric MP deposition more robustly. Nonetheless, our results provide solid evidence of the presence of atmospheric MP pollution in a South African town of Makhanda, offering essential baseline data for future research, monitoring efforts, and the development of mitigation strategies aimed at reducing MP emissions and exposure.

Conclusion

The results showed significant differences in MP deposition fluxes across the three study sites located in urban, peri-urban and semi-natural areas. Different concentrations were found in the sampling sites, likely reflecting differences in surrounding land-use intensity and human activities near each sampling area. Urban and peri-urban areas had high population density, settlements, and emission sources and were more polluted by MPs. Most of the MPs found were fibers/filaments and transparent/clear, followed by black ones. Small particles (≥ 250 – < 500 μm) made up most of the MPs found, suggesting their capacity for atmospheric transport, and the dominant polymers identified were PET, PE, and PP, with PET fibers specifically indicating a strong contribution from synthetic textile sources, while PE and PP are commonly associated with packaging materials and plastic consumer products. A significant relationship between rainfall and MP deposition was observed only at one site (urban area). This study contributes to the growing research on MPs pollution in South Africa and atmospheric environments. Because the present study represents a short-term assessment conducted over six weeks, future research should prioritise longer-term and seasonally replicated monitoring programmes to evaluate temporal dynamics of atmospheric MP deposition more robustly. Airborne particles can settle in rivers, lakes, soils, and oceans, affecting ecosystems and potentially entering food chains, highlighting their contribution to the spread of plastic pollution in different environments. Therefore, greater efforts are needed in sampling and monitoring MP pollution across different environmental settings.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Received: 17 April 2026; Accepted: 24 June 2026

Published online: 30 June 2026

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Acknowledgements

We thank Liliso Mbadla (Albany Museum) for assistance during fieldwork. We are also grateful to James Williamson (Kubusi Safaris/Tuskers Lodge), Albany Museum, and the National Research Foundation-South African Institute for Aquatic Biodiversity for granting permission to conduct experiments on their properties.

Author contributions

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tigation, Software, writing—review & editing. Samuel N. Motitsoe: Supervision, validation, visualization, writing—original draft, writing—review & editing.

Funding

Open access funding was provided by Rhodes University. This work was financially supported by the Rhodes University Research Council and the National Research Foundation (grant no. TTK250305301343), both awarded to Thendo Mutshekwa.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1038/s41598-026-60015-w>.

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