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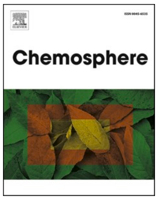

# Detection and characterisation of microplastics in tap water from Gauteng, South Africa

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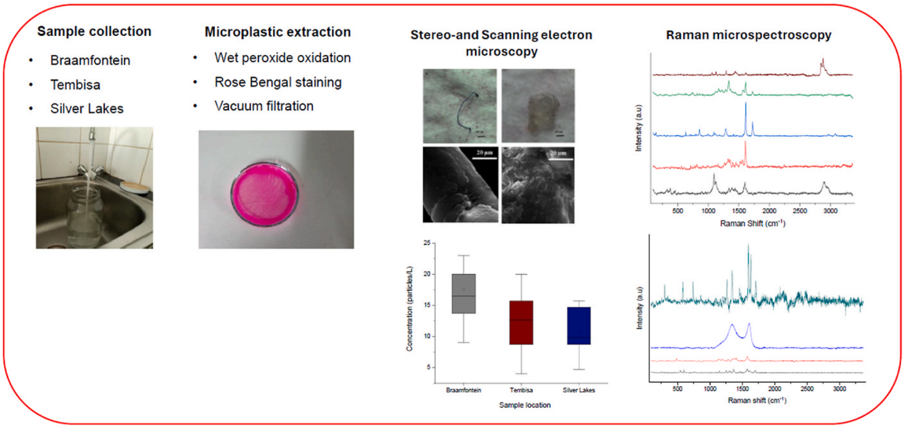
## HIGHLIGHTS

- Tap water from three suburbs in the Gauteng Province, South Africa contained MPs.
- Fibrous microplastics less than 1 mm were most prevalent in tap water samples.
- The presence of poly(AM-co-AA) polymer suggests that DWTPs could be a potential source of MPs in tap water.
- The estimated daily intake pointed to an increased likelihood of exposure of children to MPs in tap water.

## GRAPHICAL ABSTRACT



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## ABSTRACT

This study reports the presence, concentration, and characteristics of microplastics (MPs) in tap water in three suburbs in Gauteng Province in South Africa. Physical characterisation was conducted using stereomicroscopy and scanning electron microscopy following staining of MPs with the Rose Bengal dye. The concentrations of MPs in all samples ranged from 4.7 to 31 particles/L, with a mean of 14 ± 5.6 particles/L. Small-sized (<1 mm) and fibrous-shaped MPs were most abundant in all samples. Fibers accounted for 83.1% of MPs in samples from all the three areas, followed by fragments (12.4%), pellets/beads (3.1%), and films (1.5%), with a minor variation in the distribution of shapes and sizes in samples from each area. Raman microspectroscopy was used for chemical analysis, and five polymers were identified, namely: high-density polyethylene, polyurethane, polyethylene terephthalate, poly(hexamethylene terephtalamide), and poly(acrylamide-co-acrylic acid). C.I Pigment Red 1, C.I. Solvent Yellow 4, Potassium indigotetrasulphonate, and C.I Pigment Black 7 were the colourants detected. These colourants are carcinogenic and mutagenic and are potentially toxic to humans. The prevalence of MPs in tap water implies their inadequate removal during water treatment. For instance, the presence of poly(AM-co-AA) suggests that drinking water treatment plants may be a potential source of MPs in tap water. Other polymers, e.g., high-density polyethylene may be released from pipes during the transportation of drinking water.

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The estimated daily consumption of MPs from tap water was 1.2, 0.71, and 0.50 particles/kg.day for children, men, and women, respectively. The findings of this study provide evidence of the presence of MPs in drinking water in South Africa, thus giving some insights into the performance of treatment plants in removing these contaminants and a benchmark for the formulation of standard limits for the amount of MPs in drinking water.

## 1. Introduction

Microplastics (MPs) are plastic debris smaller than 5 mm. They have been detected in the hydrosphere, atmosphere, lithosphere, and biosphere (Amaral-Zettler et al., 2020; Hartmann et al., 2019). Microplastics have several potential pathways into the hydrosphere such as wastewater effluent, sewage sludge, wear and tear of tyres, atmospheric fallout, and deposition (Boucher and Friot, 2017; Dris et al., 2015; Nikiema et al., 2020a, 2020b). Microplastic pollution is a global environmental challenge recognised in the United Nations Sustainable Development Goals (UN SDGs) under Goal 14, target 14.1 and is measured by indicator 14.1.1 (Walker, 2021). However, according to Walker (2021), eleven other SDGs may have to do with MP pollution, suggesting a wider impact of these contaminants.

Microplastics have been confirmed to be present in different aquatic media and substances, including groundwater, tap water; bottled water; soft and energy drinks; white wine, beer, salt, milk, and teabags (Acarer, 2023; Diaz-Basantes et al., 2020; Fadare et al., 2021; Hernandez et al., 2019; Kutralam-Muniasamy et al., 2020; Prata et al., 2020; Samandra et al., 2022; Weisser et al., 2021). However, there are a few studies reporting MPs in South African freshwater and tap water (Bouwman et al., 2018; Ramaremisa et al., 2022; Saad et al., 2024a, 2024b; Swanepoel et al., 2023).

South Africa is a water-stressed country with a little over 1200 $m^3$/person/year of freshwater to a population of 60.6 million (Iloms et al., 2020; Statistics South Africa, 2023). Drinking water treatment plants (DWTPs) extract MPs with varying degrees of efficiency, and those that are not removed end up in tap water from where they are consumed (Acarer, 2023; Feld et al., 2021). The requirements of safe potable water quality for human consumption that are set out in the South African National Standards (SANS) 241 do not include MPs.

Gauteng is the smallest, but most populous province in South Africa, covering approximately 1.4% of the country's surface area. The City of Ekurhuleni, the City of Johannesburg, and the City of Tshwane are metropolitan municipalities in the province. Potable water in Gauteng is supplied mainly by two water utilities, namely: Rand Water, which extracts raw water from the Integrated Vaal River System (IVRS), and Magalies Water Utility, which supplies potable water extracted from the Crocodile and Pienaar Rivers (Johannesburg Water, 2022; Magalies Water, 2023; Rand Water, 2022).

This study aimed at investigating the presence and prevalence of MPs in South African tap water, thus providing data on which potential exposure could be predicated. This aim was achieved by pursuing the following objectives: determination of physical-chemical properties of MPs (shape, size, colour, surface morphology, polymer types and polymer additives) and estimation of daily intake in children, men, and women.

## 2. Materials and methods

### 2.1. Sample collection and MP extraction

Samples were collected between 25-03–2023 and 14-06-2023 from conventional taps in three suburbs in Gauteng Province, namely, Tembisa and Braamfontein in Johannesburg and Silver Lakes in Pretoria. Before collection, tap water was allowed to run for 1 min followed by collection into 3 L pre-washed glass jars, stored in cooler boxes and taken to the laboratory for further processing. The pH of all tap water samples was determined using an Insmark M-log pH meter. Their values were found to meet the minimum specifications set by SANS 241 of $5 \leq pH \leq 9.7$. The samples were filtered under vacuum using Whatman GF/F filters. To minimise any interference by organic matter during physical and chemical characterisation, each filter was subjected to wet peroxide oxidation using Fenton's reagent. This was done by adding 5 mL of 0.07 M $FeSO_4 \bullet 7H_2O$ to 5 mL of 30% (v/v) $H_2O_2$. The samples were allowed to digest at room temperature (Chu et al., 2022; Ramaremisa et al., 2022) followed by addition of 5 mL of 0.2 mg/mL Rose Bengal dye solution to each filter to stain non-plastic particles (Alarcon et al., 2017; Lam et al., 2020). The dye was vacuum-filtered and washed off with filtered Milli-Q Type 1 Ultrapure water (Milli-Q, Millipore, U.S.A.). The filters were placed in Petri dishes and dried at room temperature prior to further analysis.

### 2.2. Quality control measures

To minimise sample contamination, experiments were conducted under an ESCO laminar flow cabinet in a laboratory dedicated to research in MPs. All apparatus were washed with filtered Milli-Q Type 1 Ultrapure water and rinsed with ethanol. All solutions were filtered using Whatman GF/F glass microfiber filters (Cytiva Danaher Group, Buckinghamshire, United Kingdom). Blank experiments were conducted with filtered Milli-Q Type 1 Ultrapure water to account for possible procedural contamination (Ramaremisa et al., 2022). There were no MPs detected in the blanks.

### 2.3. Physical characterisation

#### 2.3.1. Stereomicroscopy

A Nikon stereomicroscope (Nikon MET SMZ745T) equipped with NIS Elements-D imaging software (Nikon Instruments Inc, New York, U.S.A.) was utilised for characterisation of physical properties of MPs. To ensure that the physical properties of all particles on the filter paper were recorded, the filter was divided into four quadrants, and each quadrant was examined twice. Particles that were stained by the dye were not counted as MPs. To mitigate against misidentification and subjectivity, criteria proposed by the Marine and Environment Research Institute were adopted. Furthermore, the break test was used and particles that failed the test were excluded (Marine and Environment Research Institute, 2015; Ramaremisa et al., 2022).

Potential MPs were categorised according to their shapes: fragments, pellets, fibers, and films. Fragment particles were plastic particles from degraded hard plastic materials. Films were thin sheet-like pieces of plastic from plastic carry bags and wrappers. Fibers were long and narrow plastic pieces with one dimension being noticeably longer than the other two. Pellets were round plastic particles with little sign of fragmentation. Particles were classified as fragments when they did not satisfy the criteria to be classified as a fiber, pellet/bead, or film. The MPs were grouped under seven distinct size categories, *viz*: 0.02–0.1 mm, 0.1–0.5 mm, 0.5–1 mm, 1–2 mm, 2–3 mm, 3–4 mm, and 4–5 mm. The size of the pellets was defined by measuring their diameter because of their spherical nature, whereas that of fibers, fragments, and films was measured between a particle's two most distant points (Pivokonsky et al., 2018; Tong et al., 2020). Potential MPs were further classified as transparent particles and coloured particles (with assorted colours including blue, black, brown, yellow, red, green, grey, white, purple, and red).

#### 2.3.2. *Scanning electron microscopy (SEM)*

Particles were extracted using tweezers from the filters, mounted on double-sided adhesive tape and coated with one layer of gold-palladium. The TESCAN Vega 3 Tungsten Scanning Electron Microscope (SEM) was used to examine the surface structure of MPs (TESCAN Orsay Holding, Brno-Kohoutovice, Czech Republic).

### 2.4. *Chemical characterisation*

Chemical characterisation was conducted using a Horiba LabRAM HR Raman microspectrometer (Horiba Jobin Yvon, Japan). Wavelength calibration was performed each day of analysis by focusing on a silicon wafer and analysing the first phonon band of silicon. The acquisition parameters were varied between particles to avoid polymer degradation and to acquire a better response signal. The Raman microspectrometer was operated using LabSpec 6 software (Ramaremisa et al., 2022). To determine the chemical composition of MPs and their additives, reference and sample spectra were compared using the SLOPP Library of Microplastics and KnowItAll® Informatics system software (John Wiley & Sons, Inc., New Jersey, U.S.A.) (Ramaremisa et al., 2022).

## 3. Results and discussion

### 3.1. *Quantification of microplastics*

Concentrations of MPs were expressed as the mean concentration ± standard deviation (SD). Typical shapes of MP particles are shown in Fig. 1. All tap water samples from Braamfontein, Tembisa, and Silver Lakes were found to contain MP particles (Table 1). In total, 1236 MPs were detected with concentrations ranging from 4.7 to 31 particles/L (a mean of 14 ± 5.6 particles/L). The highest concentration (ranging from 9.0 to 31 particles/L with a mean of 18 ± 6.2 particles/L) was observed in Braamfontein samples, followed by Tembisa samples, in which 391 MPs were detected, with concentrations ranging from 4.0 to 20 particles/L (a mean of 13 ± 4.9 particles/L). The lowest concentrations were detected in Silver Lakes samples (ranging from 4.7 to 16 particles/L with a mean of 11 ± 4.0 particles/L).

#### 3.1.1. *Statistical analysis of MP concentrations*

All statistical tests were conducted using IBM's SPSS Statistics version 27 (SPSS, Chicago, Illinois., USA). Differences were considered statistically significant if the p-value was less than 0.05 at a 95% confidence level. According to the Shapiro-Wilk test for normality and Levene's test for homogeneity of variances, MP concentration data satisfied the requirements for parametric tests with $p > 0.05$ for both tests. Microplastic concentrations in all tap water samples were normally distributed according to the Shapiro-Wilk normality test. The One-Way ANOVA test revealed statistically significant differences between MP concentrations for the three areas Tembisa ($F(2,27) = 4.827$, $p < 0.05$)). The Tukey post-hoc test was used for bivariant comparison. However, this increased the chance of committing a Type One error (i.e., the rejection of the null hypothesis when it is true). Hence, the Bonferroni correction was applied and the adjusted p-value for statistical significance was set to $p = 0.016$ (Lam et al., 2020; Weideman et al., 2020). The Tukey post-hoc test revealed that concentrations of MPs in Braamfontein samples were significantly higher than those for Silver Lakes samples ($p < 0.016$). On the other hand, there was no significant difference in concentrations between the Tembisa and Braamfontein samples ($p > 0.016$) and the Tembisa and Silver Lakes samples ($p > 0.016$) (Fig. 2).

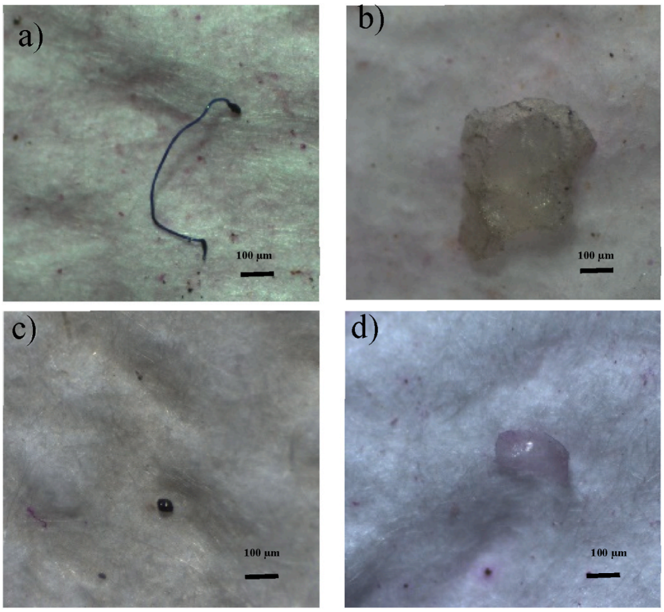

**Fig. 1.** Microscopic images of microplastics in tap water samples: a) fiber, b) fragment, c) pellet, and d) film.

#### 3.1.2. *Comparison to other studies*

The findings of this study were compared to those of seventeen other studies that reported mean concentrations of MPs in tap water samples. The concentrations were found to be the tenth highest (Fig. 3). The highest was reported in Chinese tap water, ranging from 0 to 1247 particles/L (a mean of 440 ± 275 particles/L) (Tong et al., 2020). Mean concentrations of over 29 particles/L were reported in tap water from Brazil (Brasilia), Japan, Finland (Helsinki), Germany (Munich), and France (Paris) (Mukotaka et al., 2021; Pratesi et al., 2021). Lower MP concentrations were reported in Danish tap water (Feld et al., 2021). The first occurrence of MPs in South African tap water was reported by Bouwman et al. (2018). The authors reported MP concentrations ranging from 0.189 to 1.800 particles/L in Tshwane (Pretoria) and Johannesburg. A recent study by Swanepoel et al. (2023), reported MP concentrations (0.26–0.88 particles/L) in samples collected from drinking water distribution networks in Johannesburg, Mabopane, Ga-rankuwa, and Pelindaba. These values are much lower than those reported in this study. However, it should be emphasised that different sampling, extraction, and characterisation methods were used in these studies, which may limit the accuracy of this comparison.

### 3.2. *Physical characteristics of MPs*

#### 3.2.1. *Surface morphology*

Surface morphology of MPs was conducted using SEM and the most frequently detected shapes are shown in Fig. 4a-d. The images showed that the surfaces of MPs were rough, cracked and porous, with some containing smaller particles pitted on the surfaces. MPs may be exposed to different weathering and degradation processes which increase the surface area of MPs, resulting in increased adsorption capacity. This enhances their potential to act as vectors for chemicals and microorganisms (Saad, 2023). Degraded MPs have a higher adsorption capacity and as such portray affinity towards pollutants. For instance, degradation introduces oxygen-containing functional groups which increase their polarity and affinity towards hydrophilic pollutants.

#### 3.2.2. *Braamfontein*

*3.2.2.1. Shape and colour.* Fibers were the most abundant shape in Braamfontein samples (86.0%, n = 453), accounting for at least 77% in each sample (Fig. S1a). The majority of fibers were black (37.5%, n = 170), green (33.1%, n = 150), and blue (15%, n = 68). Other colours including red, brown, transparent, grey, and yellow were detected in minor proportions (14.3%, n = 65). Fifty-one fragments were detected

**Table 1**
MP concentrations, sizes, and shapes in tap water samples from Braamfontein (BS), Silver Lakes (SL), and Tembisa (TS).

| Sizes (mm) shapes | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample code | Total per sample | Concentration (particles\L) | 0.02–0.1 | 0.1–0.5 | 0.5–1 | 1–2 | 2–3 | 3–4 | 4–5 | Fibers | Fragments | Pellets | Films |
| **BS1** | 69 | 23 | 18 | 37 | 13 | 1 | 0 | 0 | 0 | 56 | 7 | 6 | 0 |
| **BS2** | 48 | 16 | 4 | 20 | 19 | 5 | 0 | 0 | 0 | 40 | 6 | 0 | 2 |
| **BS3** | 51 | 17 | 5 | 29 | 13 | 3 | 1 | 0 | 0 | 45 | 2 | 3 | 1 |
| **BS4** | 94 | 31 | 9 | 51 | 17 | 16 | 1 | 0 | 0 | 86 | 6 | 1 | 1 |
| **BS5** | 55 | 18 | 6 | 26 | 13 | 10 | 0 | 0 | 0 | 50 | 4 | 1 | 0 |
| **BS6** | 60 | 20 | 8 | 37 | 10 | 4 | 1 | 0 | 0 | 50 | 9 | 0 | 1 |
| **BS7** | 45 | 15 | 7 | 20 | 13 | 5 | 0 | 0 | 0 | 37 | 8 | 0 | 0 |
| **BS8** | 37 | 12 | 0 | 25 | 10 | 2 | 0 | 0 | 0 | 32 | 2 | 1 | 2 |
| **BS9** | 41 | 14 | 1 | 23 | 14 | 3 | 0 | 0 | 0 | 36 | 2 | 0 | 3 |
| **BS10** | 27 | 9 | 5 | 12 | 5 | 5 | 0 | 0 | 0 | 21 | 5 | 1 | 0 |
| **SL1** | 44 | 14 | 8 | 19 | 8 | 9 | 0 | 0 | 0 | 33 | 9 | 2 | 0 |
| **SL2** | 14 | 4.7 | 2 | 3 | 7 | 1 | 1 | 0 | 0 | 9 | 5 | 0 | 0 |
| **SL3** | 29 | 9.7 | 6 | 14 | 5 | 4 | 0 | 0 | 0 | 20 | 6 | 3 | 0 |
| **SL4** | 45 | 15 | 5 | 19 | 11 | 5 | 4 | 0 | 1 | 38 | 3 | 4 | 0 |
| **SL5** | 41 | 14 | 8 | 17 | 9 | 5 | 1 | 0 | 1 | 33 | 5 | 3 | 0 |
| **SL6** | 47 | 16 | 8 | 20 | 6 | 11 | 1 | 0 | 1 | 39 | 6 | 2 | 0 |
| **SL7** | 15 | 5 | 0 | 9 | 2 | 0 | 3 | 1 | 0 | 14 | 1 | 0 | 0 |
| **SL8** | 30 | 10 | 2 | 15 | 9 | 3 | 0 | 1 | 0 | 27 | 1 | 1 | 1 |
| **SL9** | 26 | 8.7 | 10 | 9 | 3 | 4 | 0 | 0 | 0 | 14 | 8 | 3 | 1 |
| **SL10** | 27 | 9 | 5 | 10 | 7 | 5 | 0 | 0 | 0 | 20 | 4 | 3 | 0 |
| **TS1** | 24 | 8 | 3 | 10 | 9 | 2 | 0 | 0 | 0 | 21 | 3 | 0 | 0 |
| **TS2** | 47 | 16 | 6 | 23 | 15 | 3 | 0 | 0 | 0 | 38 | 8 | 0 | 1 |
| **TS3** | 60 | 20 | 8 | 29 | 15 | 7 | 1 | 0 | 0 | 46 | 14 | 0 | 0 |
| **TS4** | 46 | 15 | 5 | 26 | 12 | 2 | 0 | 1 | 0 | 38 | 8 | 0 | 0 |
| **TS5** | 24 | 8 | 1 | 8 | 10 | 5 | 0 | 0 | 0 | 21 | 2 | 0 | 1 |
| **TS6** | 40 | 13 | 6 | 20 | 8 | 6 | 0 | 0 | 0 | 32 | 6 | 0 | 2 |
| **TS7** | 36 | 12 | 5 | 15 | 9 | 6 | 1 | 0 | 0 | 31 | 4 | 1 | 0 |
| **TS8** | 33 | 11 | 4 | 17 | 8 | 4 | 0 | 0 | 0 | 28 | 4 | 1 | 0 |
| **TS9** | 26 | 8.7 | 3 | 11 | 5 | 7 | 0 | 0 | 0 | 21 | 5 | 0 | 0 |
| **TS10** | 55 | 18 | 3 | 28 | 15 | 8 | 0 | 1 | 0 | 51 | 0 | 2 | 2 |

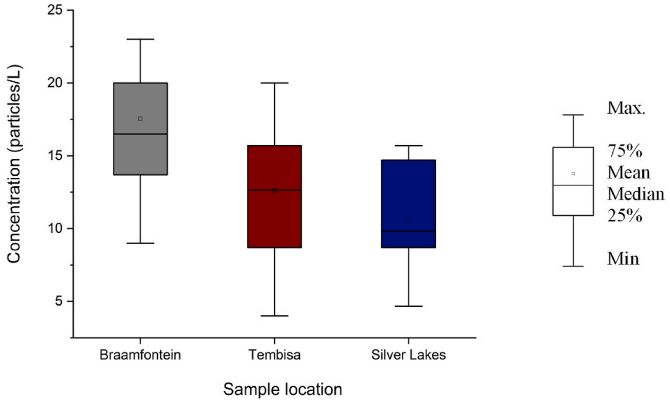

**Fig. 2.** Box plots showing variation in MP concentration in tap water.

(9.68%) in blue (43.1%, n = 22), green (19.6%, n = 10), white (13.7%, n = 7), and black (11.8%, n = 6). The remaining were a combination of transparent, red, and grey. A few pellets 13 (2.47%) were detected in blue (46.2%, n = 6), black (23.1%, n = 3), yellow (15.4%, n = 4), and green (15.4%, n = 2). Only 10 films were detected (1.9%), which showed an equal distribution of green, transparent, and white (90%, n = 3 each), and one black film (10%, n = 1).

*3.2.2.2. Shape and size.* Microplastics in Braamfontein samples were detected in five of the seven size categories, all smaller than 3 mm with a mean size of 0.49 ± 0.42 mm (Fig. 5a). The distribution of sizes per shape showed that fibers (0.02–2.41 mm, mean of 0.55 ± 0.42 mm) > films (0.13–0.33 mm, mean of 0.24 ± 0.09 mm) > fragments (0.07–0.28, mean of 0.09 ± 0.06 mm) > pellets (0.02–0.15 mm, mean of 0.06 ± 0.03 mm). At least 80% of the particles in all samples were less than 1 mm (Fig. S1b).

On the other hand, the distribution of shapes per size showed the following: 0.02–0.1 mm (12.0%) with n = 63 (33 fragments, 11 pellets, and 19 fibers). Most of MPs (53.3%) were in the 0.1–0.5 mm size range with n = 280 (250 fibers, 18 fragments, 2 pellets, and 10 films). All 184 particles in the ranges 0.5–1 mm (24.1%, n = 127), 1–2 mm (10.3%, n = 54), and 2–3 mm (0.57%, n = 3) were fibers.

### 3.2.3. *Tembisa*

*3.2.3.1. Shape and colour.* The most abundant shapes in Tembisa samples were fibers (83.6%, n = 327) and fragments (13.8%, n = 54). Films (1.5%, n = 6) and pellets (1.0%, n = 4) were present in smaller quantities. Similar to findings in Braamfontein samples, fibers represented at least 77% of all shapes in each sample (Fig. S2a). The majority of fibers were black (33.6%, n = 110), green (28.1%, n = 92), and blue (24.5%, n = 80). Fibers of other colours (red, brown, transparent, grey, orange, yellow, purple, and white) were present in minor proportions, representing 13.7% (n = 45) altogether. A higher number of blue (33.3%, n = 18), red (31.5%, n = 17), and green (20.4%, n = 11) fragments were detected. Other colours (white, yellow, and black) only accounted for 13.0% (n = 7). Only one (1.9%) transparent fragment was detected. There was an equal distribution of green, transparent, and white films (33.3% each, n = 2). Black and blue pellets accounted for 25% (n = 2) each, and the remaining 50% (n = 2) were red pellets.

*3.2.3.2. Shape and size.* Microplastics in Tembisa samples were detected in six of the seven size categories and ranged in size from 0.02 to 3.33 mm with a mean of 0.55 ± 0.49 mm (Fig. 5b). The mean size of fibers, fragments, pellets, and films were 0.62 ± 0.49 mm, 0.12 ± 0.10 mm, 0.1 ± 0.08 mm, and 0.61 ± 0.61 mm, respectively. This is similar to the distribution of sizes per shape observed in Braamfontein samples. Forty-four particles were smaller than 0.1 mm (30 fragments, 12 fibers, and 2 pellets). Almost 48% of MPs were observed in the size range of 0.1–0.5 mm (159 fibers, 23 fragments, 2 pellets, and 3 films). About 27% of MPs were detected in the range of 0.5–1 mm, accounting for 103

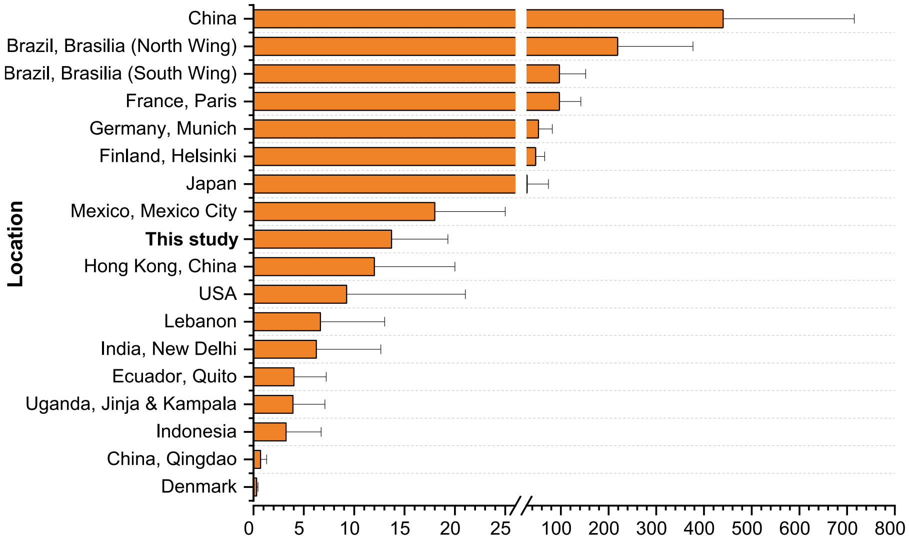

**Fig. 3.** Microplastic concentrations in tap water samples from different studies
Data from: Diaz-Basantes et al. (2020); Feld et al. (2021); Kosuth et al. (2018); Lam et al. (2020); Mukotaka et al. (2021); Pratesi et al. (2021); Shruti et al. (2020b); Tong et al. (2020); Zhang et al. (2020).

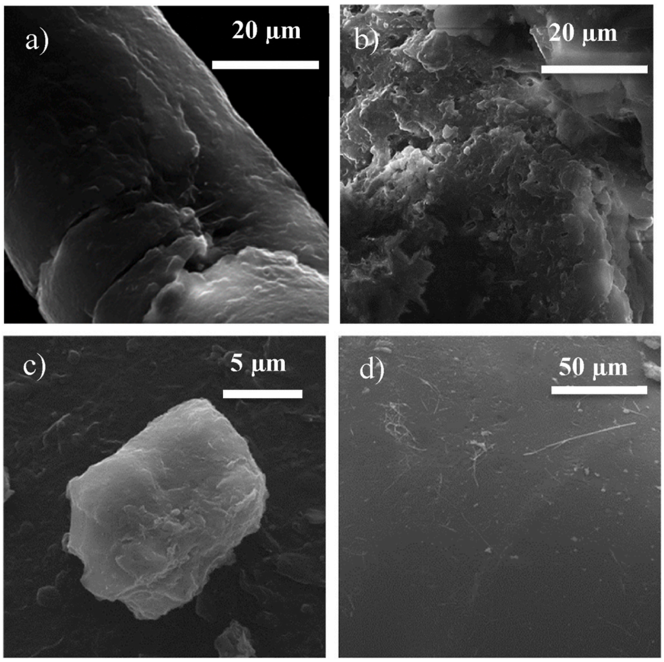

**Fig. 4.** SEM images of a: (a) fiber, (b) fragment, (c) pellet, and (d) film.

fibers, 1 fragment, and 2 pellets. Fifty particles were detected in the range of 1–2 mm (49 fibers and one film). Only fibers were detected in the size ranges 2–3 mm (0.51%, n = 2) and 3–4 mm (0.51%, n = 2) (Fig. S2b).

### 3.2.4. *Silver Lakes*

*3.2.4.1. Shape and colour.* Similar to observations in Tembisa samples, fibers (77.7%, n = 247) and fragments (15.1%, n = 48) were most abundant in samples collected from Silver Lakes, while films (6.6%, n = 21) and pellets (0.63%, n = 2) were observed in smaller quantities. Fibers represented at least 53% of all shapes in each sample (Fig. S3a). The majority of fibers were blue (30.4%, n = 75), black (26.7%, n = 66), and transparent (17.4%, n = 43) while the rest were green (8.91%, n = 22), red (6.5%, n = 16), and other colours (brown, grey, purple, white, and yellow) that were present in smaller quantities (10.1%, n = 25). Most fragments were red (31.0%, n = 15), blue (25.0%, n = 12), and transparent (14.6%, n = 7). Some fragments were also detected in other colours (red, brown, black, green, yellow, purple, and white), a few each, altogether representing 29.1% (n = 14). Pellets were distributed as follows: blue (57.1%, n = 12), purple (19%, n = 4), transparent (14.3%, n = 3), green and white (9.5%, n = 2).

*3.2.4.2. Shape and size.* Microplastics in Silver Lakes samples were detected across all seven size categories with a minimum size of 0.02 and a maximum of 4.44 mm (mean of 0.63 ± 0.79 mm). Fibers ranged in size from 0.08 to 4.44 mm, with a mean of 0.78 ± 0.75 mm. Fragments had a mean of 0.13 ± 0.17 mm, with a minimum of 0.03 mm and a maximum of 1.02 mm. Pellets ranged from 0.02 to 0.09 mm, with a mean of 0.05 ± 0.02 mm, and films ranged from 0.07 to 0.19 mm, mean size of 0.77 ± 0.77 mm. At least 72% of the particles in all samples were less than 1 mm (Fig. S3b).

Fig. 5c shows the distribution of shapes across the different size categories: 16.98% of MPs in the range 0.02–0.1 mm (51.9%, n = 28 fragments; 9.26%, n = 5 fibers; and 38.9%, n = 21 pellets), 134 particles in the range of 0.1–0.5 mm (42.1%). Of these, 115 (85.8%) were fibers, 17 (12.7%) fragments, and 2 (1.50%) films. There were 68 particles in the range of 0.5–1 mm (21.4%), with 66 (97.1%) fibers, and 2 (2.94%) fragments. There were 42 particles in the range 1–2 mm (13.2%) with 41 (97.6%) fibers and 1(2.38%)) fragment. Only fibers were detected in the size range 2–3 mm (4.4%, n = 14), 3–4 mm (0.94%, n = 3), and 4–5 mm (0.94%, n = 3).

### 3.2.5. *Statistical analysis of physical characteristics of MPs*

The Pearson Chi-square ($\chi^2$) test was used to determine if the

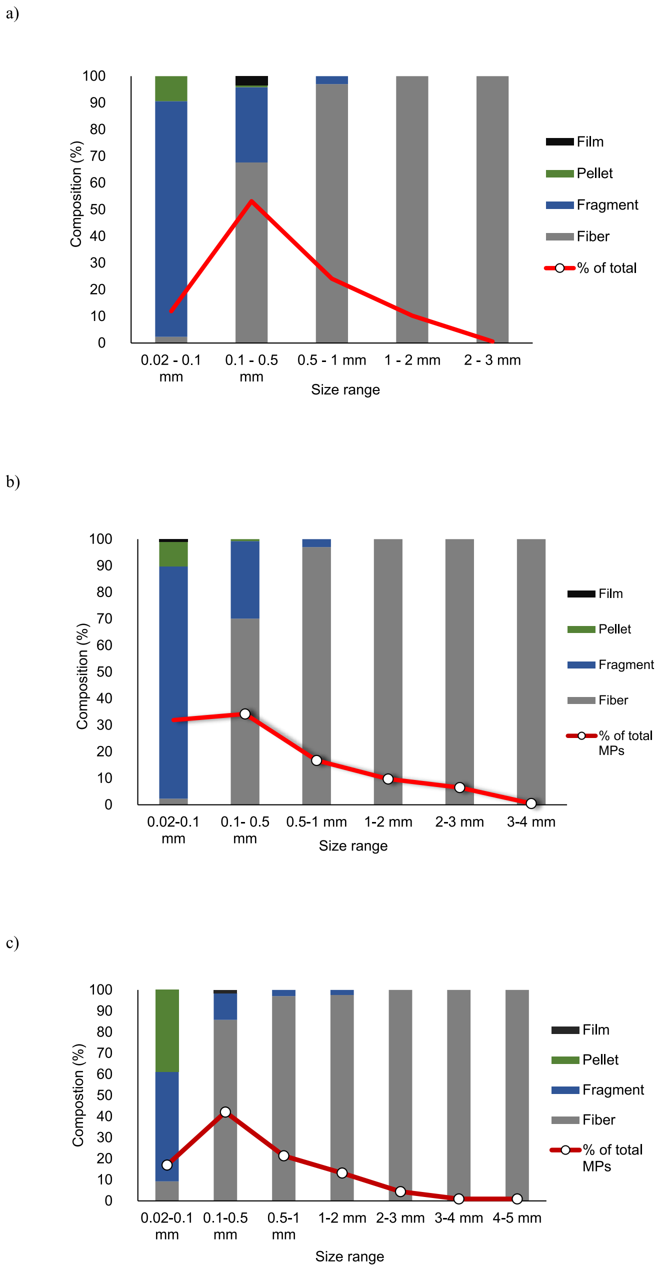

**Fig. 5.** Composition of shapes per size in a) Braamfontein, b) Tembisa, and c) Silver Lakes samples..

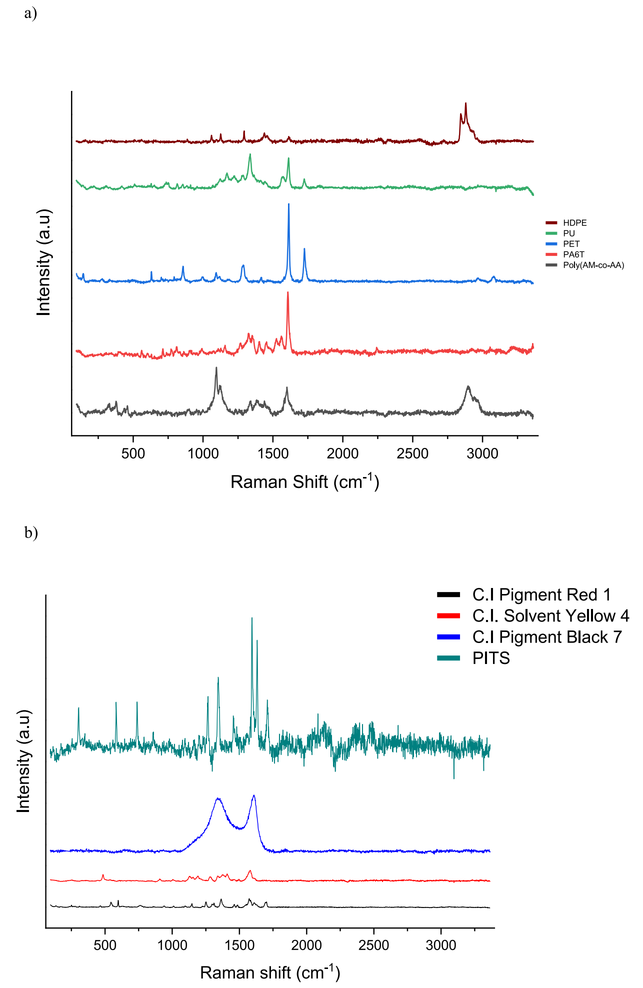

**Fig. 6.** Raman spectra of detected a) polymers (HDPE, PU, PET, PA6T, and Poly (AM-co-AA)) and b) additives (C.I Pigment Red 1, C.I. Solvent Yellow 4, C.I Pigment Black 7, and Potassium indigotetrasulphonate (PITS)). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

physical properties of MPs (size range, colour, and shape) differed for the three study areas. The test showed that there is a statistically significant association (i.e., similarity) amongst MP shapes, size ranges, and colours for the three areas: $\chi^2 = 28.392$, $p < 0.05$ (Braamfontein); $\chi^2 = 39.558$, $p < 0.05$ (Tembisa); and $\chi^2 = 211.383$, $p < 0.05$ (Silver Lakes). The association indicates a similarity in sources of MP pollution. Notably, tap water from Braamfontein and Tembisa is sourced from the IVRS and is processed by the same water utility in Johannesburg.

## *3.3. Chemical identification*

### *3.3.1. Polymer types*

Five polymers were identified, namely: high-density polyethylene (HDPE), polyurethane (PU), polyethylene terephthalate (PET), poly (hexamethylene terephtalamide) (PA6T), and poly(acrylamide-co-acrylic acid) (Poly(AM-co-AA) (Fig. 6a). HDPE is one of the most largely produced polymers and its applications include large containers, drums, fuel tanks, bottles, pipes, crates, and wrapping film (Novotna et al., 2019). PET has an extraordinary blend of physical-chemical, thermal, and electrical properties, leading to its extensive use in various industries. About two-thirds of PET polymers are manufactured for the textiles industry and a quarter for the bottled water industry. The rest are used for films, geotextiles, roof insulation, and automotive parts.

Other studies reported the release of PET monomers from PET polymers (Aigotti et al., 2022; Bach et al., 2013). Human exposure to PET MPs was reported in New York State infant meconium and adult faecal samples (Zhang et al., 2021). Thus, exposure to PET and its associated additives may begin from birth. PUs are used in flexible and rigid foams, catheters, adhesives, coatings, and sealants (De Souza et al., 2021; Matías, 2022). PA6T is part of a class of high-performance engineering polyamide polymers used for automotive parts, electronics, and applications requiring high strength (such as cable ties and plastic gears). Poly(AM-co-AA) and its sodium salts are extensively used in primary sewage and municipal and industrial wastewater treatment (CROW polymerdatabase, 2022). DWTPs are not designed to remove MPs which explains the presence of these polymers in tap water. However, the presence of poly(AM-co-AA) suggests that DWTPs may also be a potential source of MPs in tap water.

### 3.3.2. Polymer additives

From Raman microspectroscopy analysis, four colourants, *viz*: C.I Pigment Red 1, C.I. Solvent Yellow 4, potassium indigotetrasulphonate, and C.I Pigment Black 7 were identified (Fig. 6b). These colourants have extensive applications in the synthetic polymer industry. C.I. Pigment Red 1 and C.I. Solvent Yellow 4 are azo dyes and form part of the largest group of organic dyes. Azo dyes are used as colourants in polyamides, polyethylenes, and antioxidants in rubber (Singh et al., 2015; Xu et al., 2010). Certain azo dyes can undergo reduction to produce carcinogenic amines when ingested hence, some azo dyes are listed as probable cancer-causing agents in humans and animals (International Agency for Research on Cancer IARC, 2010). Potassium indigotetrasulphonate is an aromatic dye that is chemically stable, has high heat and light stability, and is highly toxic even at low concentrations (Camargo et al., 2014; Nunes Costa et al., 2020). C.I Pigment Black 7 is a reinforcing agent in polymers and polymer blends and is used widely by the plastic industry, ranking it second in this regard to C.I. Pigment White 6. It is stable in polymers and not considered a toxicant (Chaudhuri et al., 2018; Lenz et al., 2015).

## 3.4. Estimated daily intake and ecotoxicological implications

The estimated daily intake/consumption (EDI) of MPs from tap water was calculated based on MP concentration and the recommended daily intake using equation (1) (Li et al., 2023; Makhdoumi et al., 2021; Zuccarello et al., 2019).

$$\mathrm{EDI}_{\mathrm{MPs/kg.day}} = \frac{\mathrm{C} \times \mathrm{IR}}{\mathrm{BW}} \tag{1}$$

Where C is the MP concentration (particles/L), and the ingestion rate (IR) is the recommended daily intake of consumable liquids. The IRs per South African dietary guidelines are 1.7 L/day for children aged 4–8 years, 2.7 L/day for women, and 3.7 L/day for men older than 19 years. The corresponding body weights (BW) for children, women, and men were set to 20.3 kg, 74.1 kg, and 71.9 kg, respectively (Bourne et al., 2007; Lemein, 2019; Wenhold and Faber, 2009). The EDIs of MPs from tap water in children, men, and women were found to be 1.2, 0.71, and 0.50 particles/kg.day, respectively. These were higher than the EDIs reported by Zhou et al. (2021) for Chinese adults (0.27 particles/kg.day) and children (0.60 particles/kg.day). According to these estimates, South African children consume more MPs compared to women and men.

Human senses cannot detect the small MP particles in tap water and can thus be ingested. Various sources of literature have reported MP particles in the placenta (Ragusa et al., 2021), stool (Schwabl et al., 2019), infant meconium and adult faeces (Zhang et al., 2021), lung tissue (Amato-Lourenço et al., 2021), and human blood (Leslie et al., 2022). Drinking water in South Africa is therefore a potential oral exposure source of MPs. Future studies may further assess MPs in air and food samples from Gauteng and compare their intake to that for tap water.

A high number of fibers were present in tap water, a finding that is consistent with studies by Ramaremisa et al. (2022), Saad et al. (2022a, and 2022b), and Weideman et al. (2020). In those studies, high concentrations of MP fibers were reported in surface water, sediment, and fish of the Vaal River (Gauteng Province). Furthermore, Ramaremisa et al. (2022), also observed a high prevalence of green (22.3%), black (19.1%), and blue (18.3%) MPs. This is similar to the findings of this study, in which a high concentration of black (29.3%), green (23.8%), and blue (23.8%) MPs were obtained. Thus, similarities exist between MPs in tap water and surface water from the Vaal River, which forms part of the IVRS, the primary source of potable water in Gauteng. Fibrous particles were reported to be retained longer, have higher acute toxicity, and mortality rates in freshwater organisms than other shapes (Gray and Weinstein, 2017; Qiao et al., 2019; Saad, 2023). Evidence suggests that fibrous MPs behave the same way in humans. Ibrahim et al. (2021), detected up to 96% of MP particles in colectomy samples from adults as fibrous. The longer retention of fibrous MPs may cause more harm as a result of additives and unreacted residual polymers leaching from them. In species with longer gut retention, like humans and fish, the leaching of chemicals might be enhanced (Ibrahim et al., 2021; Wright and Kelly, 2017). In this study, small, coloured MPs were most abundant (<1 mm). This is particularly concerning because coloured MPs may contain toxic chemicals, and MPs <1 mm can pose various threats to organisms (Saad et al., 2023; Saad and Alamin, 2024). For instance, the desorption of toxic additives has been reported to increase with a decrease in the size of MPs and may be more pronounced in MPs less than 1 mm (Liu et al., 2020; Luo et al., 2020). Liu et al. (2020), reported higher leaching of cadmium-based pigment in MPs less than 0.85 mm compared to those with sizes above 0.85 mm. Consequently, the majority of MPs detected in tap water in this study have potential to act as micro-vectors and enhance the bioavailability of plastic-derived toxicants. Microplastics have been reported to be retained in the digestive systems of various freshwater organisms (Saad et al., 2022a; Wright and Kelly, 2017), there is a possibility of translocation to various tissues, organs (liver and muscle), circulatory and lymphatic systems (Daniel et al., 2020).

## 4. Conclusions

This study examined the physical-chemical properties of MPs in tap water in three suburbs in Gauteng Province in South Africa (Tembisa, Braamfontein, and Silver Lakes). The concentrations of MPs were: 4 to 20 particles/L (mean of 13 ± 4.9 particles/L), 9.0 to 31 particles/L (mean of 18 ± 6.2 particles/L), and 4.7 to 16 particles/L (mean of 11 ± 4.0 particles/L) in Tembisa, Braamfontein, and Silver Lakes, respectively. The most prevalent shape was fibers (83.1%), and the most abundant colours were black, blue, and green. Different polymer types and additives were detected, with some that are potentially toxic e.g., C. I. Pigment Red 1 and C.I. Solvent Yellow 4. The physical characterisation provided insights into the shape and size of MPs that are more likely to pass through DWTPs. This is essential if future technologies are to be developed for MP removal in DWTPs and faucet systems in household taps. In general, the findings of this study have pointed to the implications of the presence of MPs in tap water on potential exposure of humans, with children showing an elevated likehood of intake. This offers a benchmark for further work to draw on for the formulation of standards for MP content in drinking water in South Africa.

## Statements & declarations

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## CRediT authorship contribution statement

**Gibbon Ramaremisa:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Hlanganani Tutu:** Writing – review & editing, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Dalia Saad:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization.

## Declaration of competing interest

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

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chemosphere.2024.141903.

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