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Occurrence and characteristics of microplastics in South African beverages☆

Gibbon Ramaremisa [a], Rudolph M. Erasmus [b], Hlanganani Tutu [a], Dalia Saad [a,c,*]

[a] School of Chemistry, Molecular Sciences Institute, University of the Witwatersrand, South Africa
[b] School of Physics and Microscopy and Microanalysis Unit, University of the Witwatersrand, Johannesburg, South Africa
[c] Department of Chemistry, University of Pretoria, Pretoria, South Africa

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ABSTRACT

This study presents the first comprehensive assessment of microplastics (MPs) in alcoholic (AB) and non-alcohol (NAB) beverages in South Africa. Beverages in various packaging materials, specifically glass, aluminium, and polyethylene terephthalate (PET) were tested for MP content. The samples were filtered and digested, then stained with Rose Bengal dye to facilitate particle identification, followed by physical and chemical characterisation using stereomicroscopy and micro-Raman spectroscopy, respectively. Fibers were the prevalent shape observed in AB packaged in glass, as well as in NAB (PET), and NAB (Aluminium). The Aluminium samples also exhibited a high abundance of fragments. Multivariate principal component analysis and Pearson correlation coefficient matrix revealed positive correlations between fibers of size ranges 0.02–0.1 mm and 0.1–0.5 mm in NAB samples. While in AB samples, the ranges were observed to be 1–2 mm and 2–3 mm. Six polymers were identified, namely: polypropylene (PP), polyethylene (PE), polyurethane (PU), polyamide (PA), PET, and polybutylene terephthalate (PBT). This study offers a holistic appraisal of MPs in commercially sold beverages in South Africa. It establishes a framework for assessing the socioeconomic impacts of MPs, including their commercial, environmental, social, and sustainability implications.

1. Introduction

Microplastics (MPs) were first documented in the Sargasso Sea and are now considered anthropogenic indicators of the "Anthropocene" epoch due to their ubiquity and impact on ecosystems (Nikiema et al. 202a; 2020b). This notion is motivated by their propensity to form diverse technofossils in the Earth's stratigraphic profile. Nevertheless, there is no recorded occurrence of technofossils in Africa (Carpenter and Smith, 1972; Shruti et al., 2023; Torres and De-la-Torre, 2021).

This knowledge gap extends to African marine, freshwater, drinking water, sediments, biota, fauna, and beverages. Only recently have studies provided an African perspective on MP as contaminants of emerging concern (CECs) in food sources (crabs, fish, oysters, mussels, and molluscs) (Dahms et al., 2022; Khan et al., 2020; Latcheman et al., 2024; Nyaga et al., 2024; Saad et al., 2022; Saad and Alamin, 2024). To date, there is still a lack of research on the physical-chemical properties of these CECs in commercially sold African beverages and other fast-moving consumer goods (FMCG). However, any research on MPs in beverages should provide a holistic view of MP contamination in alcoholic and non-alcoholic beverages. Such data would be useful as a reference for assessing the risks MPs pose to humans, comparing pollution levels, formulating standards, and identifying their impact on achieving the United Nation's Sustainable Development Goals (SDGs) (Dahms and Greenfield, 2024; Walker, 2021).

Beverages are a diverse assortment of fluids that supply the body with macronutrients, micronutrients, energy, and water. Alcoholic beverages include beers (ale, lager, pilsener, stout, porter, and cider), wines (red wine, white wine, and spirit coolers), and spirits (brandy, whiskey, liqueur, and vodka). While tea, fruit juices, coffee, soft drinks, milk, carbonated, and noncarbonated beverages are some non-alcoholic varieties (Shruti et al., 2020; Statistics South Africa [Statistics South Africa, 2024). MPs have been previously reported in non-alcoholic beverages from Ecuador, Mexico, Italy, South Korea, Spain, and Türkiye. MPs have also been detected in alcoholic beverages from China, Germany, the United States of America (U.S.A.), Mexico, Ecuador, South Korea, Spain, and Italy (Crosta et al., 2023; Pham et al., 2023;

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* Corresponding author. Department of Chemistry, University of Pretoria, South Africa.
E-mail addresses: dalia.saad@wits.ac.za, dalia.saad@up.ac.za (D. Saad).

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Socas-Hernández et al., 2024; Zhou et al., 2023).

Beverages are sold in different packaging options and materials that preserve their physical-chemical and organoleptic properties. To this end, packaging materials are coated with tin, aluminium oxide, polyester and epoxy-acrylic copolymer resins (El Guerraf et al., 2022; Hayrapetyan et al., 2024). Socas-Hernández et al. (2024) reported high concentrations of jelly-like epoxy resin particles from all canned beverages they analysed. Packaging includes bottles (plastic polymers, copolymers, and glass), cans (aluminium and tinplate ($FeSn_2$)), cartons (paperboard and acrylic), and bags (plastic polymer or composite). Due to this diversity, the packaging sector has gained notoriety as the leading producer of plastic products and waste in South Africa (Okeke et al., 2022).

The beverage industry is a compelling area for MP research. For instance, the beverage industry uses large quantities of freshwater, from growing ingredients such as fruits, cereal grains, hemp, and vegetables to production (i.e., manufacturing, rinsing, and cooling). Approximately 3–10 L of freshwater are used for every 1 L of beverage produced. The large quantities of wastewater produced are often treated before being discharged into freshwater bodies, municipal sewer systems, or the producer's wastewater treatment facilities for reuse. Various processes are utilised including coagulation, flocculation, and membrane filtration. These processes employ metal salts, ceramics, nanomaterials, and polymers (e.g., ethylene-propylene-diene monomer rubber, polyacrylamide (PAM), cellulose acetate, polyamides (PA), polypropylene (PE), and polysulfones) (Altunışık, 2023; Mainardi-Remis et al., 2021; Simate et al., 2011). Of further concern is that MPs have previously been detected throughout South Africa's water supply chain (Bouwman et al., 2018; Ramaremisa et al., 2022, 2024; Saad et al., 2024a; Vilakati et al., 2021). Beverages may be contaminated by non-intentionally added substances (NIAS), which inadvertently migrate from the packaging, such as plastic oligomers, plastic additives, and recycling remnants (Aigotti et al., 2022; Hayrapetyan et al., 2024).

South Africa's alcoholic beverage industry is one of the biggest worldwide. The nation's largest producer produces over 3.1 billion liters of domestic and international brands annually. Alcoholic and non-alcoholic beverages accounted for 6.13% of household purchases among South Africa's 60.6 million inhabitants. Beverages ranked third behind processed (8.57%) and unprocessed (6.73%) food (South African Breweries, 2020; Statistics South Africa, 2024). Hence, South Africa has been ranked first in Africa (tenth in the world) for beer consumption and plastic production. On the other hand, South Africa ranks second to Egypt in its generation of plastic debris (Deme et al., 2022). Consequently, the alcoholic beverage industry is intricately linked to macro (micro)plastic pollution.

The presence of MP through the human body has been well documented with recent studies raising questions on their impact on reproductivity. An analysis of semen and ovarian follicular fluid samples from the Campania Region (Southern Italy) revealed the presence of MPs in 60% and 78% of the samples analysed, respectively. MPs in the body may cause Oxidative stress, apoptosis, inflammation and fibrotic response, and hormonal balance disturbance (Montano et al., 2024, 2023).

In light of the potential health risks posed by MPs and the prevalence of plastic and beverage consumption in South Africa, it is thus essential to investigate the occurrence of MPs in commercially available beverages. Additionally, the effect of packaging on the physical-chemical properties of the same brand of beverages (alcoholic and non-alcoholic) has not yet been extensively explored. To the best of our knowledge, this is the first study that aimed to provide the extent of occurrence and comprehensive physical-chemical characterisation of MPs in commercially sold beverages in South Africa. This has been achieved by providing data on MP concentrations, physical-chemical properties (polymer type, shape, size, and colour) and their correlations across samples, estimating daily intakes, investigating the impacts of packaging materials, and comparing findings to similar studies in the field.

2. Materials and methods

2.1. Quality control and chemicals

Adequate measures were adopted to avoid or reduce cross-contamination, sample loss from leakages during filtration, and interference during analysis. Blank experiments were conducted to account for procedural contamination. Chemicals were purchased from Sigma Aldrich (Merck KGaA, Darmstadt, Germany).

2.2. Sample collection and identification

Assorted brands of alcoholic and non-alcoholic beverages were purchased between May and September 2023 from supermarkets in South Africa. The brands' names will be omitted for ethical reasons. Beverages from the same brand packaged in different packaging materials were purchased to determine the effect of packaging material on MPs' physical-chemical properties. Non-alcoholic and alcoholic beverage brands are abbreviated as NABB and ABB, respectively. Non-alcoholic beverages with PET and Aluminium packaging are referred to as NAB (PET) and NAB (Aluminium), respectively. Alcoholic beverages in glass and aluminium packaging are referred to as AB (Glass) and AB (Aluminium), respectively (Table 1).

2.3. Sample preparation and microplastic extraction

To minimise sample contamination, all experiments were conducted under a laminar flow cabinet (ESCO Micro Pte. Ltd., Singapore) at the Analytical microplastic laboratory at the University of the Witwatersrand. The analyst wore a green cotton laboratory coat and nitrile gloves throughout the analysis. Samples were vacuum filtered through Whatman® GF/F glass microfiber filters (Ø = 47 mm, 0.42 mm = thickness, and pore size = 0.7 μm) (Cytiva Danaher Group, Buckinghamshire, United Kingdom). Filters were subjected to wet peroxide oxidation using 5 mL of 0.07 M $FeSO_4 \bullet 7H_2O$ and 5 mL of 30% (v/v) H_2O_2. After digestion, 5 mL of 0.2 mg/mL Rose Bengal (4,5,6,7-tetrachloro-2′,4′,5′,7′-tetraiodofluorescein) solution was applied to each filter residue, allowed to stain, and then washed off with Milli-Q Type 1 Ultrapure water. The filter was allowed to dry and stored in glass Petri dishes (Aldrich Essentials, Merck KGaA, Darmstadt, Germany) until analysis (Ramaremisa et al., 2024, 2022).

2.4. Characterisation of microplastics

2.4.1. Physical characterisation

A Nikon MET SMZ745T stereomicroscope (Nikon Instruments Inc, New York, U.S.A.), equipped with The Imaging Source camera (The Imaging Source Europe GmbH, Germany) was utilised for physical characterisation. All stained particles (non-MPs) were not characterised.

Table 1
Estimated daily intakes from beverages.

Sample (packaging)	Mean concentration (particles/L)	Children	EDI (particles/kg.day)	
			Women	Men
NAB (PET)	5.2	0.44	0.15	0.22
NAB (Aluminium)	16	1.34	0.48	0.67
NAB (PET and Aluminium)	15	1.26	0.45	0.63
AB (Glass)	16	NA	0.08	0.16
AB (Aluminium)	14	NA	0.06	0.13
AB (Glass and aluminium)	9.5	NA	0.04	0.09

NA = Not applicable.

Particle size, shape, and colour were determined and recorded with the aid of NIS Elements-D imaging software (Nikon Instruments Inc., New York, U.S.A.). MPs were classified into assorted colour categories, namely: black, blue, brown, green, grey, purple, red, white, and yellow. Particles were characterised as transparent when they did not have any visible colourants. MPs were also categorised according to their shapes, *viz*: fibers, fragments, pellets, and films (Fig. 1a-d). The shape and size of MPs were defined according to criteria reported by Pivokonsky et al. (2018).

2.4.2. Chemical characterisation

Chemical characterisation was performed using a Horiba LabRAM HR micro-Raman spectrometer (Horiba Jobin Yvon, Japan) with gratings ruled at 600 lines/nm. Samples were radiated with an Argon ion laser at 514.5 nm with a laser power in the range of 0.04–0.4 mW, a confocal pinhole of 100 μm was used. To allow visualization of MPs an Olympus BX41 microscope (NA = 0.80) with 100× objective was used. Calibration was performed on each day of analysis by using the position of the primary first-order phonon band of single-crystal silicon. Acquisition parameters were varied to avoid polymer degradation due to laser-induced heating and to acquire a better response signal. For some samples, fluorescent background interference was suppressed by carefully balancing laser power and acquisition time. Chemical analysis was performed on 70% of all non-stained particles per filter. The chemical composition of MPs was determined by comparison with reference spectra in the SLOPP Library of MPs and polymer databases of KnowItAll® Informatics system software (John Wiley and Sons, Inc., New Jersey, U.S.A.) (Ramaremisa et al., 2024, 2022; Latcheman et al., 2024).

2.5. Data analysis

Numerical data are expressed as the mean value ± standard deviation (SD) unless specified otherwise. Figures were plotted using OriginPro 2024(OriginLab Corporation, Northampton, Massachusetts). Statistical tests were executed using Statistical Package for the Social Sciences (SPSS) version 27 (SPSS, Chicago, Illinois, U.S.A.) and OriginPro 2024. The data was analysed for normality and homogeneity using Shapiro-Wilk and Levene's tests, respectively. A parametric Independent Samples T-test was used to determine whether there were statistically significant differences in MP concentrations of beverages in different packaging (PET, aluminium, and glass). Differences between samples were considered statistically significant if $p < 0.05$ at a 95% confidence interval of the mean. Pearson correlation coefficient matrix and principal component analysis (PCA) were used to determine the relationship between physical properties, different brands, and packaging.

2.6. Risk assessment

2.6.1. Estimated daily intake

An empirical approach was adopted for estimated daily intake (EDI) using equation (1), where C is the MP concentration (particles/L), IR is the recommended dietary ingestion rate (L/da), and BW is the estimated mean body weight (kg) (Altunışık, 2023).

$$EDI = \frac{C \times IR}{BW} \quad (1)$$

BW for children, women and men were 20.3, 74.1, and 71.9 kg, respectively. The IR for non-alcoholic beverages for children, women, and men is 1.7, 2.2, and 3.0 L/day, respectively. South African dietary guidelines recommend no more than two drinks (680 mL) of alcoholic beer for men and one drink (340 mL) of regular beer for women per day (Ramaremisa et al., 2024; Vorster et al., 2013). This equates to beer IRs of 0.68 L/day and 0.34 L/day for men and women, respectively.

2.6.2. Microplastic contamination factor and pollution load index

The MP contamination factor (MPCF) correlates the MP concentration in this study to literature background levels. MPCF and MP pollution load index (MPLI) in beverages were calculated using equations (2) and (3), respectively. In equation (1), MP_a is the MP concentration in sample a, and MP_m is the lowest MP concentration from the literature. The $MPCF_m$ values taken from Altunışık (2023) and Kosuth et al. (2018) for non-alcoholic and alcoholic beverages were 8.9 and 4.5 particles/L, respectively. The MPCF were divided into four groups: low contamination (MPCF < 1), moderate contamination (MPCF range: 1–3), considerable contamination (MPCF range: 3–6), and very high contamination (MPCF > 6) (Altunışık, 2023; Ibeto et al., 2023; Kabir et al., 2021). MPLI

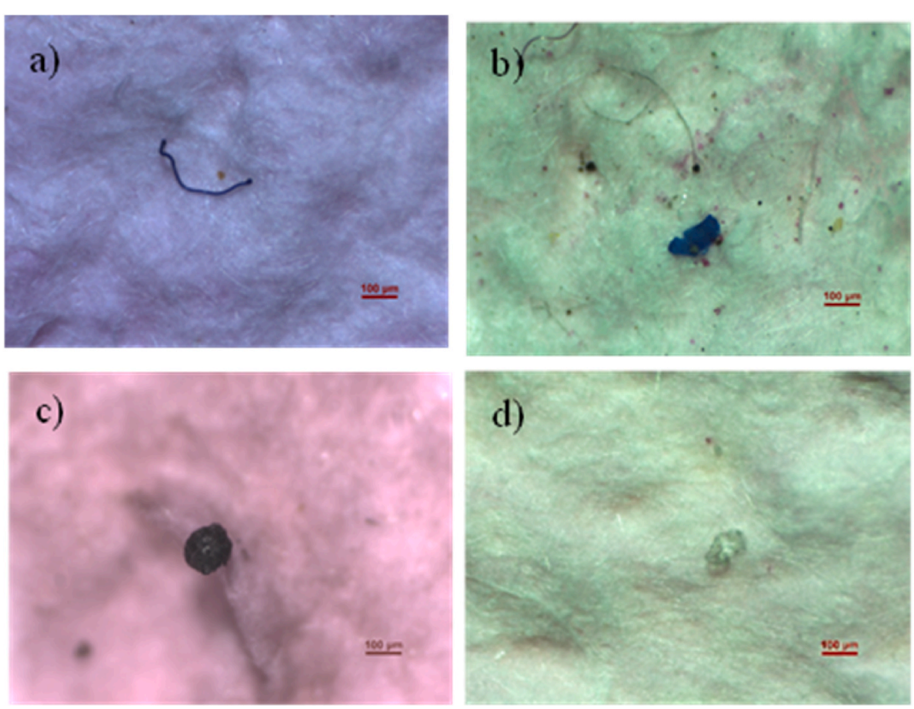

Fig. 1. Images of microplastic a) blue fiber b) blue fragment c) black pellet, and d) transparent film.

were classified as follows: ecological risk level 1 (MPLI <10), risk level 2 (MPLI range: 10–20), risk level 3 (MPLI range: 20–30), and danger level 4 (MPLI >30) (Khan et al., 2023; Li et al., 2023).

$$\mathrm{MPCF} = \frac{\mathrm{MP_a}}{\mathrm{MP_m}} \quad (2)$$

$$\mathrm{MPLI_{sample\ type}} = \sqrt[n]{\mathrm{MPCF_1} \times \mathrm{MPCF_2} \times \mathrm{MPCF_3} \ldots\ldots\ldots \mathrm{MPCF_n}} \quad (3)$$

3. Results and discussion

3.1. Microplastic concentration

MP concentrations are expressed as particles/L, and MPs were detected in all 20 samples (15 brands) of NAB (PET and aluminium). NAB (PET and Aluminium) had a mean MP concentration of 9.5 ± 8.5 particles/L (range: 2.0–38 particles/L). To assess the influence of different packaging on MP concentrations, 10 samples (5 brands) (NABB1–NABB5) were considered, which were packaged in aluminium and PET bottles. NAB (PET) concentrations ranged from 2.0 to 12 particles/L (mean: 5.2 ± 4.4 particles/L). NAB (Aluminium) concentrations ranged from 4.6 to 38 particles/L (mean: 16 ± 14 particles/L) (Table 1). However, there were no statistically significant differences for the different packaging (Independent Samples T-test, $p > 0.05$) in concentration.

Similar to non-alcoholic beverages, MPs were detected in each of the 23 samples (15 brands) of AB (Aluminum and Glass). MP concentrations ranged from 4.0 to 29 particles/L (mean: 15 ± 7.6 particles/L). To evaluate the impact of packaging materials and processes (aluminium cans versus glass bottles) on MP concentrations, 16 samples (8 brands) (ABB1–ABB8) were considered. AB (Aluminium) and AB (Glass) had mean concentrations of 14 ± 7.1 particles/L (range: 6.1–29 particles/L) and 16 ± 7.7 particles/L (range: 7.5–29 particles/L), respectively (Table S1). There were no statistically significant differences (Independent Samples T-test, $p > 0.05$) between AB (Aluminium) and AB (Glass).

3.2. Estimated daily intake

From Tables 1 and it's evident that children (EDI = 1.26 particles/kg.day) had higher EDIs than women (mean EDI = 0.45 particles/kg.day) and men (EDI = 0.63 particles/kg.day) for NAB. This is consistent with our previous study on tap water, whereby children (1.2 particles/kg.day) had higher EDIs than men (0.71 particles/kg.day) and women (0.50 particles/kg.day) (Ramaremisa et al., 2024). The EDIs from all NAB (men: 0.63 particles/kg.day and women: 0.45 particles/kg.day) were higher than EDIs from all AB (men: 0.09 particles/kg.day and women: 0.04 particles/kg.day. Specifically, NAB (Aluminium) had the highest EDIs (women: 0.48 particles/kg.day and men: 0.67 particles/kg.day) followed by NAB (PET) (women: 0.15 particles/kg.day and men: 0.22 particles/kg.day). In alcoholic beverages, AB (Glass) (women: 0.08 particles/kg.day and men: 0.16 particles/kg.day) had higher EDIs than AB (Aluminium) (women: 0.06 particles/kg.day and men: 0.13 particles/kg.day). Across all sample types, men had higher EDI than women.

The non-alcoholic beverages EDIs from this study were higher than those reported for Turkish soft drinks (0.009 particles/kg.day), Spanish soft drinks (0.02 particles/kg.day) and assorted drinks (i.e. energy drinks, Isotonic drinks, and tea) (0.003 particles/kg.day) (Altunışık, 2023; Socas-Hernández et al., 2024). Socas-Hernández et al. (2024) reported EDIs of 0.092 and 0.019 particles/kg.day for beer and wine intake, respectively. EDIs were higher than those for South African women but lower than for men (Table 1). However, socioeconomic dimensions such as lifestyle choices, race, gender, age, religion, and health disorders influence beverage intake (Vorster et al., 2013). Hence, comprehensive studies should be conducted to evaluate the influence of socioeconomic dimensions on MP ingestion through beverages.

3.3. MPCF and MPLI

The MPCF in non-alcoholic beverages ranged from 0.22 to 4.31. MPCF the contamination in non-alcoholic brands was as follows: NABB1 < NABB4 < NABB5 < NABB2 < NABB3. According to the MPCF classification, 70% of all non-alcoholic beverages had low contamination (MPCF < 1) and 20% had moderate contamination (MPCF range: 1–3). Alcoholic beverages MPCF values ranged from 1.4 to 6.4 and the following trend was observed: ABB1 < ABB2 < ABB3 < ABB6 < ABB5 < ABB8 < ABB7 < ABB4. In alcoholic beverages 50% of the samples were moderately contaminated (MPCF range: 1–3), 37.5% were considerably contaminated (MPCF range: 3–6), and 12.5% were very highly contaminated (MPCF>6) (Fig. 2). Non-alcoholic beverages were categorised as risk level 1 (MPLI<10). On the other hand, alcoholic beverages were categorised as danger level 4 (MPLI>30).

3.4. Physical characteristics

Typical shapes of MP particles in beverages are shown in Fig. 2. MP fibers were the most abundant morphotype in NAB (PET) (85%) and NAB (Aluminium) (83%). NAB (PET), fragments (10%), and pellets (5%) were present in minor proportions, and no films were detected. Fragments, pellets, and films accounted for 12%, 3.4%, and 1.4%, respectively in NAB (Aluminium) (Fig. 3a). The majority of MPs in NAB (PET) and NAB (Aluminium) were in the 0.5–1 mm (35%) and 0.1–0.5 mm (59%) size ranges, respectively (Fig. 3b). NAB (Aluminium) and NAB (PET) had mean sizes of 0.36 ± 0.36 mm and 0.82 ± 0.77 mm. In NAB (PET) samples, fibers, fragments, films, and pellets had mean sizes of 0.94 ± 0.79 mm, 0.09 ± 0.03 mm, and 0.05 ± 0.04 mm, respectively. Thus, MP particles in NAB (PET) had the following trend: fibers > fragments > pellets. On the other hand, fibers, fragments, films, and pellets had mean sizes of 0.41 ± 0.37 mm, 0.10 ± 0.05 mm, 0.13 ± 0.05 mm, and 0.04 ± 0.01 mm, respectively, in NAB (Aluminium). MP particles in NAB (Aluminium) had the following trend: fibers > films > fragments > pellets. There was a high abundance of black (33%), grey (23%), blue (13%), and red (13%) particles in NAB (PET). NAB (Aluminium) samples had a high abundance of blue (45%), black (21%), and green (18%) particles (Fig. 3c).

As shown in Fig. 3a, fibers were the most abundant morphotype in AB (Glass) (65%). Fragments (29%), films (5.9%), and pellets (0.74%) were present in minor proportions. However, AB (Aluminium) had more fragments (65%). Fibers (28%), pellets (6.1%), and films (0.87%) were present in minor proportions. The majority of MPs in AB (Glass) and AB (Aluminium) were in the 0.02–0.1 mm (61%) and 0.1–0.5 mm (33) size

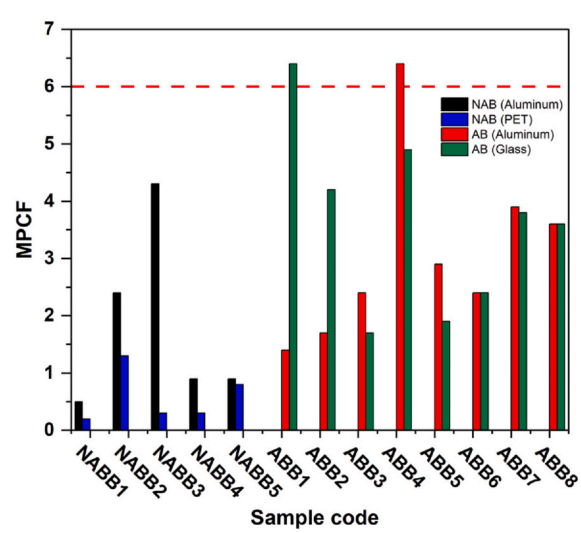

Fig. 2. Microplastic contamination factors in beverages.

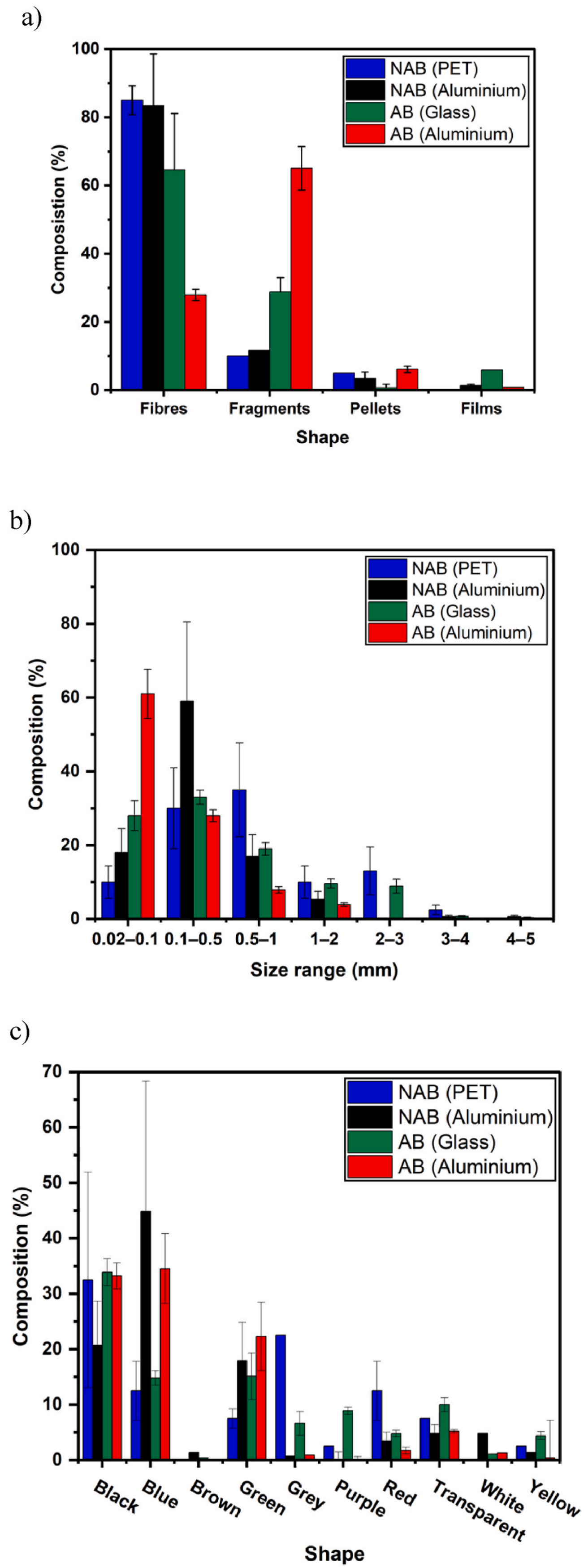

Fig. 3. Composition of microplastic a) shapes and b) colours c) size ranges.

ranges, respectively (Fig. 3b). AB (Glass) and AB (Aluminium) had mean sizes of 0.63 ± 0.78 mm and 0.21 ± 0.31 mm, respectively. In AB (Glass), fibers, fragments, films, and pellets had mean sizes of 0.92 ± 0.84 mm, 0.10 ± 0.09 mm, 0.13 ± 0.03 mm, and 0.07 ± 0.06 mm, respectively. In AB (Aluminium) fibers, fragments, films, and pellets had mean sizes of 0.55 ± 0.40 mm, 0.08 ± 0.07 mm, 0.09 ± 0.03 mm, and 0.05 ± 0.04 mm, respectively. Thus, MP particles in alcoholic beverages had the following trend: fibers > films > fragments > pellets. AB (Glass) had a high abundance of black (34%), green (15%), and blue (15%) particles. Similarly, AB (Aluminium) samples had a high abundance of blue (35%), black (33%), and green (22%) particles (Fig. 3c).

3.5. Principal component analysis and pearson correlation coefficient matrix

For PCA, PC 1 and PC 2 accounted for 72.02% of the total variance of their corresponding data set (Fig. 4a). High positive correlations (Pearson correlation coefficient: r = 0.96) were found between fibers and the 0.1–0.5 mm size range in NAB (Aluminium) 2. PC 1 and PC 2 explained 61.49% of the total variance of their corresponding data set (Fig. 4b). Fibers had high positive correlations with the 1–2 mm and 2–3 mm (Pearson correlation coefficient: r = 0.91 and r = 0.93) size ranges. Correlations were mainly due to fibers in AB (Glass) 1 and AB (Glass) 2. Moreover, fragments had high positive correlations (Pearson correlation, r = 0.96) with 0.02–0.1 mm in AB (Aluminium) 4. Nevertheless, correlations of the physical properties of beverages from the same brand in different packaging could not be ascertained, underlining the variability in their contamination sources.

3.6. Chemical characterisation

Six different types of polymers were detected in commercially sold beverages, namely: polypropylene (PP), polyethylene (PE), polyurethane (PU), polyamide (PA), polyethylene terephthalate (PET), and polybutylene terephthalate (PBT). Polymers detected in NAB (PET) were PP (42%), PET (33%), and PE (25%). In NAB (Aluminium), PET (46%), PP (31%), PE (15%), and PU (7.7%) were detected. In AB (Aluminium) samples, the detected polymers were PP (44%), PET (33%), PA (11%), and PE (11%) while the polymers detected in AB (Glass) were PE (46%), PET (27%), PBT (18%), and PP (9.1%) (Fig. 5a). Although there were no distinct patterns in polymer composition PP, PE, and PET were the most common polymers throughout the different samples.

As shown in Fig. 5b, there was a high abundance of PET (36.4%), PP (31.3%), and PE (24.2%) in all samples, which is consistent with their extensive application in the South African food and beverage industry accounting for 11%, 45%, and 35%, respectively. PP, PE, and PET were found in different shapes such as fibers, fragments and films(Figure S1a, b, and c) Thus, potential sources include packaging materials (i.e., bottles and caps) and freshwater sources. MP fragments were mostly made up of PBT (Figure S1d), the polymer possesses similar physical-chemical properties to PET and has numerous electrical, electronic, and mechanical applications in the FMCG industry (Saad et al., 2024c; Welz et al., 2022). White fragments were made of PU (Figure S1e), which has applications as a sealant, adhesive, coating, insulator, flexible and rigid foams. Potential sources include sealants and adhesives used in packaging materials (Matías, 2022). Red fibrous MPs were mostly made up of PA (Figure S1f), which has applications in automotive parts, electronics, plastic gears, and cable ties; thus, potential sources include degraded machinery parts. However, these polymers have other applications (e.g., textiles, biomedicine, and separation science) not mentioned above and their MP products have various potential pathways into beverages.

3.7. Comparison to similar studies

This study is one of a few studies that have analysed MPs in non-

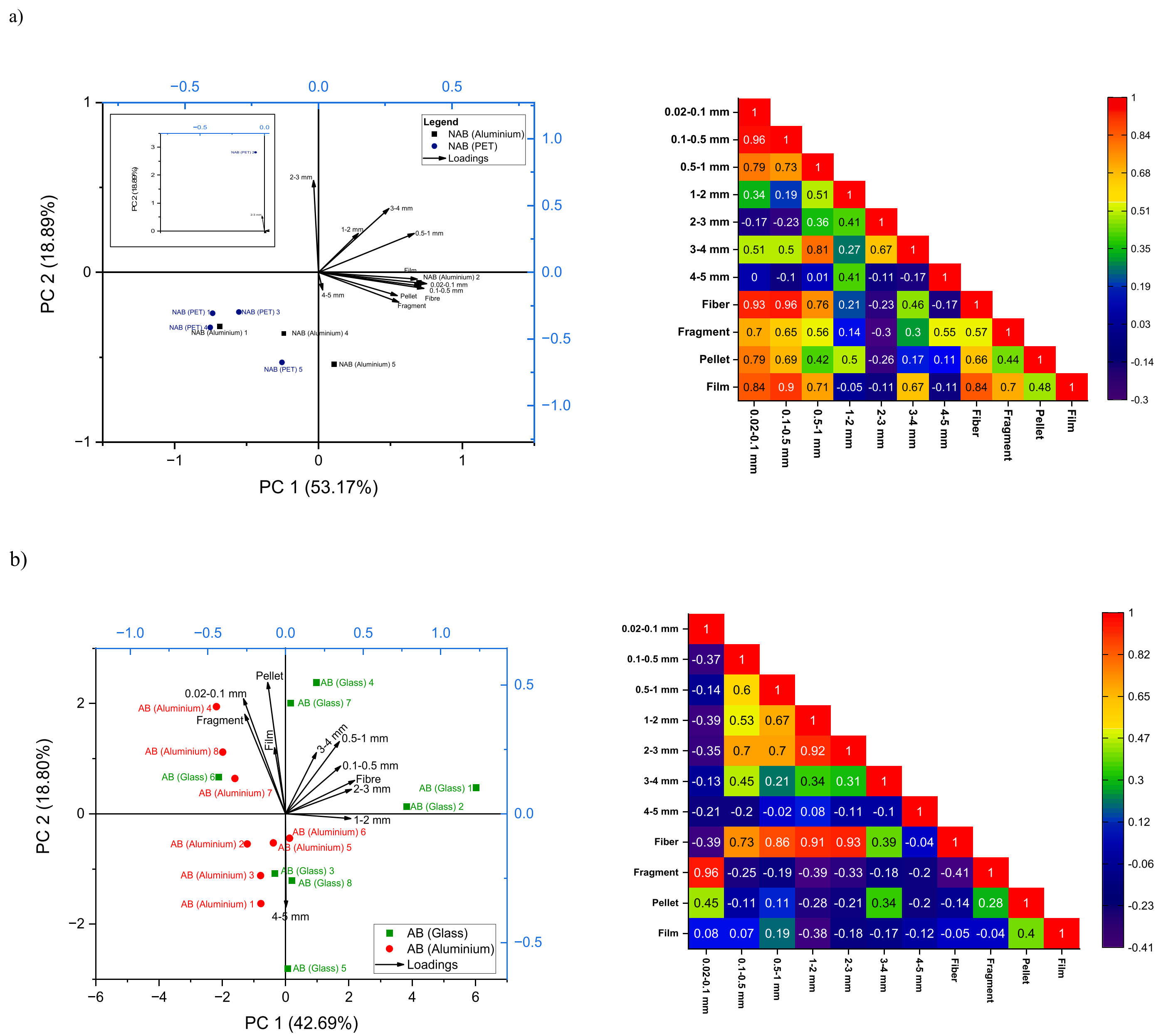

Fig. 4. PCA biplot and Pearson correlation coefficient matrix of MPs in a) non-alcoholic and b) alcoholic beverages.

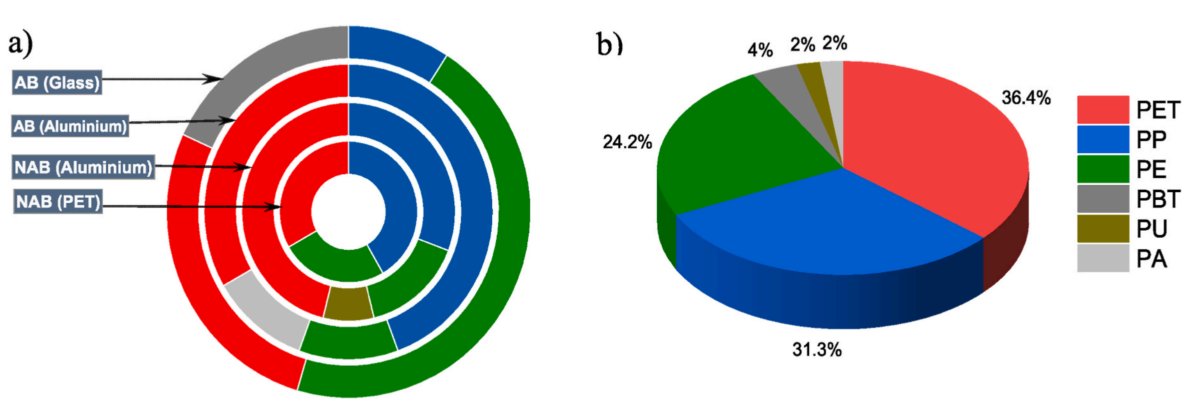

Fig. 5. a) Polymer composition in a) different sample types and b) all samples.

alcoholic beverages in the world (Table S2). The highest mean MP concentration (40.0 ± 24.5 particles/L) was reported by Shruti et al. (2020) for 19 soft drinks (PET and glass) from Mexico. The authors reported a high abundance of blue (62.5%), red (25%), and brown (12.5%) fibers. In the same study, the authors also reported a mean concentration of 14.0 ± 5.79 particles/L from 8 energy drinks with 93% of blue fibers. A recent study from Spain reported mean concentrations of 22.5 ± 18.7 and 24.8 ± 27.3 particles/L from soft drinks and other beverages (i.e., energy drinks, isotonic drinks, and tea), respectively. Soft drinks were contaminated with blue (93%) and red (7%) fibers. A mean concentration of 32.0 ± 12.0 particles/L was reported by Diaz-Basantes et al. (2020) for 14 soft drinks (PET and Tetra Pak). Altunışık (2023), analysed MPs in the top 10 soft drink brands from Türkiye and reported a mean concentration of 8.9 particles/L. The author reported the presence of fibers (60%), fragments (34%), and films (6%). Pham et al. (2023) reported median concentrations of 29.3 and 2.25 particles/L in fruit drinks and soft drinks, respectively. PP and PE were the dominant polymers in fruit juices and soft drinks, respectively. This study had a mean MP concentration of 9.5 ± 8.5 particles/L in non-alcoholic beverages (PET and aluminium). The high abundance of fibers and PP, PE, and PET polymers in this study is consistent with a majority of studies considered for comparison.

Table S3 shows the characteristics of alcoholic beverages contaminated with MPs. Prata et al. (2020) reported an MP concentration of 183 ± 123 particles/L in 26 glass bottles of white wine from Italy. The authors reported the presence of contaminants such as insect parts, fibers, wood fragments, and minerals. Shruti et al. (2020) reported a mean concentration of 152 ± 50.97 particles/L with a high abundance of fibers (93.42%) in Mexican alcoholic beverages. Mean concentrations of 56.7 ± 73.5 and 95.2 ± 91.8 particles/L were reported in wine and beer samples in Spain, respectively (Socas-Hernández et al., 2024). In Ecuador, Diaz-Basantes et al. (2020)reported mean concentrations of 32 and 47 particles/L from glass-packaged craft and industrial beer, respectively. The authors reported the presence of fibers and fragments in various colours (red, green, violet, yellow, and blue). In one of the earliest studies to report on MPs in alcoholic beverages, Liebezeit and Liebezeit. (2014) reported a mean of 22.6 particles/L from 24 German beer brands. A median concentration of 9.00 particles/L was reported for 18 imported and domestic beer samples (Pham et al., 2023). Kosuth et al. (2018) reported low MP contamination (4.05 ± 1.76 particles/L) in 12 American beer brands, with a high abundance of fibers (98.4%). This study had relatively low mean MP concentration (mean: 15 ± 7.6 particles/L) in alcoholic beverages. MPs were classified as fibers, fragments, pellets, and films with a high number of them being black, blue, and green. Five polymers detected in alcoholic beverages were PP, PE, PA, PET, and PBT.

3.8. Source apportionment and recommendations

The level of MP concentration in beverages analysed in this study was as follows: NAB (Aluminium) > AB (Glass) > AB (Aluminium) > NAB (PET). Thus, the source of MPs in beverages could not be linked to specific packaging material. There are numerous possible sources of MPs in drinks, which complicates the task of identifying their origins. MPs in beverages may be introduced during processing, storage, and packaging (Altunışık, 2023; Sewwandi et al., 2023).

Potential sources include municipal tap water, rainwater, and groundwater used during production (Jin et al., 2021; Lee et al., 2024). Recent evidence of MPs in South Africa's FMCG water supply chain justifies this assertion and further suggests that water treatment and beverage production facilities are not equipped to extract MPs. Weideman et al. (2020) and Dahms et al. (2022) reported a high abundance of filaments/fibers and green particles from an FMCG industry freshwater source (i.e., the Orange-Vaal River system). Swanepoel et al. (2023) reported the presence of PE, PU, and polyester in South Africa's two main drinking water treatment plants. Bouwman et al. (2018) reported the presence of fibers and fragments in Gauteng tap water samples. Furthermore, studies by Ramaremisa et al. (2022, 2024) and Saad et al. (2024b) reported a high abundance of fibrous green, black, and blue MPs in surface water and tap water. The mean sizes of MPs were less than 1 mm and MPs were made up of PE, PP, PU, and PET polymers. Thus, the physical-chemical properties of MPs in beverages are consistent with those from freshwater sources, distribution networks, and tap water.

Ingredients such as grains, fruits, and vegetables used during the production of beverages may uptake MPs from soil and freshwater and release them into beverages (Chen et al., 2023; Lazăr et al., 2024). Other potential sources include MPs from workers' textiles, atmosphere, and degraded plastic machinery parts. Intrinsic and extrinsic factors such as the capping system, copolymers, temperature, pH, and bottle age are also suspected to play a role in the release of MPs and NIAS (Acarer, 2023; Aigotti et al., 2022; Jin et al., 2021; Shruti et al., 2021). PCA revealed no correlations of physical properties in the same brands, which further confirmed the broad spectrum of contaminants. Around the world, there has been an increase in the number of unregulated counterfeit food and beverages (Amankwah-Amoah et al., 2022; Okorie et al., 2019). This significantly exacerbates contamination sources as unregulated beverages flood the market, making source apportionment more challenging.

Given the current global expectation that businesses operate within appropriate environmental, social, and governance (ESG) principles and ethos, the presence of MPs in beverages has significant ramifications for the FMCG sector. Moreover, there is a need to monitor the quality of these CECs in the same way that parameters such as pH, total carbohydrates and proteins; salt and sugar levels; macronutrients and micronutrients are monitored. The general environmental laws and city by-laws are still lagging in terms of the promotion of recycling plastics. This can be addressed by introducing financial penalties or incentives, reducing the extensive use of single-use and non-biodegradable plastics, and eliminating illegal dumping activities (Deme et al., 2022; (a and b); Vilakati et al., 2021; Welz et al., 2022). Moreover, there should be amendments to South Africa's Foodstuff, Cosmetics and Disinfectants Act (Act 54 of 1972) to address the issue of MPs in FMCG. Alternatively, new laws specifically aimed at addressing MPs in South African food and beverages can be introduced. In the future, the FMCG industry should be mandated to utilise biodegradable plastic alternatives provided that adequate investments are made. This would greatly reduce the perpetual cycle of macro(micro)plastic pollution.

3.9. Limitations of this study

Fruit juices were excluded from this assessment due to their tendency to clog filter pores. Including fruit juice samples in the study could offer a more comprehensive view of microplastic contamination. Colourants, fillers, reinforcements, and functional additives can cause high fluorescent background interference which can overlap polymer spectra (Lenz et al., 2015; Schymanski et al., 2018). Despite the use of countermeasures like photobleaching, some interferences persisted, which could still lead to an underestimation of the polymer composition. Moreover, the use of Rose Bengal dye which serves to enable the exclusion of natural polymer can result in further underestimation if natural polymers are still present on MP surfaces after digestion.

4. Conclusions

The mean MP concentrations in non-alcoholic beverages (9.5 ± 8.5 particles/L) and alcoholic beverages (15 ± 7.6 particles/L) were determined, indicating the extent of occurrence of these contaminants. Statistically, there were no significant differences between alcoholic (glass versus aluminium) and non-alcoholic beverages (PET versus aluminium). Men had a higher potential estimated daily intake of MPs compared to women. Fibers were the most abundant shape in all non-alcoholic beverages and AB (Glass); however, fragments were the most abundant shape in AB (Aluminium). The mean sizes of MPs across all sample types were less than 1 mm with a high abundance of black, blue, and green MPs. PCA and Pearson correlation coefficient matrix revealed high positive correlations between fibers and various size ranges in alcoholic and non-alcoholic beverages. This highlights their wide distribution across different size ranges. However, correlations between the same brands could not be established. Micro-Raman spectroscopy identified six types of polymers in commercially sold beverages, namely: PP, PE, PU, PA, PET, and PBT. A comparison of MP concentration to other studies revealed relatively low levels of MP contamination in South African beverages. This study provides a holistic view of MPs in commercially sold beverages. Moreover, it serves as a framework for a socioeconomic evaluation that considers the commercial, environmental, social, and sustainability repercussions of MP contamination in South Africa. Furthermore, findings can be used in future policy formulation and technology fabrications for MP extraction and control.

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CRediT authorship contribution statement

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2024.125388.

Data availability

Data will be made available on request.

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