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Research Paper

Macro- and microplastics in composts from municipal solid waste industrial composting Plants in Uganda

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ABSTRACT

Organic fertilizer use constitutes one of the main pathways through which (micro)-plastics enter the environment. However, little is known about the extent of plastic contamination in biowaste composts from Sub-Saharan Africa, where municipal biowaste collection involves minimal to no source separation. This study assessed macro- and microplastic contamination in composts from two Clean Development Mechanism composting facilities in Uganda processing mixed municipal solid waste for agricultural use. Finished composts were sampled per Plant at monthly intervals for four months (September 2023 to January 2024), and sieved into different size fractions: >5, 1.18–5, 0.6–1.18, 0.212–0.6, and 0.063–0.212 mm. Microplastics in each fraction (<5 mm) and macroplastics (>5 mm) in composts were analyzed. The results indicated heavy macro- and microplastic contamination in composts from both Plants. Macroplastics (>5 mm) ranged from 0.11 to 4.70 (1.50 ± 1.24) g/kg dry weight in Plant 1 and 0.36–4.93 (1.78 ± 1.27) g/kg dry weight in Plant 2. Total microplastics in composts exceeded all previous literature studies, averaging about 49,000 ± 7,000 and 62,000 ± 6,000 items/kg dry weight, respectively. For both facilities, compost fraction 0.212–0.6 mm showed the highest microplastic contamination, followed by 0.063–0.212, 0.6–1.18, and 1.18–5 mm. Total microplastics in composts depended on facility pile turning, feedstock contamination, and local population density. Polyethylene and polypropylene were the most dominant polymers in macro- and microplastics from composts, with fragments and fibers most dominant microplastic shapes. Estimations of plastic load show that such MSW compost can input into amended soils macroplastics of 2.0–106.7 kg/ha and 2.9×10^{8} – 2.4×10^{9} microplastic items/ha per recommended application.

1. Introduction

The management, or rather mismanagement, of the organic fraction of municipal solid waste (MSW) is one of the most challenging issues of the present time. As the global population continues to grow, urbanization becomes widespread, and consumers become more affluent, MSW generation continues to grow annually (Khan et al., 2022). Nearly 2.1 billion tonnes of MSW were produced globally in 2023, and this is projected to reach 3.8 billion tonnes by 2050 (UNEP, 2024). Developing and low-income economies with inadequate waste management and disposal practices characterized by poor technical, financial, and infrastructural capabilities are experiencing the most significant increase in MSW generation (Zhang et al., 2024). The inadequate management of MSW biowaste in these countries poses several consequences, including pollution of water, air, and land resources (Mor and Ravindra, 2023), disease transmission (Khan et al., 2022), emissions of greenhouse gases (Maria et al., 2020), and obstruction of drainage channels (Zhang et al., 2024). There are increasing calls to sustainably manage the biowaste component of MSW.

Biowaste composting is a key component of sustainable waste management through which biodegradable organic matter is processed into compost under appropriate environmental conditions. This is an essential concept in the circular economy of MSW biowaste that helps mitigate its environmental and social impacts on the one hand (Ddiba et al., 2022; Magazzino et al., 2020), and promote nutrient circularity on the other (Naqvi et al., 2022). Notably, global compost production has

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been increasing in the last few decades. In the European Union (EU), for example, MSW compost production increased from 14 million tonnes in 1995 (Rajaeifar et al., 2017) to 42 million tonnes in 2019/2020 (ECN, 2022). Composting remains the main form of biowaste treatment in the EU (Siebert et al., 2020). Similarly, there are increasing trends in compost production in Africa, the Middle East, and the United States (Cao et al., 2023).

While sub-Saharan Africa (SSA) faces several challenges in MSW biowaste composting, the practice is slowly gaining popularity. About 10 to 15 years ago, Uganda implemented an ambitious plan to improve MSW management through composting. With financial support from the World Bank through the UNFCCC's Clean Development Mechanism (CDM), the country piloted the establishment of up to twelve industrial composting Plants in different municipalities between 2008 and 2015 (UNFCCC/CCNUCC, 2014). The facilities process mixed MSW into compost for agricultural and horticultural use (Kabasiita et al., 2021). Resultantly, the finished compost is of low quality, including heavy contamination by macroplastics (MaPs) and microplastics (MiPs), as well as other inert physical pollutants. Uganda generates an estimated 600 metric tonnes of plastic waste daily (GIZ, 2023), with only about 40 % of this collected for disposal in the waste management system, and the rest left in the environment. About 10 % of the uncollected plastic waste in Uganda ends up in the country's water bodies (NEMA, 2024), with potential immediate and long-term implications. Waste collection in Uganda is done in the mixed mode (not separated at source), negating the potential recoverable benefits from the high content of biodegradable organic matter in the country's waste. Plastics constitute about 4 % of the total waste generated in Uganda, with at least 40 % of this improperly disposed (NEMA, 2024). The plastic recycling rate in Uganda is abysmally low, with some informal sources estimating this at just about 1 % of the total generated plastic waste (Africanews, 2018).

Despite the potential environmental risks, plastics in organic fertilizers such as compost are not given considerable attention and are inadequately monitored (Brťková et al., 2024; Kaur et al., 2025). Some of the threats posed by plastics include induced environmental ecological imbalance, physical, chemical, and biological transformation leading to toxicity and mobility (Bamigboye et al., 2024), transport of pollutants in the environment (Laskar and Kumar, 2019), and constrained growth and development of soil fauna (Huerta Lwanga et al., 2016; Zhang et al., 2022). MaPs and MiPs have recently gained notoriety as a severe environmental threat that may enter the environment through recycled fertilizer use, including compost and sewage sludge, plastic mulching, irrigation water, littering, and atmospheric input (Bläsing and Amelung, 2018). In compost, plastics originate from inappropriate waste management systems where plastic bags are used for biowaste collection and disposal, which are not or unsatisfactorily removed during biowaste composting. Other sources of plastics include food and non-food packaging containers, films, plastic-coated items, and other forms of plastics, which are collected with biowaste. During composting, these plastics may disintegrate due to mechanical turning and thermophilic temperatures achieved, releasing macro-, micro-, and nanoplastics, contaminating the finished compost.

While studies elsewhere have provided evidence of plastic pollution in recycled organic fertilizers, including compost (Brťková et al., 2024; Magni et al., 2024; Premarathna et al., 2024; Steiner et al., 2024; Zafiu et al., 2023), there is very scanty information on the occurrence and abundance of plastics in compost from SSA. Specifically, there is a lack of evidence on the degree and extent of macro- and microplastic pollution in MSW compost from Uganda, where mixed MSW composting is practiced for agricultural use. Further, knowledge about the size distribution of MiPs presents a guide in evaluating their potential environmental implications, interactions, and transportation. The present study analyses the macro- and microplastic pollution of compost from two CDM MSW composting facilities in Uganda. Besides plastics, other inert physical contaminants in composts were quantified and compared with the regulatory limits. Specifically, the study's objectives are to:

1) determine the particle size distribution of composts sampled from two CDM MSW composting plants in Uganda;
2) determine the occurrence, distribution, and characteristics of macro- and microplastics in the different compost size fractions; and
3) assess the potential implications of using such composts on amended agricultural soils.

2. Materials and methods

2.1. Description of study sites and sampling period

Firstly, two out of the 12 CDM MSW composting facilities in Uganda were selected following rigorous multi-selection criteria to choose facilities that were operational, with their management willing to participate in the study (2.1 S1). Eventually, two facilities were selected in January/February 2023 for sampling and performance evaluation. The two facilities are located in Masindi Municipality (in Western Uganda) and Mukono Municipality (in Central Uganda). From here on, Plant 1 will refer to the facility in Masindi Municipality, while Plant 2 will refer to the facility in Mukono Municipality.

Compost sampling was undertaken between September 2023 to January 2024. The MSW composition brought to the facilities comprised a high fraction of biodegradable organic matter. During the sampling period, biodegradable organic waste fraction accounted for 88.9 $\pm$ 1.2 % (wet weight) and 79.1 $\pm$ 4.8 % (wet weight) for Plant 1 and Plant 2, respectively. The total MSW received in Plant 1 is about 35–60 tonnes per day and 60–70 tonnes per day for Plant 2.

2.2. Description of the facilities and composting systems used

MSW received for composting in both facilities is a mixture of household and commercial wastes from markets, restaurants, schools,

Table 1
Summary of the main features of the two CDM MSW composting Plants in Uganda where the studied composts were sampled.

Parameter	Plant 1	Plant 2
Design capacity (metric tonnes per day)	70	70
MSW collection systems	Trucks collect waste from households, markets, streets, schools, and other commercial enterprises.	Same as Plant 1
Biodegradable organic fraction of MSW	≈ 89 % mass	≈ 79 % mass
Non-compostable fractions in delivered MSW	≈ 11 % mass	≈ 21 % mass
Facility information	The composting yard is made of concrete flooring, divided into 6 windrow bays, and roofed with iron sheets. A leachate tank is provided to collect leachate draining from the decomposing organic waste.	Same as Plant 1
Composting technology	Passive, naturally aerated windrow system.	Same as Plant 1
Total Municipality population (Year 2022)	120,000	200,000
Population density (persons/km^2)	About 330	About 1,000
Pretreatment	Some preliminary manual sorting of received waste before composting.	No sorting to remove non-biodegradable materials takes place.
Sieving of the final compost	Manually performed using a 5 mm metallic sieve.	Same as Plant 1

green cuttings, and street sweeping. Table 1 describes the main information about the two facilities. Each facility operates in a different region of Uganda, with Plant 1 operating in a rural to intermediate region, while Plant 2 operates in an urban and high-density population area. Besides, Plant 1 is used to dispose food waste from an oil exploration company, in addition to the municipality collected waste. Resultantly, Plant 1 receives MSW highly rich in biodegradable organic fraction compared to Plant 2.

Once in the Plant, the received MSW undergoes minor pre-composting operations where some non-biodegradable materials are removed. Pre-composting operations are activities undertaken on the received waste prior to the commencement of composting. In the two Plants investigated, these operations included the manual removal of some non-compostable materials such as plastics, metals, and glass from biowaste, followed by mixing and lining the waste in the windrows to begin the degradation process. While shredding of large-sized feedstock is recommended for proper biowaste composting, this step was not performed in the investigated facilities. Following preliminary storage and manual separation at the reception bay, the wastes are transferred with the aid of a motorized wheel loader to the first windrow to begin the decomposition process.

In both facilities, the passive aerobic windrow composting system is used. Composting occurs in a yard made of concrete floors and several double-pitched iron sheet roofs (Fig. S1). Composting feedstock is piled in the windrows, naturally aerated, moistened, and is required to be turned periodically until maturity. However, due to resource and workforce constraints, the composting process is often not carried out as recommended, with insufficient pile turning (Kabasiita et al., 2022), and low pile moisture content. Leachate generated from the composting process is collected in an underground tank and often recycled back to the composting materials to facilitate better composting.

The decomposition process lasts 6 to 12 weeks, upon which maturation is allowed for a few more weeks in the maturation windrow. The final stabilized material is sieved using a 5 mm sieve to attain finished compost. Fractions less than 5 mm are retained as finished compost, while those greater than 5 mm are disposed of as rejects in a designated area at the facility.

Currently, there are issues regarding the acceptability and use of composts from the two Plants by farmers. Farmers often complain that the compost is low-grade due to significant visible physical impurities, including plastic, glass, and metal in the compost. While the usability of compost is notably high at Plant 1, the same cannot be said for Plant 2. Farmers have largely shunned compost from this facility for an extended period, resulting in the compost being disposed of on municipal land at no cost.

2.3. Compost sampling and preparation

All composts analyzed in this study were sampled monthly for four months between September 2023 to January 2024. Three replicates of approximately 6,000 g each were collected per Plant per sampling month. During sampling, sub-samples of finished compost were collected from different points within the pile at least 30 cm deep and quartered on a flat surface until the desired amount was obtained. Collected samples were stored in sealed aluminium bags and transported to the laboratory for analysis. Each replicate was divided into two equal portions, with one portion used to determine moisture content, microbial quality, and compost stability (*results are not presented in this manuscript*). In contrast, the other half was used to determine the remaining parameters, including plastic contamination. For the second part, the samples were air-dried until constant weights before analysis.

2.4. Analysis of the investigated parameters

2.4.1. Particle size distribution of compost

Before conducting the particle size distribution, sampled composts were air-dried to the same equilibrium moisture content (until no moisture loss for all drying samples). Due to the bulky nature of samples, a solar dryer, which maintains temperature between 40–65 °C, was used to dry the compost. For the particle size distribution study, approx. 1000 g of air-dried composts were fractionated in a 5, 1.18, 0.6, 0.212, and 0.063 mm dry-sieves tower. The sieves were arranged in a decker in the respective order, and the samples were screened for approximately 30 min using continuous vibration. Small screens (0.212 mm and $<$ 0.063 mm) occasionally experienced clogging and were dislodged by mild amplitude changes. The sieves were selected based on commercially available certified mesh sizes in the laboratory and sieving practices at the composting plants. The six-size fractions obtained were weighed, and their mass percentages calculated. The different fractions were analyzed for plastic (MiPs and MaPs) pollution and other relevant parameters. The sieving process was performed under laboratory conditions to mitigate the influence of moisture absorption from the ambient environment by dried samples.

2.4.2. Inert physical impurities in the compost

Undesirable impurities measuring at least 2 mm, including glass, stone, metal, and plastic, were hand-separated, washed, dried, weighed, and expressed as a percentage of the total compost dry weight. The purpose of washing was to get rid of fine particles hanging on the contaminant materials, and accurately estimate contaminant amounts per unit compost weight. The difference in weight before and after washing was negligibly small, as care was taken to remove most of the materials during the particle size distribution of compost.

2.4.3. Determination and characterization of macroplastics/mesoplastics in compost

Microplastics (MiPs) are synthetic polymers measuring less than 5 mm in size (Frias and Nash, 2019); however, the studied composts contained plastics larger than 5 mm. Mesoplastics (MePs), conversely, are plastics that range between 5–25 mm in size (Braun et al., 2021), while macroplastics (MaPs) are those in excess of 25 mm (Romeo et al., 2015). In this text, MaPs are used to refer to all plastics measuring at least 5 mm in size.

For compost size fractions of at least 5 mm, suspected plastics were visually identified, handpicked, and subdivided using sieves into 5–25 mm and $>$ 25 mm, representing MePs and MaPs, respectively. Since these are large-sized plastics (5 mm and above), it was easy to visually identify and isolate from the sieved compost fraction. 50 % of all MaPs/MePs per facility were randomly selected to analyze their polymer identity. The random sampling selection was done to include plastic particles of different sizes, shapes, and colors. Given the large number of MaPs/MePs in composts from the two Plants sampled for four months, the use of random sampling of 50 % plastics in compost from each facility was taken to be a more representative estimate of polymer composition for MaPs. The selected MaPs/MePs from Plant 1 and Plant 2, respectively, were collected and cleaned with tap water before washing in an ultrasound bath, air dried at room temperature, counted, and weighed. The polymer identity was analyzed using ATR-FTIR. Further, MaPs/MePs were characterized for color.

2.4.4. Extraction of microplastics in the compost

The other compost fractions (1.18–5 mm, 0.6–1.18 mm, 0.212–0.6 mm, 0.063–0.212 mm) were used to determine the microplastic content in the respective size fraction. For large MiPs (1.18–5 mm), $\approx$ 10 g of compost was weighed, and suspected MiPs visually identified and manually handpicked with a tweezer, washed in an ultrasound bath, air-dried at room temperature, counted, and weighed. To avoid identifying non-plastic items, e.g., glass and stones, suspected MiPs were subjected to density separation using saturated K_2CO_3 solution (density $\approx$ 1.5 g/cc), and only those able to float in the solution were considered (Naeem et al., 2024). All identified plastics were stored in glass petridishes before ATR-FTIR examination for polymer identification.

For compost fractions < 1.18 mm (0.6–1.18 mm, 0.212–0.6 mm, and 0.063–0.212 mm fractions), MiPs were extracted through oxidative digestion and density separation, as has been widely used for samples rich in organic matter (Radford et al., 2021; Surendran et al., 2024).

Sample preparation was done by digesting approximately 10 g of compost using 50 ml of 30 % H_2O_2 and 50 ml hydrated $FeSO_4$ (13.9 g/L). Digestion was done to remove organic matter that would otherwise compromise microscopic and spectroscopic examination of MiPs. Additional H_2O_2 was added in 10 ml increments until foaming was considerably reduced. Digestion was allowed to continue for 24 h at 50 °C to allow time for all organic matter to be digested. Digested samples were vacuum filtered through a 45 μm-stainless steel sieve and washed with deionized water to remove any residual H_2O_2. The resultant digestate was subjected to density separation using saturated K_2CO_3 (density ≈ 1.5 g/cm^3). The contents were briefly stirred and allowed to settle for 12 h in a glass beaker. The supernatant layer containing MiPs was vacuum-filtered through a 0.5-μm glass filter and rinsed with distilled water to remove any residual K_2CO_3 solution. The density separation process was repeated for the items remaining in the beaker for maximum recovery. The filtrate was discarded, and the samples in the glass filter were dried at 50 °C and stored in glass petridishes.

Before implementing microplastic extraction and density separation, the effectiveness of the procedure was tested by performing a recovery test as described in 2.2 S2. The results of the recovery test were deemed effective and are shown in 2.2.1 S3 and Table S1.

2.4.4.1. Identification of microplastics and resin type. A stereomicroscopic examination was performed for each piece of MiP-loaded glass fiber filter using a ZEISS Stemi 508 Stereomicroscope (Carl Zeiss Microscopy GmbH, Germany) for preliminary microplastic identification. The microscope was fitted with AxioCam 208 color camera to take pictures. Different magnifications were used depending on the size of each suspected item. The images were obtained using Labscope imaging software. The following criteria were applied to examine and identify the isolated MiPs: 1) homogenous colour, 2) clearly defined shape, 3) melting with a hot needle to confirm the plastic (if necessary), and 4) no powdering or breaking upon pressing with a needle (Naeem et al., 2024). The identified MiPs were counted and classified based on their shape (fragment, fiber, film, bead, pellet, and foam) and color (white, transparent, yellow, red, green, blue, black, purple, orange, and pink). The definitions of shapes to classify microplastic items in this study are explained in 2.3 S4 and Table S2. The quantitative results were expressed as the number of plastic items per unit dry weight of compost.

MiPs were classified for their polymer characteristics. 21 % of suspected MiPs were randomly selected (Gui et al., 2021), by choosing all shapes, colors, and size ranges, and the chemical nature of MiPs in the 1.18–5 mm range was identified using ATR-FTIR spectroscopy (AIM-9000), operating with LabSolutions IR software (Shimadzu, Japan). In comparison, those < 1.18 mm were performed using the ATR mode of the micro-FTIR spectrometry. In both cases, a total of 20 scans were used at a spectral resolution of 4 cm^{-1} and 4000–400 cm^{-1} spectral range. Before FTIR analysis, a background scan was performed. The obtained spectra of MiPs were compared with the reference spectra of polymers in the library of software LabSolutions IR. The polymer similarity threshold was set to 60 % for positive identification, except in some specific cases for which a case-by-case evaluation was performed.

2.5. Mitigation of contamination during sampling and analysis

Microplastic analysis requires careful attention during sampling, handling, and analysis as these are highly prone to contamination, resulting in errors in reported results. Careful precautions were taken to avoid contamination. During sampling, compost was carefully collected in aluminium foil, sealed, and transported to the laboratory. Plastic containers and tools were avoided during sampling, handling, and analysis. All laboratory analyses were conducted by one and only the same person, wearing nitrile gloves and a laboratory coat made of cotton. All laboratory equipment used were made of glass or metal and thoroughly cleaned and dried in an oven before use. The saturated K_2CO_3 solution was prepared with distilled water and filtered through 45 μm stainless steel sieve before use. All glass-fiber filters containing extracted MiPs were stored in glass petridishes, sealed with aluminium foil, and opened only when needed. Laboratory blanks were analyzed with each batch of samples to confirm the integrity of the analysis, and these showed negligible contamination.

2.6. Statistical analysis

Data were analyzed using Microsoft® Excel® 365 and SPSS (IBM, 25.0, USA), and results were presented as average values ± standard deviation. Before statistical analysis, Shapiro–Wilk and Kolmogorov-Smirnov normality tests were used to check the normality of macroplastic and mesoplastic abundance, total number of MiPs, and total content of inert impurities > 2 mm in compost. One-way ANOVA and an independent sample *t*-test were performed to compare the differences among groups. Differences were significant at $p < 0.05$.

3. Results and discussions

3.1. Particle size distribution and inert physical impurity content in MSW compost

The particle size mass fractionation of compost from two composting facilities in Uganda showed similar patterns (Fig. 1). Compost particles of 1.18–5 mm size represented the largest fraction in both Plants, followed by 0.212–0.6 mm and 0.6–1.18 mm (Fig. 1). Compost size < 0.063 mm represented the least fraction in compost from both facilities, constituting 2.8 ± 0.7 % and 3.0 ± 0.3 % for Plant 1 and Plant 2, respectively. For particle size fraction > 5 mm, this contributed 21.4 ± 1.8 % and 5.9 ± 1.5 % in compost from Plant 1 and Plant 2, respectively. Despite sieving the stabilized materials using a 5 mm sieve, materials > 5 mm were still found in finished composts (Fig. S2).

The contribution of 1.18–5 mm particle size forming the largest fraction in MSW compost has been reported elsewhere. For example, in the study of Brťková et al. (2024), size fraction 1.25–5 mm constituted the largest percentage (39.9 %) in MSW compost from Czech Republic. The fractionation results obtained in this study are also comparable to studies by Sharifi and Renella (2015) and Saha et al. (2013). Saha et al.

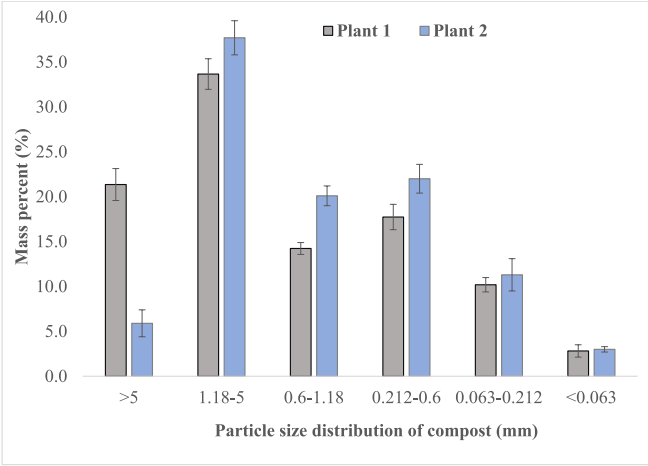

Fig. 1. Particle size distribution of compost sampled from 2 CDM MSW composting Plants in Uganda. Values are the arithmetic means ± standard deviation of samples collected in triplicate monthly for four months and given in dry mass %.

(2013) reported the lowest compost mass fraction for < 0.075 mm size, irrespective of preparation method.

The inert physical impurity content measuring at least 2 mm contributed 18.0 ± 2.1 % and 9.1 ± 1.1 % of the compost dry weight in Plant 1 and Plant 2, respectively (Fig. 2). The total physical impurity content in compost was significantly higher ($p < 0.05$) in Plant 1 compared to Plant 2. Stones constituted the most common physical impurity content in compost from both facilities, contributing 16.3 ± 2.0 % and 7.4 ± 1.4 % of the compost dry mass, respectively. In a study by Sharifi and Renella (2015), stones also formed the largest physical impurity content (18.2 %) in Iranian compost of mixed MSW origin. In Uganda's MSW compost, stones originate from solid waste collection systems, including street sweepings of gravel roads and markets, which are fragmented during the mechanical turning process of composting. Additionally, stones have a higher density than all physical contaminants, and their small occurrence dominates the weight in compost compared to other contaminants such as plastic, glass, or metal. Physical pollutants remain the most important limitation to composting in Uganda and SSA in general, where mixed MSW collection is practiced. Despite attempts to perform manual separation of non-compostable materials at the facilities in Uganda before, during, and after composting, this is ineffective as significant amounts of physical pollutants remain in the final compost. While some adequate removal of non-biodegradable materials is practiced in Plant 1, there is minimal to no separation in Plant 2, and composting is performed for the waste as it is received.

Compared to other legislations, compost from Uganda's CDM composting plants would not be recommended for agricultural use elsewhere. Most regulations on compost use specify the stone content above 2 mm not to exceed 5 % compost dry weight (Okori et al., 2024), for which composts from Uganda's composting Plants exceeded 1.5 to 3.6-fold. On the other hand, the limit for total metal, glass, and plastic impurities greater than 2 mm in compost is restricted to no more than 0.4 % for Austria (BMSGPK, 2004), <0.8 % in Belgium (VLACO, 2011), and < 0.25 % in the United Kingdom (Okori et al., 2024). In the present study, the total content of metal, glass, and plastics in compost ranged from 0.6-2.6 % (average 1.7 ± 0.6 %) and 0.8–2.6 % (average 1.6 ± 0.6 %) in Plant 1 and Plant 2, respectively. These values exceed the physical impurity limit specified for most countries. The inert impurity content is an essential parameter in compost quality, especially for MSW compost that originates from solid waste that does not undergo source separation (Barreira et al., 2008). There is a regulatory impediment in this regard in Uganda, as there is no regulation on physical impurity limits for compost or organic fertilizers for agricultural use. Despite the vast biodegradable organic fraction in Uganda's MSW, valorization through biological means is constrained by non-biodegradable material fractions.

3.2. Occurrence and abundance of macroplastics and mesoplastics in the compost

All the investigated composts from Uganda's two CDM composting facilities showed an immense abundance of MaPs/MePs (Fig. S3), validating the widespread assumption of the risk of plastic contamination in composts derived from mixed MSW. Figs. 3 and 4 show the number and mass concentration of MaPs/MePs, respectively, in composts sampled from the two facilities. The total concentrations of MaPs/MePs in composts ranged from 0.1 to 4.7 (average 1.503 ± 1.235) g/kg dry weight in Plant 1 and 0.4 to 5.0 (average 1.783 ± 1.265) g/kg dry weight in Plant 2, respectively. The mean mass concentrations of these plastics > 5 mm in composts were, though, not statistically different ($p > 0.05$) between the two Plants. Regarding the number of plastic items, the sampled composts contained several items of MaPs/MePs ranging from 18 to 37 (average 25.7 ± 6.4 items/kg dry weight) and 10–106 (average 59.9 ± 30.7 items/kg dry weight) in Plant 1 and Plant 2, respectively. Composts sampled from Plant 2 showed a significantly ($p < 0.05$) higher total number of MaPs/MePs than from Plant 1.

The occurrence of plastics of at least 5 mm size in Uganda's MSW compost mirrors other studies of plastic contamination in compost. In Finland, the total concentration of MaPs/MePs in composts averaged 6.5 g/kg dry weight (Scopetani et al., 2022), while in Italy, it ranged between 1 to 15.3 g/kg dry weight in two MSW compost samples (Watteau et al., 2018). In Germany, composts produced from urban biowaste were reported to contain plastics of at least 5 mm with a concentration of 1.4 ± 0.6 g/kg dry weight (Braun et al., 2021).

Composts from Uganda's CDM MSW composting plants originate from mixed MSW, which shows an abundance of plastics and other unsuitable materials. Although the final stabilized material is sieved using a 5 mm screen, materials exceeding 5 mm, including plastics, are often found in the finished compost. This occurs due to broken sieves and the negligence of Plant workers who may not pass all finished materials through the sieve. Imasha and Babel (2024) also described the ineffectiveness of sieving in removing plastics of unwanted size in compost produced from a mechanical–biological treatment in Thailand. Due to improper waste disposal and lack of separation of plastics from biodegradable organic matter, the occurrence of MaPs and MePs in compost can lead to plastic accumulation in amended soils (Colombini et al., 2022; Ren et al., 2024), with the potential risk of entering the food chain through trophic transfer.

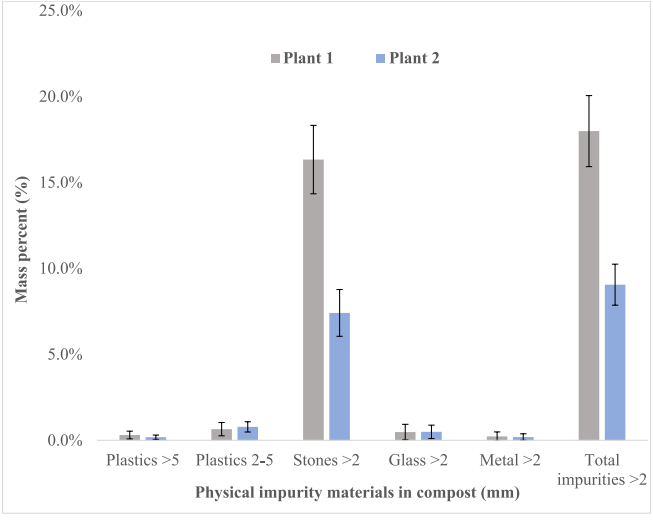

Fig. 2. The content of physical pollutants in compost from two CDM MSW composting Plants in Uganda. Values are the arithmetic means ± standard deviation of samples collected monthly in triplicate for four months and are given in dry mass %.

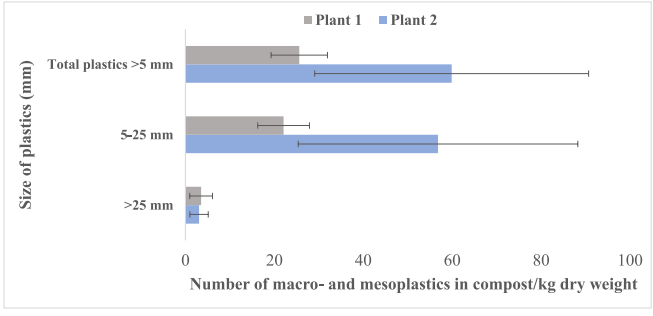

Fig. 3. Total number of macro- and mesoplastic items in composts sampled from two CDM MSW composting Plants in Uganda. Values are the arithmetic means ± standard deviation of samples collected monthly in triplicate for four months.

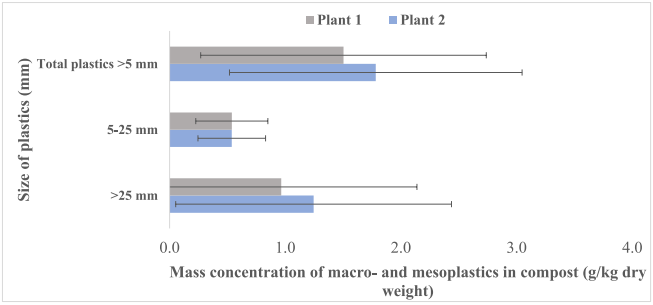

Fig. 4. Mass concentration of macro- and mesoplastics in composts sampled from two CDM MSW composting Plants in Uganda. Values are the arithmetic means ± standard deviation of samples collected monthly in triplicate for four months.

3.2.1. *Characteristics of macro-/mesoplastics in the composts*

Polyethylene (PE), polypropylene (PP), polystyrene (PS), polycarbonate (PC), and polyester (PES) represented at least 85.8 % of the total polymer of MaPs/MePs in composts. Overall, in composts sampled from Plant 1, PE (41.8 %) and PP (26.4 %) were the most abundant polymers in MaPs/MePs, followed by PC (7.7 %), PS (7.7 %), polyethylene terephthalate (PET) (4.4 %), polyvinyl chloride (PVC) (3.3 %), and polyurethane (3.3 %). Other identified polymers from Plant 1 composts were styrene acrylonitrile (2.2 %) and polyisoprene (1.1 %) (Fig. 5). In compost from Plant 2, PE (51.7 %) was the most abundant polymer, followed by PP (25.0 %), PS (7.5 %), PES (6.7 %), PC (4.2 %), and nylon (2.5 %) (Fig. 5).

In related studies, PE and PP dominated the total MaPs/MePs in composts of MSW origin (Scopetani et al., 2022; Zafiu et al., 2023), even though the composts were from different countries. PE and PP are among the most produced and used plastics globally (Fotopoulou and Karapanagioti, 2019). In Uganda, PE bags and other plastics in different forms and sizes are commonly used for several household purposes and face post-use disposal challenges.

In terms of color, white and transparent were the most dominant colors in MaPs/MePs, representing 76 % and 79 % of the total plastic colors isolated in composts from Plant 1 and Plant 2, respectively. Other plastics were colored and included black, red, yellow, green, pink, blue, and purple (Fig. 5).

3.3. *Microplastics occurrence, distribution, and characteristics in compost*

3.3.1. *Size distribution of microplastics in the compost*

Fig. 6 shows the average abundance of MiPs in the different compost size fractions. All the composts sampled from the two composting facilities showed an immense abundance of MiPs in all the investigated size fractions. However, the abundance varied depending on the size range and Plant. The total average abundance of MiPs in compost was 49,000 ± 7,000 items/kg dry weight in Plant 1, while it was 62,000 ± 6,000 items/kg dry weight in Plant 2. Composts from Plant 2 showed a significantly ($p < 0.05$) higher total number of MiPs than Plant 1. A relatively higher average microplastic contamination occurred in all compost size fractions sampled from Plant 2, in which waste from a more urban and densely populated municipality is processed, compared to Plant 1 (processing waste from a rural and less densely populated municipality). Further, MSW disposed at Plant 2 includes some industrial waste, even though this is not permitted for disposal at the composting facility.

The findings on compost from a densely populated municipality showing higher microplastic contamination agree with the study of Zafiu et al. (2023), which found composts from high-density populated areas in Austria to contain more microplastic contamination than those from low-population density areas (Zafiu et al., 2023). The study on Uganda's MSW composts also indicates that the partial removal of plastics and other non-biodegradable materials in the feedstocks before, during, and after composting may, to a small extent, lower the level of microplastic pollution in finished composts. Plant 1, which practices the partial manual removal of plastics and other non-biodegradable materials, showed lower MiPs and MaPs/MePs in composts than Plant 2, which does not practice any removal. Further, it can be assumed that the total number of MiPs in the studied composts would be much higher if pile turning was exercised as recommended during feedstock composting. During composting at these facilities, minimal pile turning occurs due to resource constraints, including the lack of fuel for operating machinery (Kabasiita et al., 2022).

In terms of the fractional distribution, compost fraction 0.212–0.6 mm showed the highest level of microplastic contamination in composts from both plants, making up 38.7 % and 35.7 % of total MiPs in compost from Plant 1 and Plant 2, respectively (Fig. 7). This was followed by particle size fractions 0.063–0.212, 0.6–1.18, and 1.18–5 mm in that order for both Plants (Fig. 7). The number of MiPs in the 1.18–5 mm size range was the least among all size fractions investigated, accounting for only 2.5 % and 2.7 % of the total MiPs in compost from the respective facilities. The dominance of 0.212–0.6 mm MiPs in compost can be closely contrasted with other studies of microplastic contamination in compost. The study of Naeem et al. (2024), for example, reported the majority of MiPs in MSW compost to be in the range of 0.1–0.5 mm, while 1–5 mm fraction was the least (Naeem et al., 2024). In the study of plastic degradation during MSW composting in two Austrian composting Plants, Zafiu et al. (2023) observed a trend towards the formation of more plastic particles in the size range 0.2–0.63 mm. However, particles smaller than 0.2 mm were not investigated in their study, and thus, difficult to contrast with the present study.

During composting, the size distribution of MiPs is altered, with the generation of smaller microplastic sizes as the process progresses. In the current study, total MiPs less than 1.18 mm constituted 97.5 % and 97.3 % of total MiPs in composts from Plant 1 and Plant 2, respectively. The dominance of MiPs less than 1 mm in MSW compost has been reported in previous studies. In the study of Sholokhova et al. (2021), MiPs < 1 mm accounted for 83.8–94.9 % of the total MiPs in mixed MSW compost from Lithuania. Small-sized MiPs were also reported to dominate MSW composts from Iran (Massahi et al., 2024) and China (Gui et al., 2021). The plastic transformation process can explain this dominance during composting. During biowaste composting, the frequent mechanical turning may cause the fragmentation of MaPs and large MiPs to form small MiPs or nanoplastics in finished composts (Braun et al., 2023). Besides, plastics develop more brittleness during composting, becoming vulnerable to fragmentation during the mechanical turning and sieving processes (Zhang et al., 2023). Further, plastics gradually degrade in the environment, forming MiPs or nanoplastics. While previous attention on microplastic studies mainly focused on those at least 1 mm in size, small sub-millimeter MiPs deserve considerable attention as these may be more hazardous to the environment (Steiner et al., 2024).

The knowledge of microplastic size in composts plays a crucial role in assessing their environmental and ecological implications (Zhao et al., 2023). The dominance of small MiPs in our study is of great concern since these easily bind to and transport environmental pollutants due to their large surface area-to-volume ratio, bioaccumulating in the food web (Naeem et al., 2024). On the other hand, large MiPs pose lower lethal toxicity compared to small MiPs. Thus, limiting the entry of small MiPs into the terrestrial environments is important to mitigate their ecological implications.

3.3.2. *Shape of microplastics in compost*

Fig. S4 shows the relative frequency of shapes of the different MiPs isolated from composts sampled from the two CDM MSW composting facilities in Uganda. Fig. S5 shows some of the shapes of MiPs isolated from composts during microscopic examination. Overall, fragments were the most dominant shape in all the compost size fractions

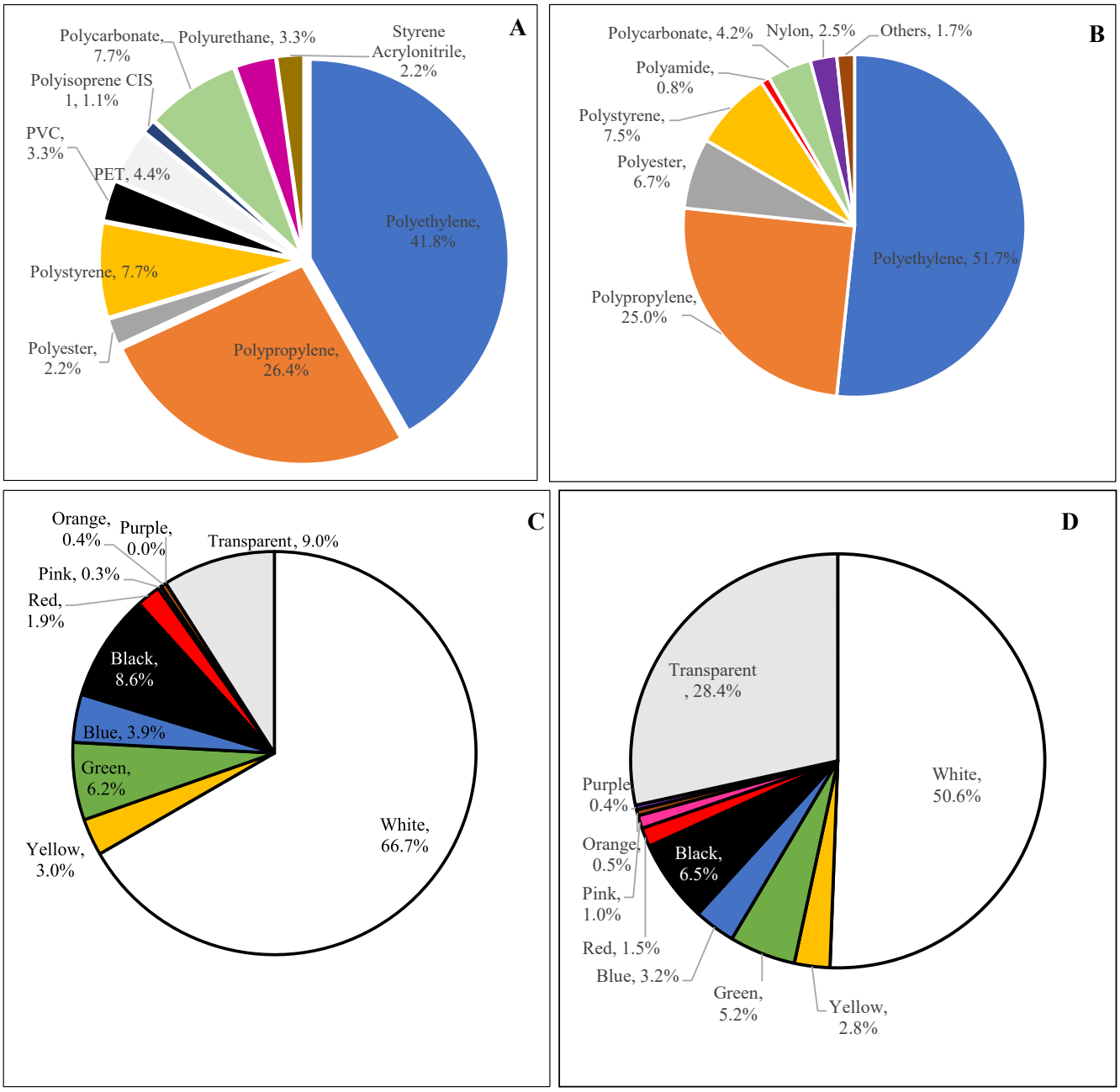

Fig. 5. Characteristics of macro- and mesoplastics isolated from MSW composts from CDM composting facilities in Uganda. A and B show the polymer composition of plastics in compost from Plant 1 and Plant 2, while C and D are the colors of polymers in composts from the respective facilities.

investigated. In compost from Plant 1, fragments represented 50.2 % of total MiPs, followed by fibers (44.9 %), and films (4.9 %). In compost from Plant 2, fragments represented 50.5 % of total MiPs, followed by fibers (43.9 %), films (5.2 %), and other shapes (0.3 %). Our results are similar to other studies where fragments and fibers dominated microplastic shapes in composts from Lithuania (Sholokhova et al., 2021), Indonesia (Iswahyudi et al., 2024), and Pakistan (Naeem et al., 2024).

The shapes of MiPs in organic fertilizers can provide fundamental information about the plastic origin and potential risks. Microplastic fragment shapes broadly include fragments, fibers, films, and foams. These generally show the appearance of having broken down from large plastic debris (Lusher et al., 2020). During aerobic composting, MaPs and large MiPs are broken down into small-sized forms as fragments, possibly due to the attained thermophilic temperature, microbial activities, and mechanical turning events (Gui et al., 2021). Among all factors, the mechanical turning process during composting is thought to be the most significant factor influencing plastic fragmentation, as evidenced in composts from Austrian composting facilities (Zafiu et al., 2023). The mechanical turning process is considered more important for the degradation of plastic types such as PET and polyamide, as the thermophilic temperature of composting may have minimal influence on such plastic degradation. Further, during aerobic composting, MaPs may undergo some oxidation with possible mild changes in color, texture, and surface morphology (Müller et al., 2018), increasing their vulnerability to fragmentation during mechanical turning.

Fiber MiPs, including filaments, on the other hand, may be formed from synthetic textiles, including plastic ropes and carpets (Frost et al., 2022), materials commonly present in solid waste in Uganda's CDM composting facilities. The study of Yang et al. (2023) demonstrated that the abrasion process of textiles, similar to the disturbance during

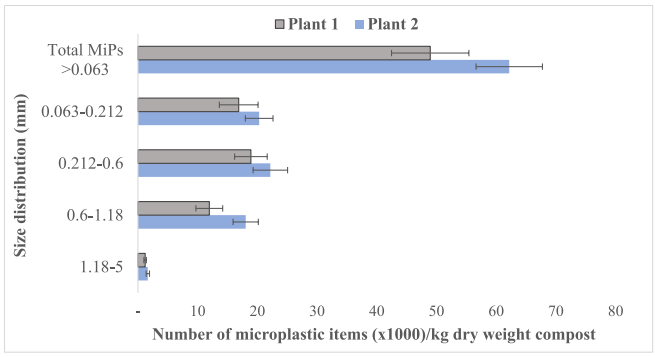

Fig. 6. The average abundance of microplastics in the different size fractions of MSW composts sampled from 2 composting facilities in Uganda. Values are the arithmetic means ± standard deviation of samples collected monthly in triplicate for four months and are given as number of particles per kg dry weight.

composting, may lead to the release of microplastic fibers.

3.3.3. Color of microplastics in compost

While microplastic shapes provide a pivotal clue about the plastic origin, the color of an object may not easily deduce its origin (Hartmann et al., 2019). Nevertheless, color is an additional descriptor to classify MiPs in different environmental compartments. Fig. S6 shows the distribution of microplastic colors in the investigated composts. In composts from Plant 1, white/transparent (40.6 %) were the most abundant microplastic color, followed by green (17.6 %), blue (16.6 %), red (13.4 %), yellow (6.4 %), black (3.1 %), and purple (1.5 %). In compost from Plant 2, white/transparent represented 46.2 % of the total microplastic colors, while others were green (16.2 %), blue (12.8 %), red (10.8 %), yellow (8.6 %), black (2.9 %), and purple (1.4 %). Thus, white and transparent colors were the most predominant in MiPs from sampled composts. These plastic colors are commonly found in packaging materials in Uganda, thus significantly contributing to the dominance of microplastic color.

Colored MiPs (green, blue, red, yellow, black, and purple) represented about 59 % and 53 % of the total microplastic color in composts from Plant 1 and Plant 2, respectively. During the plastic manufacturing process, pigments may be added to yield attractive and durable plastic products (Zhang et al., 2023). However, some of these pigments are toxic and may be slowly released into the environment during the plastic aging and degradation processes (Imhof et al., 2016). However, little is still understood about the effects of color on the potential impact of MiPs on soil ecosystems.

3.3.4. Polymer composition of microplastics in compost

The polymer share of MiPs (numbers) in composts is shown in Fig. S7. The result shows that most MiPs comprised mostly PE and PP, representing at least 75.2 % and 63.5 % of total MiPs in composts from Plant 1 and Plant 2, respectively. This result contrasts well with that for plastics > 5 mm in composts, indicating that MiPs in the composts were linked to the MaPs/MePs found in the MSW. The dominance of PE and/or PP polymers in MiPs from composts has been previously reported (Colombini et al., 2022; Steiner et al., 2024). PE and PP are common household plastics in Uganda, but face post-use disposal challenges, and often end up in collected solid waste and the environment.

4. Influencing factors for the formation of microplastics in mixed MSW compost

Regression analysis was performed using Microsoft® Excel® 365 to estimate the relationship between the number of MiPs in compost and two possible influencing factors of turning and feedstock contamination with non-biodegradable materials. The results showed that total MiPs in composts were positively correlated with pile turning frequency (R^2 = 0.9879) and feedstock contamination with non-biodegradable materials (e.g., plastics) (R^2 = 0.9657). Further, microplastic contamination in compost depended on the local population density of the municipality hosting the Plants. As previously discussed in Sec 3.3.1, turning the composting pile increases the plastic fragmentation process, forming MiPs. While there was minimal pile turning during waste decomposition at the studied facilities, the minor difference in total turning between the two facilities during compost production showed that turning is highly influential in microplastic formation.

In Uganda's investigated MSW composts, the Plant receiving low-quality waste (high non-biodegradable fraction content) showed more microplastic contamination compared to that receiving less non-biodegradable material fractions. While Plant 1 practiced the removal of some large plastics in the composting materials before, during, and after composting, the initial contamination by plastics is linked to microplastic occurrence in finished composts. The degree of contamination in the raw wastes depended on the local population density, with a high-population municipality showing higher contamination of MiPs & MaPs in composts than the less-populated one.

5. Implications of MSW compost use in Uganda

MSW compost fertilizers are an emerging source of macro- and microplastic accumulation into amended soils and the wider terrestrial environment. This study demonstrated plastic pollution in Uganda's MSW composts to be immense. Total MaPs in composts averaged 1.50 ± 1.24 g/kg dry weight and 1.78 ± 1.27 g/kg dry weight, while total MiPs (>0.063 mm) averaged 49,000 ± 7,000 items/kg dry weight and 62,000 ± 6,000 items/kg dry weight in two respective facilities. Applied at a recommended rate of 7–35 tonnes/ha, using such MSW compost would input between 2.9×10^8 to 2.4×10^9 microplastic items/ha, and MaPs of 2.0 to 106.7 kg/ha per compost application. These composts showed the highest level of microplastic contamination compared to previously

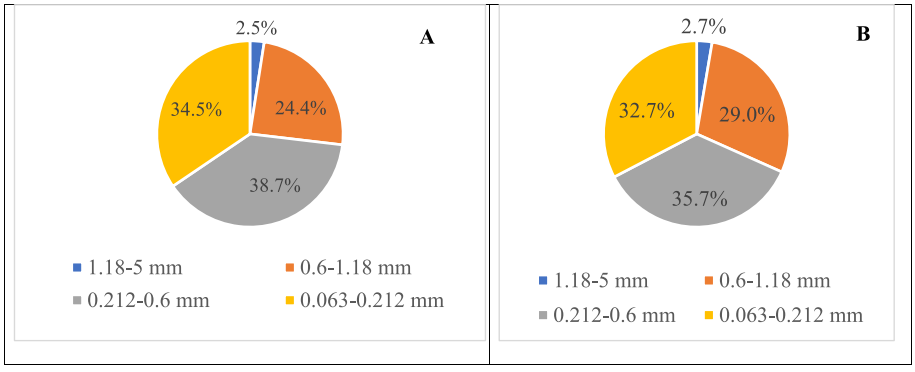

Fig. 7. The size distribution of microplastics (based on number) isolated from composts sampled from Plant 1 (A) and Plant 2 (B) composting facilities in Uganda.

reported levels in compost contamination literature. The use of Uganda's MSW compost would input approximately 1.8 to 600-fold more MiPs into amended soils than "cleaner" composts from other countries (Table S3).

The degree of microplastic contamination in compost differs depending on the origin of biowaste, degree of contamination with plastics, sorting and sieving practices, and the composting processes. Some of the global literature studies (Table S3) investigated composts from source-separated biowaste, or at least with some level of separation at the Plant before composting. In contrast, compost from CDM MSW composting Plants in Uganda originates from mixed solid waste with plastics, making up a substantial fraction of the input material. Improper materials in such collected biowaste, primarily plastics, complicate the composting process and lower compost quality.

6. Limitations of the current study and future recommendations

This study investigated plastic contamination from only two of the 12 CDM MSW composting Plants in Uganda due to time and financial constraints, in addition to the non-functionality of some of the Plants at the time of conducting this investigation. While the study was conducted for only two Plants, the results raise critical information on severe plastic contamination in compost from mixed MSW composting in Uganda. The results from the two Plants provide a critical need to undertake a country-wide investigation, or the wider SSA region, to determine the severity of microplastic contamination in the urban biowaste composting industry.

The study also reports on microplastic contamination in compost samples in the range 0.063 to 5 mm, with contamination in the compost fraction less than 0.063 mm not investigated. It is thus impossible to assert if there is more microplastic contamination in the compost fraction less than 0.063 mm compared to the size investigated. This study thus recommends the investigation of the occurrence of smaller MiPs in compost of less than 0.063 mm from mixed MSW composting.

Biodegradation is currently being thought of as a promising alternative to the global plastic crisis, but its limited success is currently achievable under laboratory conditions and not in the natural environment (Jadaun et al., 2022). Biodegradation performance is also limited to plastic type, environmental conditions, and the diversity of biodegradation microorganisms (Bahl et al., 2021). There is a need to test the role of biodegradation microorganisms in mixed MSW composting, such as in the waste collection systems practiced in SSA.

Lastly, we recommend the future investigation of plastic-contaminated compost, such as the one from our study on soil health and plant performance. While compost is a beneficial and sustainable organic fertilizer for agriculture, it is not clear what the short-term and long-term effects of the use of microplastic-contaminated MSW compost on soil ecology would be, as this is commonly used in Uganda.

7. Conclusions

This study investigated the occurrence, distribution, and characteristics of macro- and microplastics in different size fractions of mixed MSW compost from two CDM MSW composting Plants in Uganda. The MSW compost showed heavy macro- and microplastic contamination, with MiPs in the compost exceeding global values 1.6 to 600-fold. This compost can input an estimated MaPs of 2.0–106.7 kg/ha and 2.9×10^{8}–2.4×10^{9} microplastic items/ha per recommended compost application. The study validates the widespread concept that mixed MSW should not be used for composting for agriculture due to the potential contamination and environmental risks resulting from significantly high levels of macro- and microplastics and their metabolites in finished composts.

The study showed that microplastic contamination in the two MSW composting Plants provided a clear correlation between the input waste quality and compost microplastic contamination. Between the two Plants, the one receiving input waste with a higher level of contamination (Plant 2) showed a higher level of microplastic contamination compared to the one with a lower contamination level. The study provides a critical urgency for improving waste management in Uganda and SSA overall, especially if collected MSW biowaste is to be treated through composting for agricultural use. While a significant fraction of MSW generated in this region is biodegradable organic matter, the lack of source separation renders biological treatment for fertilizer production ineffective. Source separation in biowaste collection is the most recommended approach to mitigating plastic pollution in compost. However, this practice is still out of reach in SSA due to lack of planning, supporting infrastructures, awareness, and a non-existent legal supporting regulatory framework.

CRediT authorship contribution statement

Francis Okori: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Therese Schwarzböck:** Writing – review & editing, Resources, Project administration, Funding acquisition, Conceptualization. **Sara Neuburg:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Allan John Komakech:** Writing – review & editing, Supervision, Investigation, Formal analysis, Conceptualization. **Jakob Lederer:** Writing – review & editing, Project administration, Methodology, Conceptualization. **Johann Fellner:** Writing – review & editing, Supervision.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2025.114942.

Data availability

Data will be made available on request.

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