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ORIGINAL PAPER

Plastics and plastic-bound toxic metals in municipal solid waste compost from Sri Lanka

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Abstract This study examined plastics and toxic metals in municipal solid waste compost from various regions in Sri Lanka. Plastics were extracted using density separation, digested using wet peroxidation, and identified using Fourier Transform Infra-Red Spectroscopy in Attenuated Total Reflection mode. Compost and plastics were acid-digested to quantify total Cd, Cu, Co, Cr, Pb, and Zn concentrations and analyzed for the bioavailable fraction using 0.01 M $CaCl_2$. Notably, plastics were highly abundant in most compost samples. The main plastic types detected were polyethylene, polypropylene, and cellophane. However, the average Cd, Cu, Co, Cr, Pb, and Zn levels were 0.727, 60.78, 3.670, 25.44, 18.95, and 130.7 mg/kg, respectively, which are well below the recommended levels. Zn was the most bioavailable (2.476 mg/kg), and Cd was the least bioavailable (0.053 mg/kg) metal associated with compost. The Contamination factor data show that there is considerable enhancement of Cd and Cu, however, Cr, Cu, Co, and Pb are at low contamination levels. Mean geo accumulation index values were 1.39, 1.07, −1.06, −0.84, −0.32, and 0.08 for Cd, Cu, Co, Cr, Pb, and Zn. Therefore, the contamination level of compost samples with Cd and Cu ranges from uncontaminated to contaminated levels, whereas Co, Cr, Pb, and Zn are at uncontaminated levels. Despite no direct metal-plastic correlation, plastics in compost could harm plants, animals, and humans due to ingestion. Hence, reducing plastic and metal contamination in compost is crucial.

Keywords Plastic · Microplastic · Composting · Bioavailability · Municipal solid waste · Trace metal

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Introduction

Composting is a natural process of decomposing organic matter, such as food scraps, residential waste, and agricultural residues, into nutrient-rich soil amendment called compost (Hussain et al., 2022). It

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has been widely practiced to reduce the waste volume in landfills where municipal solid waste (MSW) is disposed. In Sri Lanka, a majority of Municipal Councils (MCs), Urban Councils (UCs), and Pradeshiya Sabha (PSbs) composting facilities produce compost using organic waste collected from relevant administrative areas as a waste management measure to control the overfilling of open dumps (Dandeniya & Caucci, 2020). Up to 2.8% of plastics in MSW are food packaging, polyethylene (PE) bags, and other plastic products, which should be sorted out via manual sorting or sieving before beginning the composting process (Bläsing & Amelung, 2018; van Schothorst et al., 2021). Nevertheless, it is impossible to make 100% removal of plastics from organic waste in a commercial compost production plant. Therefore, the prevalence of microplastics in the end product is approximately 12–46 particles/kg (Braun et al., 2021).

During the windrow composting process, organic material and plastics can rapidly break down; due to the extended time of 3 months (Esan & Yurgel, 2019). Due to mechanical crushing, temperature variations, and microbial degradation, larger plastics could break into tiny particles (EPA, 2021; Huhe et al., 2017). Hence, at the end of the composting, the presence of minute plastic particles is higher in the compost than in the feedstock materials (Gui et al., 2021). Additionally, composting conditions alter the properties of plastics; for example, the high temperature, humidity, and oxygen-rich environment speed up the oxidation of plastics, increasing the number of oxygen-containing functional groups present on the plastics' surface and enhancing the roughness of the plastics' surface (Chen et al., 2020). Moreover, the hydrophobic nature of the plastics decreases due to the presence of oxygen-containing functional groups that promote microbial colonization and are directly involved in the biodegradation of plastics (Chen et al., 2020). Furthermore, the potential of adsorption of trace metals can be increased due to the alternations results during the composting process. Compost can be contaminated with metals due to improper sorting at the time of disposal. Household waste contaminated with metals can be used for composting. The main toxic metal sources of household waste are old batteries, plastic containers, household dust, inks, paints, and household pesticides (Briffa et al., 2020). The composting process enhances the complexation of trace metals in organic waste and strongly binds those metals to the composting matrix and organic matter decreasing their solubility and bioavailability (Smith, 2009). As an example, Pb and Ni exhibited the strongest and weakest binding to organic matter, and Cu, Cd, and Zn showed intermediate sorption properties (Wang et al., 2022). However, incomplete composting can increase the bioavailability of the aforementioned metal levels in the compost (Smith, 2009), and aged plastic particles present in compost adsorb these trace metals. Additionally, trace metals are added as additives to enhance the properties and improve the characteristics of plastics during the manufacturing of plastics (Gilani et al., 2023). These trace and toxic metals can be adsorbed to plastics in compost. Thus, plastics can act as a career and source of toxic trace metals such as Cr, Pb, Cu, and Ni in agricultural soils through MSW compost (Premarathna et al., 2023; Vithanage et al., 2021). The presence of toxic trace metals can influence soil fertility, microbial community, and nutrient cycling, and can persist in the soil for an extended period (Priya et al., 2023).

Only a few studies have been conducted to quantify the plastics in composts; for example, Gui et al. (2021) analyzed the compost produced from rural solid waste (RSW) collected from Zhejiang Province in China. The average abundance of microplastics in compost produced from rural domestic waste was 2400 ± 358/kg dry weight. Edo et al. (2022) recently extracted microplastics from compost produced by composing facilities located in northeast Spain that used the organic fraction of MSW and reported abundance ranging from 10 to 30 items in 1 g of dry compost. With the recent "organic farming" policy implementation and banning of chemical fertilizers in Sri Lanka, MSW compost received a high demand (De Costa, 2022; Weerahewa & Dayananda, 2023). However, no studies were conducted to quantify plastics and plastic-bound trace metals in MSW. While several research publications have shed light on the prevalence of plastics in MSW compost (Gui et al., 2021; van Schothorst et al., 2021; Weithmann et al., 2021), a significant knowledge gap persists in understanding the comprehensive picture of these contaminants. Aheeyar (2007) detected Cu, Zn, Cd. Pb, and Ni in mg/L in MSW compost produced from solid waste collected from Colombo municipal area. Rathnathilaka et al. (2017) quantified Cd, Cr, Ni, Cu, Pb, and Zn in MSw compost samples collected from different municipal areas around the country and noted that in some compost samples, Cu, Ni, and Zn levels were higher than the standard values. However, no study has investigated the bioavailable metal concentrations in composts, nor have they investigated the total metal concentrations bound to plastics hosted in compost. Furthermore, research into potential links between coexisting metals and polymers in compost is mostly unexplored ground. Therefore, the main objectives of the project are 1. Quantify plastic present in MSW compost, 2. Determine the total and bioavailable fraction of metals in MSW compost, and 3. Quantify total metal concentrations in plastic particles collected from MSW compost. Due to the lack of research on this concept, the research we propose is a first in South Asia, more specifically in Sri Lanka. It has the potential to close a key gap in our understanding of the complicated interplay of plastics and metals in MSW compost. Our research will be the first of its type, assessing plastic pollution in MSW compost supplied from a variety of composting sites around the country.

Materials and methodology

Sample collection

Compost samples were collected from composting facilities operated by main dumping sites in the Western province and local authorities (MCs, UCs, and PSbs) in Sri Lanka. There are 24 MCs, 41 UCs, and 276 PSbs in the country as legislative bodies to administrate the municipalities; MCs preside over first-tier municipalities with the largest cities, while UCs and PSbs preside over second and third-tier municipalities.

Random samples were collected from five locations of the mature compost pile using the sampling technique proposed by Basnayake and Karunarathna (2004). These random samples which were collected specifically, three at the lower strata of the pile and two at the upper strata were mixed well to make a composite sample weighing 5 kg. Subsequently, the quartering technique was used to reduce the sample quantity after transportation to the laboratory, and samples were kept at a temperature of 4 ℃ for further analysis.

Plastics extraction and identification

First, air-dried compost samples were subjected to density separation. About 100 g of air-dried compost was added to a beaker containing 500 mL of saturated NaCl solution, prepared by dissolving NaCl in ultrapure water. The mixture was stirred using a glass rod for about 5 min and kept aside to settle down (Liu et al., 2018). The supernatant was filtered through a set of stainless-steel sieves of 0.25, 0.50, 1, and 2 mm opening sizes. The separation continued until no more visible particles were floating in the supernatant (Vianello et al., 2019). After that, the material trapped in each sieve was washed several times with distilled water to remove salt, and then, the remaining material on the sieves was air dried.

Next, the dried material was subjected to wet peroxidase digestion to remove organic matter. Approximately 20 mL from both 0.05 M Fe(II) solution and 30% H_2O_2 was added to the compost collected from each sieve (Radford et al., 2021). All the organic matter in the samples was digested by heating up to 75 °C while stirring. Then, digested samples were passed through the same sieve set. Finally, the solid residue was air-dried, and plastic particles were collected manually from the sieves and air-dried at room temperature. Then, all the plastics collected from 1 and 2 mm sieves were observed through a Fourier Transform Infra-Red (FTIR) analyzer using Attenuated Total Reflection (ATR) mode. After that, the FTIR spectra of plastic particles were compared with the polymer database of the OMNIC spectra 7.3 software, and finally, the polymer type of each plastic particle was identified.

Furthermore, the extracted plastic particles were categorized based on shape, size, color, and polymer type. Also, the abundance of plastics in each compost sample was calculated using Eq. 1.

$$Abundance = \frac{Number\ of\ plastic\ particles}{100\ g} \times 1000\ g \tag{1}$$

Quantification of total trace metal concentration in compost and plastics

Compost samples were digested using a Microwave-assisted digestion system (Multiwave GO Plus, Anton Paar). About 1.5 mL of 69% HNO_3 and 4.5 mL of 35% HCl were added to the digestion vessels containing approximately 0.1000 g of dried compost. The following temperature program was used in the digestion system. First, the temperature of the vessels was raised to 165 °C within 10 min; then, the vessels were maintained at the same temperature for 10 min. The samples were allowed to cool and filtered using 0.45 µm PTFE filters into 10 mL volumetric flasks. The residue remaining in the vessels was also washed with ultrapure water and transferred the solution into the same volumetric flask. The solution was made up to 10 mL using ultrapure water.

About 0.1000 g of plastic particles collected from each compost sample were transferred into digestion vessels. Then, about 1.5 mL of 69% HNO_3 and 4.5 mL of 35% HCl were added to plastic particles in digestion vessels. Digestion vessels were loaded into a block digestion system, and temperature was maintained at 165 °C for 30 min. The samples were allowed to cool and then filtered into 10 mL volumetric flasks using 0.45 µm PTFE filters. The residue in digestion vessels was washed with ultrapure water and transferred to the same volumetric flask. Finally, the total Cr, Cu, Co, Cd, and Zn concentrations in digested compost and plastic samples were quantified using an Inductive Coupled Plasma-Optical Emission Spectrophotometer (ICP-OES).

Determination of bioavailable fraction of trace metals in compost

Approximately 3 g of compost was measured into centrifuge tubes, and to each tube, about 30.0 mL of 0.01 M $CaCl_2$ solution was added and shaken in the shaker for 3 h. Finally, the extract was filtered using 0.45 µm nylon filters, and bioavailable Cr, Cu, Co, Cd, Pb, and Zn were determined using ICP-OES.

Assessment of compost contamination

Contamination factor (CF) is a tool that can be used to determine the pollution status of compost samples over a period of time (Nobi et al., 2010; Varol, 2011). CF was calculated using Eq. (2) to determine whether compost samples are polluted with trace metals (Nobi et al., 2010; Varol, 2011; Weerasundara et al., 2018).

$$CF = \frac{C_n}{B_n} \tag{2}$$

Where C_n is the concentration of contaminant in compost, and B_n is the background concentration for the Cd, Cu, Co, Cr, Pb, and Zn are 0.10, 13.52, 4.64, 25.59, 9.31, and 68.31 mg/kg, respectively. If the CF value is more than 1 for a particulate metal, it indicates that the metal contaminates the compost sample, while if the CF is lower than 1 there is no metal contamination (Nobi et al., 2010). Accordingly, the geo accumulation index (I_{geo}) is used to assess the contamination levels. Equation (3) was used to determine I_{geo} (Ma et al., 2017; Zheng et al., 2015).

$$I_{geo} = \left[\frac{\log_2 C_n}{1.5B_n}\right] \tag{3}$$

C_n is the concentration of contaminant in compost, and B_n is the background concentration for Cd, Cu, Co, Cr, Pb, and Zn are 0.10, 13.52, 4.64, 25.59, 9.31, and 68.31 mg/kg, respectively. A constant of 1.5 is introduced to minimize the effect of possible variations in the background values. The I_{geo} classified into seven different categories the trace metal pollution level in the compost.

$I_{geo} \leq 0$—class 0, uncontaminated
$0 < I_{geo} \leq 1$—class 1, uncontaminated to moderately contaminated
$1 < I_{geo} \leq 2$—class 2, moderately contaminated
$2 < I_{geo} \leq 3$—class 3, moderately contaminated to heavily contaminated
$3 < I_{geo} \leq 4$—class 4, heavily contaminated
$4 < I_{geo} \leq 5$—class 5, heavily contaminated to extremely contaminated
$5 < I_{geo}$—class 6, extremely contaminated

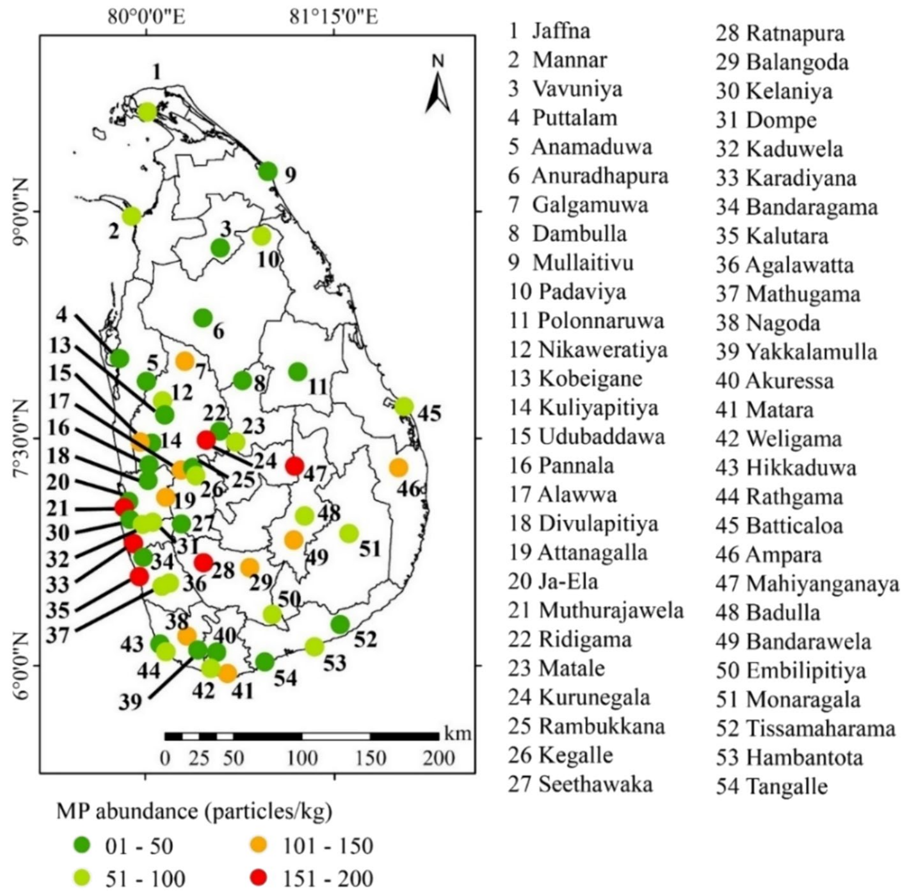


Fig. 1 Abundance of plastics in selected MSW compost samples obtained from local authorities and dumping sites

Results and discussion

Abundance and properties of plastics collected from compost

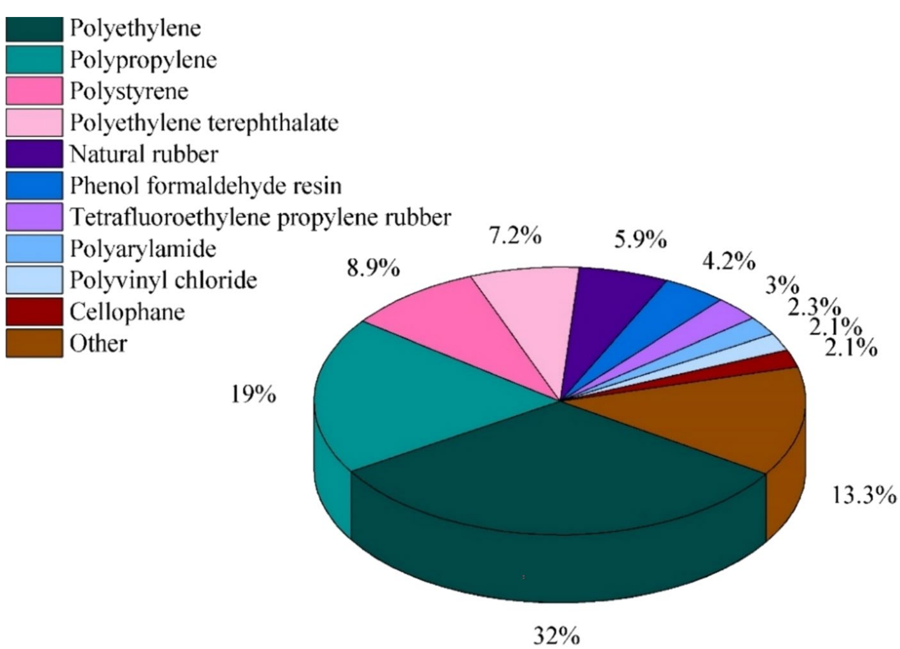
The abundance of plastic particles was high in MSW compost samples collected from Kurunegala, Kalutara, Mahiyanganaya, Ratnapura, Karadiayana, and Muthurajawela composting plants (200, 180, 180, 170, 170, and 160 particles/kg respectively) (Fig. 1). Karadiyana and Muthurajawela dumping sites receive garbage from multiple local authorities in highly populated and industrialized areas in the Western province of Sri Lanka. Panadura (UC), Maharagama (UC), Moratuwa (MC), Kesbewa (UC), and Sri Jayawardenepura Kotte (MC) are a few of the authorities that dump the waste into the Karadiyana dumping site. Muthurajawela dumping site receives waste from Colombo, Kelaniya, and Gampaha. Similarly, Kurunegala Ratnapura, Kalutara, and Mahiyanganaya are highly populated town areas that collect huge amounts of waste daily. Usually, the biodegradable portion of waste received at the compost production facility is sorted for the second time before introduction to the pile to ensure the waste is free from non-perishable wastes. However, this practice depends on the resource availability in the production facility and the quantity of waste received daily. Therefore, the considerable abundance of plastics in the MSW compost produced by these municipalities and dumping sites may be due to the difficulty of carefully sorting huge waste quantities daily due to high population density.

Gui et al. (2021) detected 2400 ± 358 items/kg of plastic particles less than 1 mm in size in compost produced from RSW collected from Zhejiang Province of China. A study was conducted in the Netherlands to compare the microplastic contamination in compost produced using municipal organic waste (MOW) and garden and greenhouse waste and found that the abundance of microplastics in the compost produced using MOW was twice higher than the abundance in compost produced with garden and greenhouse waste, with respectively 2800 ± 616 and 1253 ± 561 microplastics/kg (van Schothorst et al., 2021). Edo et al. (2022) observed a much higher abundance of microplastic in compost produced using the organic fraction of MSW (10–30 items/g of dry compost). However, the abundance of plastics observed in MSW compost samples produced by local authorities of Sri Lanka was much lower than the results of the studies conducted in other countries. The assumed application rate of compost to have successful agricultural output is 10–100 tonnes/ha (Vithanage et al., 2021). Therefore, there is a possibility of introducing around 1.81×10^6–1.81×10^7 items/ha microplastics to the soil per year.

The PE was the most common polymer type detected in MSW composts (Fig. 2). Low-density PE (PE-LD), linear low-density PE (PE-LLD), medium-density PE (PE-MD), and high-density PE (PE-HD) were the four main PE types detected in compost samples (Fig. 3a). The second and third most abundant polymer types were polypropylene (PP) and Polystyrene (PS) (19 and 8.9%). Other polymer types were less abundant and detected in very few compost samples, and their FTIR spectra are presented in Fig. 3b.

Between 70 and 80% of the microplastics found in the compost produced using RSW collected from the Zhejiang Province of China were polyester, PP, and PE (Gui et al., 2021), van der Zee and Molenveld (2020) also identified PP and PE as the two major polymer types in composts from Dutch organic treatment facilities. Among the collected microplastics from compost obtained from composting producers in northeast Spain, 94% were PE, PS, PP, PVC, and acrylic polymers (Edo et al., 2022). PE and PP were the main microplastic types detected in the landfills in China (He et al., 2019), and styrene-based polymers and PEs are the predominant polymers included in the plastic packaging and wrappings. For instance, usually, PE-LD is used to produce plastic bags, trays, mulching materials for agriculture fields, materials for polyhouses, and as a packaging material for food items and non-food items (Ghatge et al., 2020). The organic fraction of the MSW mainly comprises market, garden, and kitchen wastes; thus, the possibility of contamination with PE is high. Therefore, the main reason for the abundance of the above polymer types is the usage of plastic-contaminated organic waste in composting facilities as feedstock. Microbial activity in the soil was reduced when microplastics were transferred to the soil, especially PP fragments (20%), and PE-LD films (17%) showed the highest reduction of microbial activity in soil (Lozano et al., 2021).

Fig. 2 Polymer-type distribution of plastics collected from MSW compost samples from the MSW disposal sites in the selected local authorities in Sri Lanka



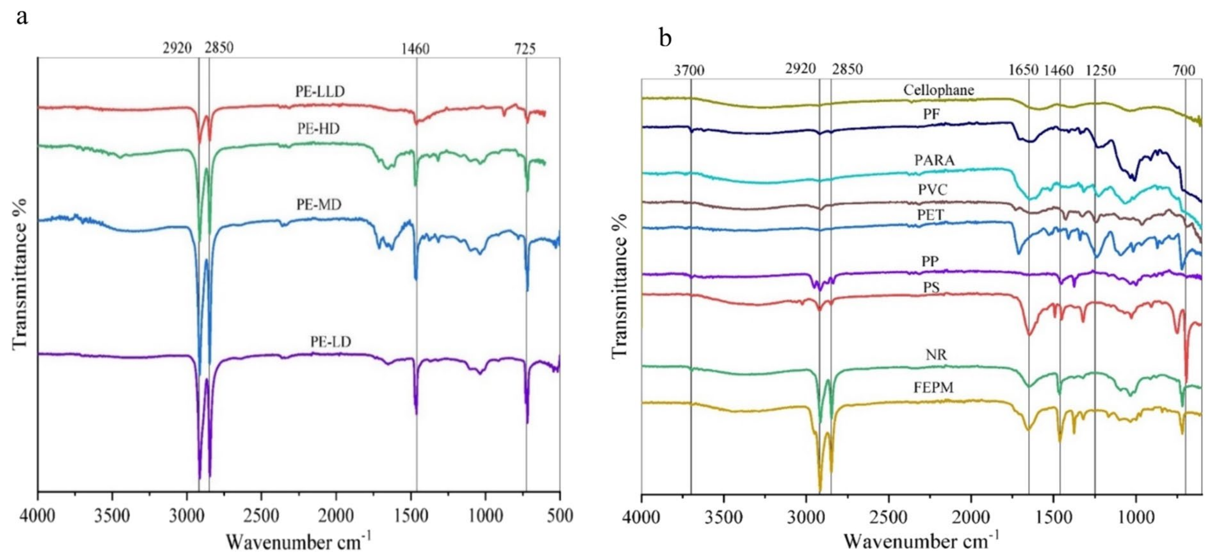


Fig. 3 **a** The FTIR spectra of four types of Polyethylene (PE): low-density PE (PE-LD), linear low-density PE (PE-LLD), medium-density PE (PE-MD), and high-density PE (PE-HD) detected in MSW compost samples collected from selected MSW collecting local authorities in Sri Lanka. **b** FTIR spectra of the most prominent polymer types collected from MSW compost samples collected from selected MSW collecting local authorities in Sri Lanka. *Note**: PF: Phenol formaldehyde resin, PARA: Polyacrylamide PVC: Polyvinyl chloride, PET: Polyethylene terephthalate, PP: Polypropylene, PS: Polystyrene, NR: Natural rubber, FEPM: Tetrafluoroethylene propylene rubber

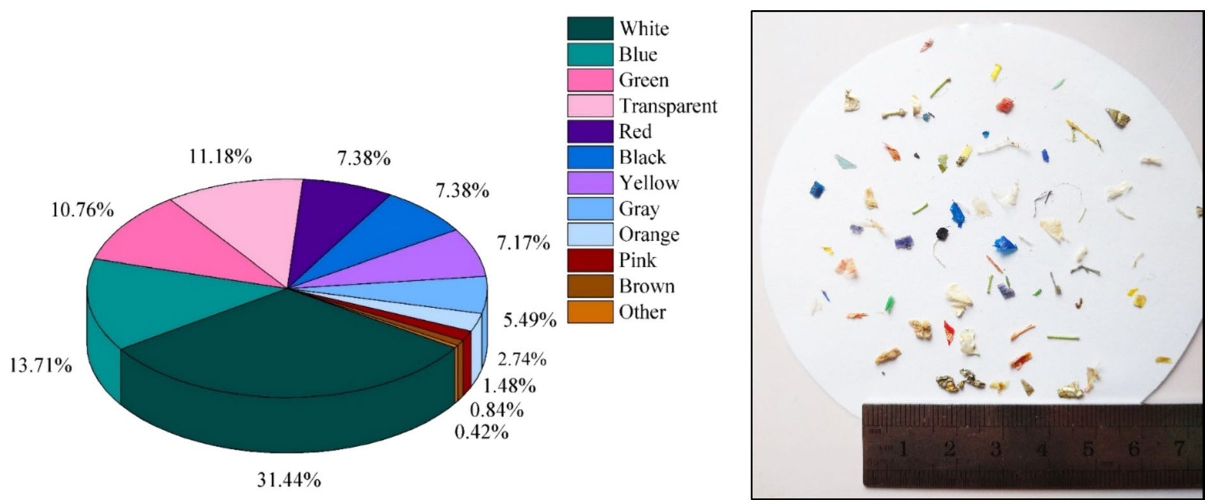


Fig. 4 Color distribution of plastics collected from MSW compost samples collected from the MSW composting plants functioning under the selected local authorities in Sri Lanka

Therefore, the polymer types present in compost impact the compost quality.

Plastics of various colors were detected in MSW compost samples; the most common colors were white, transparent, blue, green, red, black, yellow, and gray (Fig. 4). Among these, more than 30% of plastic particles were white, and percentages of blue, green, and transparent plastic particles exceeded 10% (13.71, 10.76, and 11.18% respectively). Other than the colors in the pie chart, purple and silver plastic particles were also detected in MSW compost samples. The dominance of white and transparent plastic particles may be because MSW used to produce composts are usually collected from open dumping sites, and they are directly exposed to sunlight for an extended period; hence, due to the UV degradation and weathering color of plastic particles may have faded away (Huang et al., 2020). Bandow et al. (2017) observed the white color of PS turning to a yellowish color after exposure to UV radiation for one day and turning to dark yellow at the end of the experiment; the color of green color PE-HD started to fade after six days, and gray PVC started to change their color after two weeks exposure and became white after eight weeks UV exposure period. Red, blue, and green microplastics were highly abundant in compost produced from RSW (Gui et al., 2021). There is a possibility of releasing color slowly over time, which can cause negative impacts on microorganisms (Kumar et al., 2020).

The percentages of plastic fragments and films were approximately similar (45.11 and 43.83%, respectively) (Fig. 5a). Generally, the shape, color, and form of plastics can support the determination of the source of plastics (Gao et al., 2020). In the tested compost samples, films, fragments, foams, and filaments were detected; in some, only one plastic type was present, while others contained all four types. Foams and filaments were comparatively less abundant in compost samples (4.91 and 6.15%, respectively). Similarly, microplastic fragments were the most common type found in the compost produced via aerobic digestion of bio-waste (Weithmann et al., 2021). These may come from the degradation of macro plastics such as bags and containers used to wrap food items. Films were the dominant shape of microplastics in compost, and the source of microplastics in green and food compost was plastic bags and packaging materials (Sholokhova et al., 2022). Plastic films are also more prominent in compost because these films are tightly adhered to wet organic materials due to the high moisture content of the feedstock; therefore, removal is difficult (David, 2013). The application of MSW compost introduces microplastics into the soils of agricultural lands. Microplastics in soil reduced soil aggregation by 25% due to introducing fracture points to aggregates and negatively affecting soil biota (Lozano et al., 2021). Fiber-shaped plastics create a distinct negative impact on the soil structure, while film-shaped plastics create both positive and negative impacts on the soil structure (Lehmann et al., 2021). However, the studies on the shape of plastics available in MSW compost are important for the identification of the source of plastics.

Most plastics collected from compost samples were smaller than 5 mm (62.66%), and only 37.35% of collected plastics were larger than 5 mm (Fig. 5b). Weithmann et al. (2021) collected microplastics from compost produced by different production plants, and most of the microplastics fell under the 2–5 mm size category. Microplastics from 50 µm to 5 mm were detected in compost manufactured from RSW, and above 0.5 mm size microplastics were found in German compost (Bläsing & Amelung, 2018; Gui et al., 2021). Microplastics in the 200–2000 µm category were the most abundant in MSW composts (Watteau et al., 2018). Surface areas of microplastics collected from compost manufactured from MOW and greenhouse waste were 0.08 and 0.05 mm^2, respectively (van Schothorst et al., 2021). Sholokhova et al. (2022) found the release of 56–122 microplastics from a 5 cm^2 conventional plastic sample during a full cycle of open windrow composting of green wastes. Different

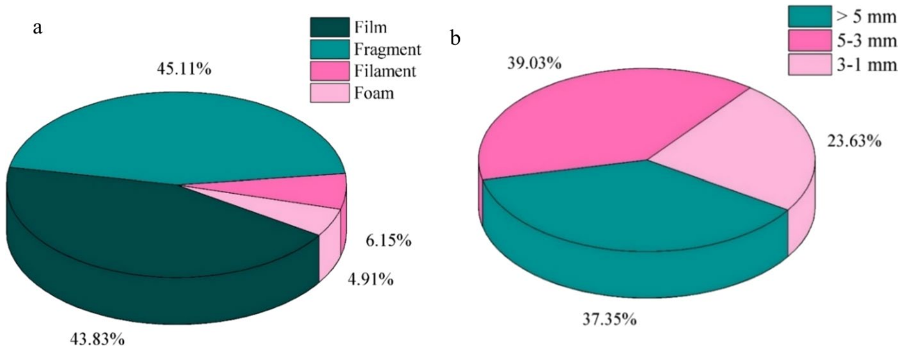


Fig. 5 **a** Shape distribution of plastics collected from MSW composts and main types of plastics collected from compost, **b** Size-wise distribution of plastics extracted from MSW comp

studies have observed the various size proportions of microplastics in compost. The composting process alters microplastics' size, shape, and distribution, producing more microplastics of various sizes (Gui et al., 2021). Frequent turning of piles in the windrow composting process increased the plastic fragmentation, and complete removal was impossible by sieving (Zafiu et al., 2023). Polymer type and thickness also influence the microplastics produced during composting (Sholokhova et al., 2022). Similarly, evidence was there to confirm that during the course of the compost manufacturing process, PE, PP, and expanded polystyrene (EPS) macro plastics released around 4–6 microplastic particles, and 63 and 150 mm PE-HD pieces were generated by PE-HD macro plastics (Gui et al., 2021). However, Sun et al. (2021) observed a decrease in the abundance of PE, Polyvinyl Chloride (PVC), and Polyhydroxyalkanoates (PHA) microplastics after composting, which indicated that the composting process also has the potential to degrade microplastics in organic waste. Therefore, the size distribution of microplastics in the MSW compost may depend on the available polymer types, the polymers' thickness, and the composting piles' turning frequency.

Trace metals in composts and bound to plastics

The concentration ranges, average concentrations, and permissible metal concentrations in compost, soil, and growth media are presented in Table 1. The concentration of Cd ranges between 0.054 ± 0.003 and 8.213 ± 0.411 mg/kg; the highest Cd concentration was detected in compost produced by using solid waste from the Muthurajawela dumping site, and in most of the compost samples, Cd concentration was less than 1.00 mg/kg. The average Cu concentration was 60.78 ± 3.039 mg/kg; the Cu concentration exceeded 100 mg/kg in compost obtained from Muthurajawela, Karadiyana, Kalutara, Ratnapura, Balangoda, Matale, Matara (PSb), and Kuliyapitiya (MC) composting plants. The maximum Cu concentration was 215.0 ± 10.75 mg/kg, detected in Matara (PSb) compost. In almost all compost samples, very low Co concentrations were detected, and the average Co concentration was 3.670 ± 0.183 mg/kg. Apart from the Jaffna (MC) compost sample, in all other compost samples, the Cr concentration was less than 100 mg/kg, and the average Cr concentration was 25.44 ± 1.272 mg/kg. The average Pb concentration in composts was 18.95 ± 0.948 mg/kg, ranging from 1.154 ± 0.058 to 207.8 ± 10.39 mg/kg, except the

Table 1 Total and bioavailable metal concentrations in compost and plastics and their permissible levels in compost, soil, and plants

Metal		Total metal concentration (mg/kg)		Bioavailable metal concentration (mg/kg)	Permissible concentration (mg/kg)	
		Compost	Plastic	Compost	*Compost	**Soil and growth media
Cd	Range	0.054 ± 0.003–8.213 ± 0.411	ND–238.3 ± 11.92	0.001 ± 0.00–0.420 ± 0.021	3.00	1.60
	Average	0.727 ± 0.036	11.30 ± 0.565	0.053 ± 0.003		
Cu	Range	4.098 ± 0.205–215.0 ± 10.75	ND–5457 ± 272.9	0.079 ± 0.004–1.996 ± 0.010	–	40.0
	Average	60.78 ± 3.039	132.05 ± 6.603	0.604 ± 0.030		
Co	Range	1.195 ± 0.060–10.87 ± 0.544	ND–123.93 ± 6.197	0.002 ± 0.00–0.715 ± 0.036	–	33.0
	Average	3.670 ± 0.183	2.593 ± 0.130	0.216 ± 0.011		
Cr	Range	4.740 ± 0.237–105.4 ± 5.270	ND–10895 ± 544.8	ND–0.599 ± 0.030	50.0	100
	Average	25.44 ± 1.272	421.4 ± 21.07	0.176 ± 0.009		
Pb	Range	1.154 ± 0.058–207.8 ± 10.39	ND–441.1 ± 22.05	ND–0.329 ± 0.016	50.0	140
	Average	18.95 ± 0.948	37.42 ± 1.871	0.050 ± 0.003		
Zn	Range	23.26 ± 1.163–485.0 ± 24.25	ND–5332 ± 266.6	ND–449.5 ± 22.48	–	160
	Average	130.7 ± 6.535	283.5 ± 14.18	2.476 ± 0.124		

*SLSI (2019), **Crommentuijn et al. (2000), *ND* not detected

Minimum detection limits: Cd: 0.45 µg/L Cu: 1.08 µg/L, Co: 0.89 µg/L, Cr: 1.48 µg/L, Pb: 2.45 µg/L, Zn: 1.19 µg/L highest concentration recorded in the MSW compost sample obtained from the Ratnapura composting plant, in other compost samples Pb concentrations were well below the 100 mg/kg. The Zn concentration was very high in most compost samples compared to other quantified metals. In nearly 50% of samples, Zn concentration has exceeded the 100 mg/kg level, and the maximum concentration was detected in compost produced by Kuliyapitiya (MC). The permissible level of Cd, Cr, and Pb in compost is 3, 50, and 50 mg/kg, respectively; in all other compost samples, the reported levels of the metals mentioned above were lower except in some compost samples; Cd (Muthurajawela and Polonnaruwa), Cr (Jaffna (MC), Hambantota (MC), and Polonnaruwa), and Pb (Ratnapura and Puttalam) (Table 1).

The Cd, Cu, Co, Cr, Pb, and Zn were not detected in plastic particles collected from most of the compost samples; however, Zn, Cu, Co, and Cr levels were high in some plastic samples. The maximum Cr and Co concentrations were reported in plastics collected from the Tissamaharama (PSb) compost sample, and those were 10,895 ± 544.75 and 123.93 ± 6.20 mg/kg, respectively. The highest Cu concentration was detected in the compost sample obtained from Divulapitiya (PSb) which is 5457 ± 272.9 mg/kg. The highest Cd and Pb concentrations were detected in plastics collected from Muthurajawela: 238.5 ± 14.18 mg/kg and Ridigama (PSb) 441.1 ± 22.05 mg/kg, respectively.

Although plastics do not have a porous surface, they can adsorb metal ions due to the negative charge developed on the surface of plastic particles because of wearing, prolonged weathering, and photo-oxidation in the natural environment (Holmes et al., 2012; Turner & Holmes, 2015; Yang et al., 2019). High concentrations of Ti and Zn were detected in pristine PVC, PS, and PE-HD, and they leach out as far as they are in contact with water, and the released amount can be increased as degradation continues (Bandow et al., 2017).

Furthermore, these plastics are believed to contain chemical additives such as flame retardants and trace metals like Cd, Cr, Hg, and Pb (Turner & Filella, 2021). Cr is most frequently detected in food contact items such as kitchen utensils (thermos mugs and flasks, meal trays, ice cream carton lids, stoppers), toys, clothing, and accessories (Turner, 2018). Thus, this indicates that plastics contain trace metals, which can be a reason for the detected high Cr concentrations in plastics extracted from compost samples obtained from Tissamaharama (PSb) and a few other composting plants. Furthermore, several studies have specified that metals remain in plastics as functional additives, and metal-based additives are widely used as inert fillers, pigments for color, and stabilizers. Fillers are used to reduce production costs and increase the plastic particle's stiffness and hardness (Janssen et al., 2016). Turner and Filella (2021) stated that Cr(VI) trioxide is used to produce PE, and various basic salts of Pb are used to stabilize and lubricate PVC. However, Ranta-Korpi et al. (2014) have testified that metal-based additives are no longer intentionally added to the plastic during manufacturing. Despite regulations and the development of safer alternative additives, these trace metals have managed to disperse among contemporary consumer goods through material recycling (Turner & Filella, 2021). This dispersion results from the historical use of trace metal-based additives commonly employed for thermal and light protection. Consequently, these plastics, which were produced in the past, are expected to exhibit greater persistence in the environment than newly produced plastics that either contain no additives or include additives that degrade over time.

The bioavailable fraction from the total quantity of trace metal in a specific environment is either available or can be made available for plant, animal, or microbial uptake (Olaniran et al., 2013). The average bioavailable Cd, Cu, Co, Cr, Pb, and Zn concentrations in compost samples were 0.053 ± 0.003, 0.604 ± 0.030, 0.216 ± 0.011, 0.176 ± 0.009, 0.050 ± 0.003, and 2.476 ± 0.124 mg/kg. The recommended ratio of garden soil: coco-peat: compost is 1:1:1, based on the assumption that the required amount of compost for 1 kg pot mixture is approximately 333 g. Therefore, the average Cd, Cu, Co, Cr, Pb, and Zn concentrations in the pot mixture are 0.02, 0.20, 0.07, 0.06, 0.02, and 0.84 mg/kg. The recommended Cd, Cu, Cr, Pb, and Zn concentrations in soil and growth media are < 1, 25–50, < 100, < 100, and < 200 mg/kg, respectively; thus, the average bioavailable fraction of the above metals in pot mixture were below the recommended levels. Similarly, the total Cd, Cu, Co, Cr, Pb, and Zn concentrations introduced into a pot mixture of 1 kg via compost was also calculated, and average values are 0.24, 20.24, 1.22, 8.47, 6.31, and 43.5 mg/kg which are also well below the minimum permissible total metal concentrations in the soil and growth media (Crommentuijn et al., 2000).

A strong positive correlation was observed between the total metal concentration in compost and bioavailable metal concentration in compost ($p < 0.005$). Therefore, with the increase of total metal concentration in compost, the probability of increasing bioavailable metal fraction in compost is high. However, the relationships between total metal concentrations in plastics and compost and total metal concentrations in plastics and bioavailable metal concentrations in compost are insignificant ($P > 0.005$) (Table 2).

Contaminant assessment of compost

The box plots for CF and I_{geo} values for the investigated trace metals in composts are displayed in Fig. 6. The CF data show that there is considerable enhancement of Cd and Cu, however, Cr, Cu, Co, and Pb are at low contamination levels. These outcomes were further confirmed by the categorization based on I_{geo} values. Mean I_{geo} values were 1.48, 1.11, −1.04, −0.79, −0.26, and 0.11 for Cd, Cu, Co, Cr, Pb, and Zn. In the ranking for Cd and Cu, most of the compost samples can be categorized into classes 0–3, indicating that their contamination ranges from uncontaminated to contaminated. According to I_{geo} values for Co and Cr, most of the compost samples fall into the class 0 category, indicating that those are uncontaminated with Co and Cr. I_{geo} values for Pb and Zn indicated that most of the compost samples are under the categories class 0 and 1, hence, contamination status varies from uncontaminated to moderately contaminated. Overall, according to the results obtained most of the compost samples are under the contamination status of uncontaminated to uncontaminated to moderately contaminated.

Table 2 The results of Pearson Correlation statistical analysis

		Compost	Bioavailable	Plastic
"Compost"	Pearson Corr	1	0.94909	−0.15416
	p-value	–	0.00382	0.77059
"Bioavailable"	Pearson Corr	0.94909	1	−0.21892
	p-value	0.00382	–	0.67686
"Plastic"	Pearson Corr	−0.15416	−0.21892	1
	p-value	0.77059	0.67686	–

The ultimate destination of plastics present in the compost is soil; therefore, microplastics were detected in the soil of agricultural farms worldwide in high concentrations. Yu et al. (2021) detected more than 65% of microplastics in the soil of greenhouse vegetable farms in Northern China; PP and ethylene propylene copolymer (EPC) were the most abundant types, and the percentage of microplastic fragments were more than 45%. In the Shanghai vegetable farm soil, the abundance of microplastics in topsoil and deep soil was 78 and 62.5 items/kg, respectively; fibers were the most common shape of microplastics present in both soil layers, and the percentage of PP was around 50.51% (Liu et al., 2018). Continuous usage of biofertilizers contaminated with microplastic is the main reason behind the plastic pollution of these vegetable farms.

The impacts of plastics on the environment are not uniform since plastics come with several chemical modifications, additives, shapes, sizes, and durable surface properties (Rillig et al., 2019). The degree of influence of plastics varies depending on those properties; for example, microfibers decrease the soil bulk density (de Souza Machado et al., 2019). Stable soil aggregates are extremely important to avoid erosion, which collaborates water retention and fertility (Boix-Fayos et al., 2001; Liang et al., 2021). Adding organic matter promotes the stability of soil aggregates; microplastics are also carbon polymers; however, the exact impact of microplastics on the stability of soil aggregates is still unidentified (Liang et al., 2021). Polyester and polyacrylic fibers were shown to impact water-stable aggregates only in the presence of organic matter (Liang et al., 2021).

Microplastics are also carbon-based polymers; they contribute to a slight increase in the soil organic carbon fraction (Rillig, 2018). However, in the future, their quantity could be increased in urban and agricultural areas due to resistance to microbial decomposition and further input (Rillig et al., 2021). Altering soil structure can cause unpredictable changes in microbial community structure and functions (Rillig et al., 2019). Some microplastics increase the abundance of microorganisms by providing a surface to aggregate them (Syberg et al., 2015). Furthermore,

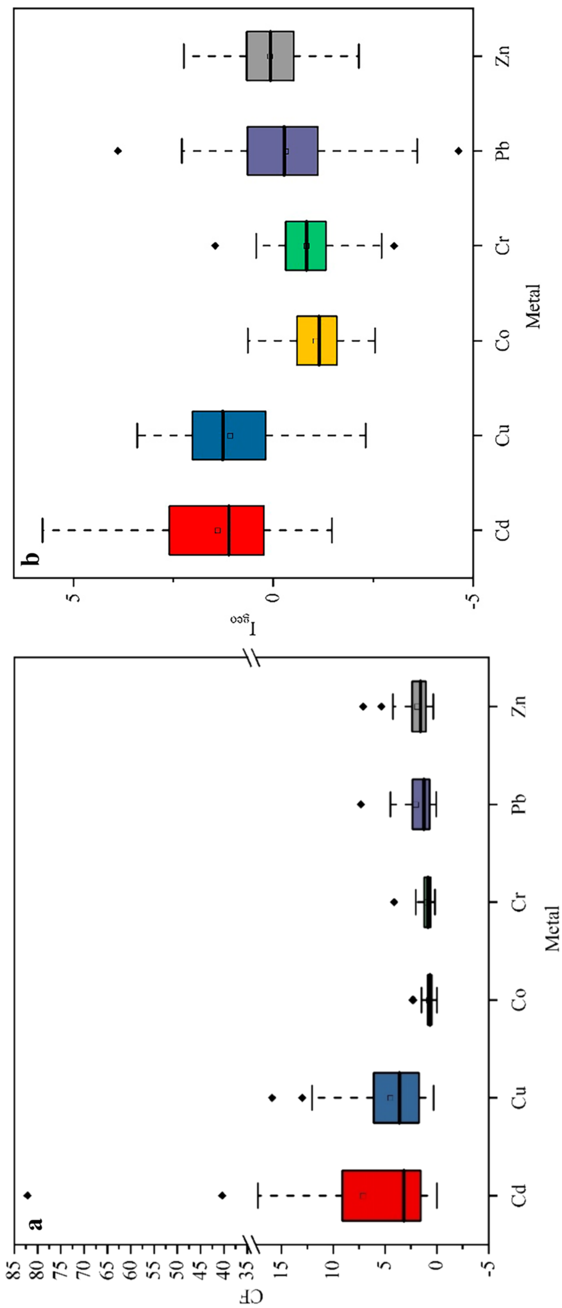


Fig. 6 **a** Box plot of CF for trace metals in MSW compost samples. **b** Box plot of I_{geo} values of trace metals in MSW compost samples

microplastics adsorb toxic chemicals and act as a transportation medium for those lethal contaminants, and they can increase their environmental persistence (Koelmans et al., 2016). Additionally, chemical additives added during the plastic manufacturing process could be transported into the soil this way (Atugoda et al., 2021; Galloway et al., 2017; Vithanage et al., 2021). These can cause harmful influences on plant roots and microbial symbionts, negatively affecting plant growth (Rillig et al., 2019). Otherwise, microplastics may sorb contaminants, reducing their effect on plants and microbial communities residing in the environment, as has been observed in aquatic environments (Kleinteich et al., 2018). However, it is hard to draw strong conclusions considering the need for more research on microplastics available in compost and their effects on plants, soil, and organisms. Therefore, further research is required to understand the negative effects of plastics. However, using plastic-contaminated waste materials in composting facilities significantly influences the composition and quality of compost products. Hence, additional steps are essential to improve compost quality by decreasing plastic contamination.

Conclusions

The abundance of plastics in MSW compost samples obtained from dumping sites and highly populated municipalities is considerably high due to the difficulty of sorting before the composting process begins. The most abundant polymer types detected in MSW compost were PE, PP, and cellophane because PE and styrene-based polymers are the polymers used in plastic packaging and wrappings. More than 30% of plastic particles were white and smaller than 5 mm, also, the most frequently detected shapes were fragments and films. Although there was no correlation between the total metal concentration in compost and plastic, a positive correlation was observed between bioavailable and total metal content in compost, suggesting that the bioavailability of metals may also increase as the total metal concentration rises. The average total concentrations of Cd, Cu, Co, Cr, Pb, and Zn were considerably less than the government-permissible levels for agriculture. The CF and I_{geo} values confirmed that the Co, Cr, Pb, and Zn are at the uncontaminated levels, and Cd and Cu are in the range of uncontaminated to contaminated levels. However, to achieve similar efficiency as commercial fertilizers a high dose of compost is required, and with the increase of the compost dose, the amount of plastics and metal reaching agricultural soil subsequently increases. Thus, the application of high doses of contaminated compost to the agricultural soil can pose potential risks by introducing both plastics and metals into the soil, with potential adverse environmental impacts. To mitigate these risks, it is imperative to enhance waste segregation practices before composting, implement stringent quality checks for compost, and delve into comprehensive studies examining the combined effects of plastics and metals on agricultural systems. In this study, our focus has not extended to organic contaminants, which could pose significant concerns given the multitude of potential contaminants and their respective degraded byproducts. Our findings underscore the importance of informed waste management practices to ensure sustainable agricultural practices and environmental health.

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Declarations

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