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Published

2025

Journal Title

Journal of Environmental Management

Version

Version of Record (VoR)

DOI

10.1016/j.jenvman.2025.124359

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Journal of Environmental Management 375 (2025) 124359

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Microplastic in Australian processed organics: Abundance, characteristics and potential transport to soil ecosystem

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ARTICLE INFO

Handling Editor: Dr. Lixiao Zhang

Keywords:
Microplastic
Compost
Compostable bag
Recycled organic

ABSTRACT

The extensive use and application of recycled organics, including biosolids and compost, has been considered as an effective waste management approach to reduce waste to landfills. However, concerns have been raised about the presence of microplastics (MPs) in these recycled organics and their subsequent transfer to soils. Although the presence of MPs in biosolids has been widely documented, our knowledge about the occurrence and characteristics of MPs in processed organic waste such as compost is still limited. The present study aimed to investigate the abundance, characteristics and potential sources of MPs (>25 μm) in processed organic waste samples collected across eleven sites with different processing systems in Australia. This includes compost, digestate from anaerobic digestion and rapidly dehydrated food waste. MPs, mainly polyethylene, polypropylene and polyester, were found across all samples with concentrations ranging from 1500 to 16,000 MP/kg dry weight. The majority of these MPs fell within the smaller size range of 25–500 μm. Using the concentration and characteristics (size range, morphology, density) of detected MPs, the mass abundance of MPs was estimated to be between 7 and 760 mg/kg dry weight. We also estimated that between 5.2×10^{10} to 6.2×10^{12} MP/year could be transferred to the land via application of processed organic waste in Australia. The findings of this study also showed compostable bags as a potential source of MPs in some samples. This study provides the first evidence of MPs in processed organic waste in Australia and emphasises the need to more comprehensively understand the fate of MPs during the composting processes, their contribution to soil MP contamination, and their impacts on soil biota.

1. Introduction

Due to their environmental persistence, plastics are expected to accumulate in the environment, exposed to biotic and abiotic weathering conditions that lead to fragmentation and the generation of smaller plastic particles (Liu et al., 2020). Among the various sizes of plastic debris, microplastics (MPs), referring to plastic particles smaller than 5 mm, have attracted significant attention over the last decade with widespread presence reported across aquatic and terrestrial compartments ranging from water, sediment, soil, air, and biota (Chouchene et al., 2023; Lu et al., 2021; Yang et al., 2021; Zhang et al., 2019). In particular, it is estimated that the number of MPs released into soil annually is 4–23 times greater than that released into oceans (Horton et al., 2017), but our understanding of their presence and distribution in terrestrial environments is still limited compared to aquatic environments. Currently, there is growing concern about the accumulation of MPs in soil and their potential to act as a vector of other soil contaminants with studies revealing negative impacts of MPs on soil, soil biota, and plant performance even at environmentally relevant concentrations (Huang et al., 2022).

MPs can enter into terrestrial ecosystems through several major potential pathways including i) direct littering and improper disposal, ii) plastic mulching, iii) recycled organics including biosolids and compost, and iv) atmospheric deposition (Lwanga et al., 2022). Processed organics or compost have recently been identified as potentially important sources of MPs to terrestrial ecosystems (Le et al., 2023; Porterfield et al., 2023). For example, Braun et al. (2023) reported that the abundance of MPs in the soil is positively correlated with the rate of compost

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https://doi.org/10.1016/j.jenvman.2025.124359
Received 21 November 2024; Received in revised form 15 January 2025; Accepted 25 January 2025
Available online 4 February 2025
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application in Dutch farmland. Likewise, Sindujaa et al. (2023) found higher MP abundance in agricultural soil receiving compost, which was positively linked with the duration of compost application. Moreover, Zhang et al. (2022) reported that MPs in the soil treated with organic compost over a long period of time (13 years) was 3–4 times higher than the levels detected in the compost itself, indicating accumulation of MPs from compost over time. In another study in Switzerland, it was estimated that 1390 tonnes of plastics have been added to soils throughout Switzerland via compost application since 1985 (Kawecki et al., 2021).

The recycling of organic waste through composting has been considered a cost-effective way to divert food waste from landfills to food systems through its application on agricultural lands. In Australia, more than 51% of organic wastes are recovered every year. These include garden organics, food organics, biosolids and agricultural organics, which equates to approximately 1.49 million tonnes processed in 2020, and with national targets to increase it to 80% by 2030 (AEAS, 2021). Most food waste and garden waste in Australia comes from households (DCCEEW, 2024) and may be contaminated with plastic, particularly packaging material which can breakdown into microplastics during the composting process. For biosolids, roughly 10% of all biosolids (400,000 tonnes/year) produced in Australia are composted and applied to soil as a soil conditioner or fertilizer (DCCEEW, 2012). Recent studies showed that Australian biosolids are contaminated with MPs with concentrations ranging from 0.8 to 23 kg MP per tonne of dry biosolid (Okoffo et al., 2020b; Ziajahromi et al., 2024b). Nonetheless, there is currently no information available regarding the abundance of MPs in organic waste/compost products in Australia (Zhang et al., 2024a).

In Australia, many local governments have provided residences with in-house kitchen caddies and packages of compostable plastic bags to place their food waste into, prior to placing into the kerbside organics bin. This was done to drive behaviour change and increase the placing of food waste into the organic's bin following the introduction of that service. This was considered more sustainable for collecting a stream of food wastes and other compostable items. Despite being considered compostable, the degradation of these compostable bags is heavily dependent on the conditions of the composting process and can only be achieved in industrial composting facilities under specific conditions. Compostable bags could therefore continue to be source of plastics or MPs in the environment after being littered (Accinelli et al., 2022; Walker, 2023). Currently, very little is known about the presence of MPs in processed organics from both conventional and compostable plastic bags. This study provides the first investigation into the abundance, characteristics, and potential sources of MPs in Australian processed organics samples including compost, digestate from anaerobic digestion and rapidly dehydrated food waste collected from multiple compost sites across Victoria, Australia. The potential MP loads transported from processed organics to soil ecosystems were also evaluated for the studied sites.

2. Materials and methods

2.1. Sampling

Processed organic waste samples were collected from 11 organic waste processing sites (residential, agricultural and industrial; A-K) across Victoria, Australia during May–June 2023. Each site has different feedstock and processing procedures (Table 1).

Table 1
Sampling site information. FO = Food Organics; FOGO = Food Organics and Garden Organics.

Site	Land setting	Feedstock	Location	Feedstock pretreatment	Output
A	Industrial rural	Commercial FO, grease trap waste, paunch	Indoor	Shredding/ Macerate	Digestate from anaerobic digestion
B	Industrial metropolitan	Municipal FOGO, commercial FO	Indoor	Shredding, sieving to 16 mm	Compost
C	Agricultural rural	Municipal garden organics (GO), commercial FO, municipal FOGO, overburden, grease trap waste, biosolids, other	Outdoor	Shredding, sieving to 15 mm, low speed turner and hurrafex	Compost
D	Industrial metropolitan	Municipal FOGO	Outdoor	Shredding	Compost
E	Residential/ commercial metropolitan	Commercial FO	Indoor	N/A	Rapidly dehydrated food waste
F	Agricultural rural	Municipal GO, animal processing waste, municipal FOGO	Outdoor	Shredding	Compost
G	Agricultural rural	Municipal GO	Outdoor	Shredding, grinding, sieving to <10 mm	Compost
H	Industrial rural	Municipal GO	Outdoor	Shredding, sieving to 16 mm	Compost
I	Industrial metropolitan	Municipal FOGO, municipal GO	Outdoor	Shredding, grinding, sieving to 20 mm	Compost
J	Agricultural rural	Municipal GO, biosolids, municipal FOGO, grease trap waste, oversize, other	Outdoor	Sieving to 16 mm, other: feedstock is shredded prior to delivery to site	Compost
K	Industrial rural	Municipal FOGO, municipal GO, abattoir waste	Outdoor	Shredding, grinding, sieving to 16 mm	Compost

The samples were collected from the piles representing the various feedstocks received by each facility. Sub-samples were then collected as per Australian standard (AS-4454.2012) (Stanton et al., 2018) from each production batch, homogenised, and transferred to pre-cleaned 300 mL glass jars with a metal lid using a metal spoon. To avoid random variability of MP content of the sampled piles, three samples were collected from each site (except for site B where four samples were collected). In total, 34 samples were collected from all sites. After collection, samples were shipped to Griffith University and stored at 4 °C for further laboratory processing and analysis.

A strict QA/QC protocol was followed during sample collection to minimise and quantify potential issues with sample contamination. Field blanks (empty opened sampling jars) were set up during sampling to monitor any MP background contamination (especially airborne MPs). One field blank was collected for each site. Detailed information about the QA/QC approach is provided in Section 2.4.

2.2. Sample processing

After homogenising and drying in an oven at 50 °C, the processed organic waste samples were processed following a method already developed and optimised for organic-rich samples, consisting of a series of oxidative and enzymatic digestion (Ziajahromi et al., 2024b). This processing method starts with an oxidative digestion using 30% *v/v* H_2O_2 (ChemSupply, Australia). This reaction was performed in an ice bath to prevent the sample from overheating due to the exothermic nature of the reaction. The samples were then heated at 50 °C for 24 h. A mixture of enzymes consisting of cellulase from *Aspergillus niger*, lipase from *Candida rugosa*, and protease from *Bacillus licheniformis* (Sigma Aldrich, Germany) was then added to the oxidatively treated sample and incubated at 50 °C using a shaker incubator for 72 h. After completion of enzymatic digestion, further oxidative treatment was performed using Fenton's reagent (30% *v/v* H_2O_2 in conjunction with 0.05M $FeSO_4$), and the samples were heated to 55 °C for 4 h.

Upon completion of the digestion procedures, the samples were put through additional digestion steps including a two-step density separation using ultrapure water and sodium iodide (NaI; 99.9%, ChemSupply, Australia) solution with an initial density of 1.8 g/cm^3. Digested samples were transferred to 50 mL centrifuge tubes with ultrapure water and then centrifuged for 5 min at 1000×*g*. The supernatant was filtered through 25 μm stainless steel filters. Density separation using ultrapure water was repeated twice to remove H_2O_2 residue before using NaI to. The filters were kept in glass petri dishes and dried in an oven at 50 °C until microscopy.

2.3. Characterisation of MPs

Filters from each sample were inspected under a stereomicroscope (Olympus SZX10). Suspected MPs (>25 μm) were counted and classified according to their morphology (fibre, fragment, bead and film) using the point counting tool in the CellSens Standard image analysis software (Version 13.1 Olympus) which enables semi-automated counting of MPs. Photos were taken by a stereomicroscope (Olympus XZ10) equipped with digital camera (Olympus DP74). The categorisation of each morphology refers to the physical feature described by Lusher et al. (2020). The size of individual particles was measured using the measuring tool available in the software by measuring the longest dimension of the particle. The counting and size measurement data was automatically exported from the software package into a spreadsheet.

All suspected MPs ($n = 1623$) were analysed using Fourier transform infrared (FTIR) spectroscopy. Spectra collection was performed using a Nicolet iS50 spectrometer equipped with a Nicolet Continuum Infrared Microscope (ThermoFisher Scientific, USA). Particles larger than 1 mm were individually transferred with tweezers from filters to the diamond crystal of the built-in Attenuated Total Reflectance (ATR) accessory of the spectrometer. Particles smaller than 1 mm were analysed directly on the filters using the microscope in reflectance mode. FTIR spectra were measured at a wavenumber resolution of 4 cm^{-1} with a total of 32 scans collected across a wavenumber range from 4000 to 650 cm^{-1}. Spectra were subjected to a library search using the search routine of the Nicolet Omnic 9.2 software with a library set that included the Nicolet polymer, forensics and common materials set in addition to the Hummel polymer library. The search routine produced a score out of 100 for goodness of match. Polymer composition of the particle was automatically accepted if the match score exceeded 80% against reference spectrum. For spectra with a match score between 60% and 80%, the polymer composition of particles was confirmed after careful spectra examination due to the potential impact of weathering on the particles.

2.4. Quality control/quality assurance (QA/QC)

A strict QA/QC protocol was followed to monitor and minimise background MP contamination. This includes two types of negative control samples, contamination control procedures, followed by further method validation (Ziajahromi and Leusch, 2022). Field blanks were sampling jars opened at the point of sample collection but left empty. Laboratory blanks include empty beakers that were processed through all steps of sample processing to determine any potential background plastic contamination from the laboratory (e.g. contamination from air, operators, and used chemicals) (Ziajahromi and Leusch, 2022). One laboratory blank was included with each sample batch. The blank beakers contained ultrapure water and were processed using the same methodology as described above for the processed organic waste samples. During sampling, all reusable equipment (shovel, spade, buckets, trowel, metal sampling sheet and sample spoon) were washed between each sample with a 5% Liquinox water solution (Alconox, U.S.A), which is a concentrated, anionic detergent and PFAS-free detergent, to decontaminate equipment between samples. Once washed, the equipment was rinsed with tap water followed a laboratory supplied ultrapure water and allowed to dry prior to reuse. Additionally, to avoid potential background contamination during the sample analysis process in the laboratory, a series of preventive measures described by Ziajahromi and Leusch (2022) were adopted, including (i) ensuring that all sampling containers and laboratory glassware were rinsed three times with ultrapure water before use and covered with aluminium foil after each step, (ii) wearing cotton lab coats and nitrile gloves during the whole process, (iii) conducting all process steps in a fume cupboard, and (iv) vacuum-filtering all chemicals through nylon filters (Whatman®, pore size: 0.45 μm, diameter: 47 mm) immediately prior to use.

Blank correction was carried out using the limit of detection/limit of quantification (LOD/LOQ) approach, which was recently recommended to analyse control data in MP research (Dawson et al., 2023). LOD is defined as mean number of particles from negative controls $+3 \times$ standard deviation and LOQ is the mean number of particles in negative controls $+10 \times$ standard deviation. Adjustment was only performed if particles with the same morphology and polymer type were found in both samples and negative controls by subtracting LOD value from the total number of MPs in each sample.

While in our previous study we validated the sample processing method for various types of microplastics (polyester, polyethylene, polypropylene, and polystyrene) and morphologies (fibre, fragment, and bead) (Ziajahromi et al., 2024b), in this study we further validated the method for compostable bin liners, as these bags could be a potential source of MPs in processed organics. Therefore, compostable bin liners, which are certified to the Australian Commercial Composting Standard (AS4736), and Australian Home Composting Standard (AS5810), were prepared by cutting into pieces with size ranging from 500 to 1000 μm to examine the potential impact of sample processing and to obtain their recovery rate. Ten pieces of compostable bin liners were spiked in compost samples and processed in duplicates with the same procedures as described in Section 2.2. Special attention was paid to whether the processing steps would affect the recovery, morphology and characteristics of the recovered MPs (i.e., FTIR spectra).

2.5. Statistical analysis

The concentration of MPs was reported as MPs/kg dry weight (dw) of processed organic waste (average ± SD). If data were normally distributed (as determined by Shapiro-Wilk test), a *t*-test was performed to compare the indoor and outdoor datasets, otherwise, a non-parametric Mann-Whitney test was applied. Additionally, the correlation between MP abundance and the age of feedstock was performed using Spearman rank correlation because the dataset was not normally distributed. Based on the concentration of MPs detected across the compost samples, we also estimated the level of MPs being transported to soil through the application of processed organics using Equation 1.

$$\textit{MPs transferred to land}\left(\frac{MPs}{y}\right) = \textit{MP concentration per unit compost}\left(\frac{MPs}{dry\ tonnes}\right) \times \textit{total organic waste processeed}\left(\frac{dry\ tonnes}{y}\right) \times \%\ \textit{rate of usage by different sectors} \quad (1)$$

All data were recorded using Excel and statistical analysis was performed using GraphPad Prism (v9.3.1). The statistical significance level was set to $\alpha = 0.05$. All graphs were produced using GraphPad Prism.

3. Results and discussion

3.1. QA/QC

A total of 25 and 24 particles were recorded from 11 field blanks and 3 laboratory blanks, respectively, with the majority in the form of fibres (23 in field blanks and 21 in laboratory blanks). After FTIR analysis, 7/25 and 11/24 particles were identified as cellulosic fibres and the rest of fibres were identified as polyester (PES). The fragments found in both field blanks (n = 2) and laboratory blanks (n = 3) were all polypropylene (PP). Blank correction was performed according to the methods described in Section 2.4. The LOD value (4.6) was subtracted from all samples containing the same polymer type and morphology as found in the blank samples, not exclusively to those paired with the blanks to ensure consistency across the entire dataset.

Across all samples, 98% (n = 1584) of all particles extracted were identified as plastics, while only 2% of the total particles (n = 39) were classified as non-plastic, with FTIR spectra of the non-plastic particles mostly identified as silica or cellulosic origins and or unidentified.

Method validation with compostable bin liners had recovery rate of 80%. The FTIR spectra (Fig. S1) of the recovered compostable bin liners did not present significant alteration (e.g., colour and morphology), suggesting that they were resistant to the chemicals used for digestion and density separation. This is consistent with Edo et al. (2022) who reported the resistance of different compostable bags to the chemicals used during microplastic processing including H_2O_2 and $ZnCl_2$.

3.2. Abundance of MPs

MPs were recorded in all processed organic waste samples. The results showed high variability in MP concentrations across different sites ranging from 1500 ± 410 MP/kg dw at site F to 16,000 ± 1900 MP/kg dw at site I (Fig. 1). There was no significant difference in MP concentration between sites that kept the processed organics indoor and outdoor (t-test, $p > 0.05$). Additionally, no significant correlation was observed between the concentration of MPs and processing time (Spearman rank correlation, $r(33) = -0.027$, $p > 0.05$).

The variation in MP concentration across different sites may be attributed to several factors, including land setting of individual sampling site, type of feedstock, and organic waste processing methods. For example, industrial rural sites such as H and K showed lower MP concentrations compared to industrial metropolitan sites (B, D, I). However, Site A, also an industrial rural site, showed higher concentrations than metropolitan sites which is likely attributed by the type of feedstock. Furthermore, sites C and J, both agricultural rural sites, have used biosolids as feedstock which can possibly explain the higher MP concentration compared to other sites as biosolids have been identified as a significant source of MPs (Harley-Nyang et al., 2023). For example, a recent study conducted in Australia reported MP concentrations ranging from 11,000 to 150,000 MP/kg dw in biosolid (Ziajahromi et al., 2024b).

MPs have been reported in organic waste, including food and garden organics in different countries (Braun et al., 2023; Edo et al., 2022; Gui et al., 2021; Iswahyudi et al., 2024; Schwinghammer et al., 2021; Scopetani et al., 2022; Sholokhova et al., 2022; van Schothorst et al., 2021; Weithmann et al., 2018; Zhang et al., 2022). The abundance of MPs found in the present study was within the range reported by previous studies on MPs in compost and biowaste in different countries in Europe and Asia (Table 2). However, our results were an order of magnitude higher than reports on MPs in compost in Germany (Schwinghammer et al., 2021; Weithmann et al., 2018). This difference could be attributed to the differences in practices, disposal and treatments of processed organics in different geographical regions (Zhang et al., 2024a). Moreover, other factors impacting the concentration of MPs in environmental samples such as differences in analytical methodology (e.g., sampling and sample processing methods, such as size of filter used), and identification and quantification techniques (e.g., lowest size detected, type of instrument) could also play important roles. For example, Schwinghammer et al. (2021) and Weithmann et al. (2018) only reported MPs between 1000 and 5000 μm and therefore reported lower concentrations compared to the studies that detected smaller MPs, including the present study. It has been shown that the concentration of MPs is negatively correlated with the minimum size of MPs detected in various environmental matrices (Koelmans et al., 2020; Leusch et al., 2023). Hence, it is expected that studies with lower size detection limits report higher MP concentrations. Moreover, Braun et al. (2023) solely relied on visual observation (microscopy) to report MPs, a method known to be unreliable and associated with significant bias. Similarly, Sholokhova et al. (2022) only identified particles smaller than 1 mm using Nile red staining and fluorescent microscopy. While the fluorescent staining method is known for being rapid and cost-effective compared to instrumental identification (e.g., FTIR and Raman spectroscopy), it can potentially lead to inaccurate quantification of MP abundance as Nile

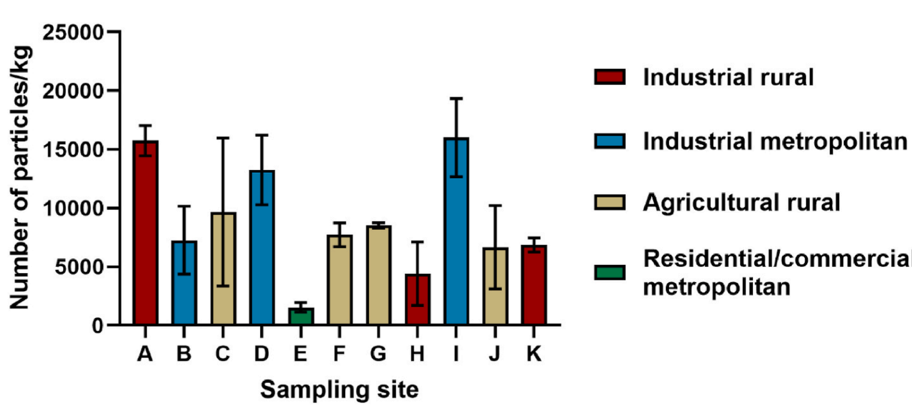

Fig. 1. Number of microplastics per kg dry weight of processed organic waste samples collected from different sites with different land setting. Data is presented as average ± SD.

Table 2
Summary of studies reporting MPs in compost and/or processed organic waste.

Location	Feedstock	Concentration (MPs/kg dry weight)	Size range (μm)	Morphology	Polymer type (>10%)	Identification method	Reference
Australia	Processed organic waste	1500-16,000	25–5000	Fibre, fragment	PP, PE, PES	FTIR	Present study
China	Rural domestic waste	2267–2533	50–5000	Fibre, fragment, spherules, film, foam	PES, PP, PE	FTIR	Gui et al. (2021)
China	Domestic Waste compost	11,640 ± 3565	100–5000	Fibre, fragment, film	PP, PE, PET	FTIR	Zhang et al. (2022)
Finland	Bio-waste & Sewage sludge	6600 ± 1500	20–5000	N/A	PET, PE	FTIR	Scopetani et al. (2022)
Germany	Compost	20–146	1000–5000	Fibre, fragment, sphere	Styrene-based, PES, PE, PP	FTIR	Weithmann et al. (2018)
Germany	Compost	39–102	1000–5000	Fibre, fragment, sphere, film	PVC, PP, PE, PET	FTIR	Schwinghammer et al. (2021)
Germany	Compost	0–64	65–5000	Fibre, fragment, sphere	N/A	Microscope	Braun et al. (2023)
Indonesia	Compost	260–1160	60–1000	Fibre, fragment, filament	PET	FTIR	Iswahyudi et al. (2024)
Lithuania	Green waste	5733–6433	50–5000	Fibre, fragment, sphere, film	PP, PE, PS	FTIR (>1000 μm)	Sholokhova et al. (2022)
Lithuania	Food waste	3783–4066	50–5000	Fibre, fragment, sphere, film	N/A	Fluorescent microscopy (<1000 μm)	Sholokhova et al. (2022)
Netherlands	Municipal compost	2800 ± 616	30–2000	N/A	PP, PE	FTIR	van Schothorst et al. (2021)
Netherlands	Garden waste	1253 ± 561	30–2000	N/A	PP, PE	FTIR	van Schothorst et al. (2021)
Spain	Municipal solid waste	5000-20,000	75–5000	Fibre, fragment, film, filament	PP, PE, PS, PES	FTIR	Edo et al. (2022)

Red only stains certain polymers (Stanton et al., 2019). Therefore, these differences make it difficult to meaningfully compare the results with other studies.

Recent studies on MPs in soil have shown that long-term application of organic waste (e.g., biosolid, compost) can increase MP accumulation in farmland soils. For example, Zhang et al. (2022) reported a concentration of 2462 MP/kg in soil that received compost for over 13 years and estimated that accumulated MPs derived from compost ranged from 3.6 to 5 $\times$ 10^9 MPs per hectare. That study also estimated that compost application contributed approximately 56% to MP accumulation in the soil. van Schothorst et al. (2021) also found MPs with concentrations ranging from 888 to 2242 MP/kg in Spanish agricultural soils receiving compost (sourced from municipal organic waste and green waste) with similar characteristics to the MPs found in the compost samples. Similarly, Sindujaa et al. (2023) compared the MP abundance in three agricultural fields with different duration of compost application and reported the highest MP abundance in samples collected from sites with the longest application duration.

We also calculated the mass load of MPs in the samples using the average MP concentration (number of particles/kg), size range, morphology and polymer density according to the equations proposed by Leusch and Ziajahromi (2021) (Section S2). The calculated average MP mass load in processed organic waste samples ranged between 7 $\pm$ 5 mg/kg dw at Site E and 760 $\pm$ 310 mg/kg dw at Site A (Table S1). This is on the lower end of the range compared to the MP abundance previously reported in biosolids in Australia (400-23,000 mg/kg dw biosolid) determined using pyrolysis gas chromatography mass spectrometry (GC/MS) (Okoffo et al., 2020a).

As indicated in Table 2, previous studies have not reported MP concentrations in compost/organic waste as mass concentrations because spectroscopic analyses (such as FTIR, LDIR, and Raman) do not directly provide information on the mass of particles. Reporting MP concentration based on the number of particles is commonly done in the literature across a wide range of matrices, including water/wastewater, biosolids, sediment, soil, organic waste, and air. The only mass concentration-based study by Růžičková et al. (2022) reported mass of plastics in compost feedstock by using GC/MS technique and reported a total of 431 mg/kg MPs in compost. However, the reported concentration was limited to particles between 5 and 10 mm, making it difficult to compare the results with the present study.

3.3. *Characteristics of MPs*

3.3.1. *Morphology and chemical composition*

Despite variability between concentrations of MPs in the processed organic waste samples across different sites, there was less variability in the morphology of MPs, with the majority of MPs across all samples present as fragments (average 62–97%) followed by fibres (average 3–38%) (Fig. 2). Fragments comprised the majority of MPs across all sites except Site I, where fibre-shaped MPs were predominant. While there were no significant differences between the abundance of fibres and fragments in indoor and outdoor sites (Mann-Whitney, $p > 0.05$), more fibres were found at some outdoor sites (Site D and I). This observation potentially suggests a contribution from atmospheric deposition to higher fibre counts in these outdoor locations. A recent review on atmospheric MPs reported that synthetic fibres were predominantly present in atmospheric samples (Munyaneza et al., 2022).

Eighteen different polymers were identified in the processed organic waste samples across different sites (Fig. 3). This includes PP, polyethylene (PE), PP-PE copolymer, polystyrene (PS), PES, acrylic (also known as polymethyl methacrylate or PMMA), alkyd resin, polyacrylonitrile (PAN), polyvinyl chloride (PVC), polyvinyl alcohol (PVA), nylon (PA), polyurethane (PU), polyetherurethane (PEU), ethylene-vinyl acetate (EVA), acrylonitrile butadiene styrene (ABS), styrene-acrylonitrile resin (SAN), phenoxy resin and epoxy resin. FTIR spectra of major polymers are provided in Fig. S2.

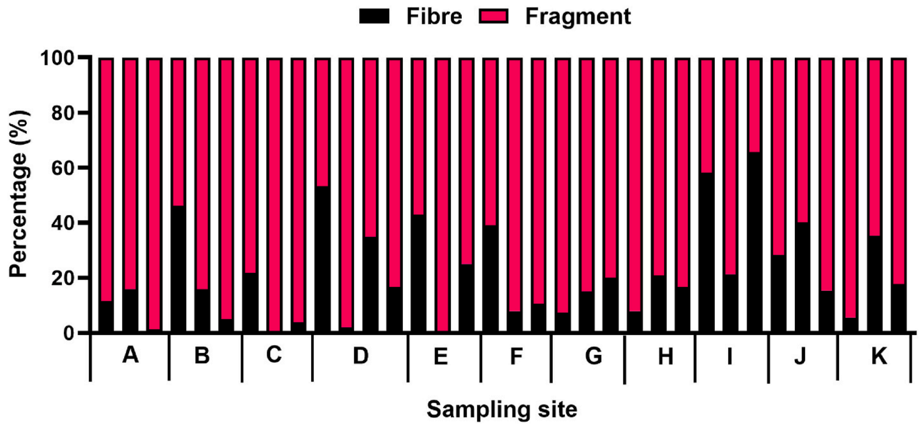

Fig. 2. Morphology of microplastics detected in the processed organic waste samples collected from different sites.

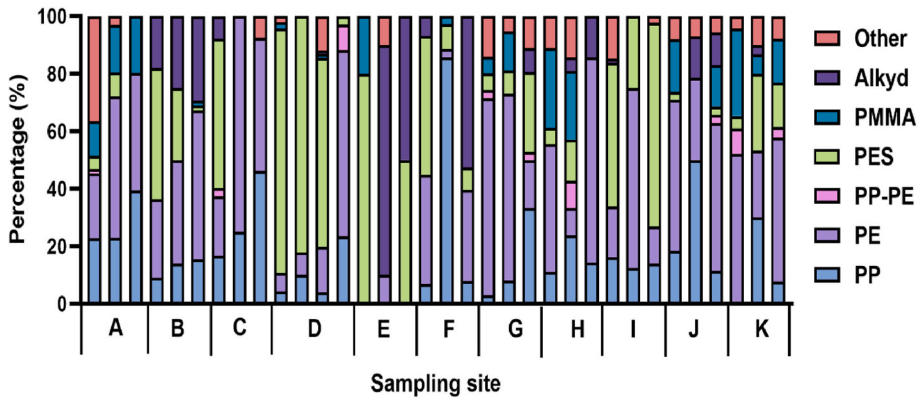

Fig. 3. Polymer composition of microplastics in processed organic waste samples collected from different sites. PP: polypropylene; PE: polyethylene; PP-PE: polypropylene polyethylene copolymer; PES: polyester polymer; PMMA: acrylic; Other: PS, PAN, PA, PVC, PVA, ABS, EVA, SAN, PU, PEU, phenoxy resin and epoxy resin.

While the polymer type distribution of MPs varied between different sites, PP and PE were consistently detected as the most abundant polymers found across all samples followed by PES, together constituting 75–100% of all polymers. The fibres were mainly PES while fragments were mainly PP, PE and PES. Polymers such as PS, PMMA, PAN, PVC, PU, PEU, PA, PVA, ABS, EVA, SAN, alkyd resin, phenoxy resin and epoxy resin only comprised between 0 and 36% of total MPs across all samples. The dominant polymer types of MPs detected in compost samples in present study is similar to those reported in previous studies (Table 2). Overall, these findings are expected because PP, PE and PES account for 51% of global plastic production (PlasticsEurope, 2023).

The morphology and chemical compositions of MPs found in the samples are both important indicators of the origins of MPs. For example, PES, which was predominantly detected (58%) as fibrous MPs across all processed organic samples (Fig. S3A), is one of the leading synthetic materials used to manufacture textiles (Zhang et al., 2020). This suggests that fibrous MPs detected in the present study likely originated from clothing or other fabrics. PP and PE comprise 57% of fragments found across all samples (Fig. S3B). These MP fragments generally form from the breakdown of larger plastic items, such as food packaging, containers and bottles (Lambert and Wagner, 2018; Sholokhova et al., 2022).

The FTIR spectra of fragments found in sites C, D, G and K exhibited high similarity (>80% match score) to polyethylene terephthalate (PET) and, interestingly, showed high similarity to the compostable bin liners that are widely used for the disposal of food organics and garden waste in Australia (Fig. S4). Comparing the characteristics of these bags with the green fragments found in this study could help identify potential sources of some of these green fragments. While poly (butylene adipate co-terephthalate) (PBAT) and polybutyl terephthalate (PBT) are common based materials found in the compostable bin liners available in the consumer market (Accinelli et al., 2022; López-Ibáñez et al., 2024), it was not possible to conclusively identify these polymers in the selected compostable bin liners simply based on the peak features observed in the FTIR spectra. Both PET and PBT are aromatic PES whereas PBAT, considered as a copolyester polymer, is synthesised from butanediol, adipic acid and terephthalic acid (Jian et al., 2020). Therefore, the green fragments reported in present study were reported as PES polymer. Currently, there is no clear evidence regarding the presence of compostable materials in processed organic samples. For example, Edo et al. (2022) reported the absence of compostable materials in analysed compost samples from a site that exclusively used compostable bags as input material.

3.3.2. *Size*

MPs found in the present study were classified into three size classes of 25–100, 100–500 and 500–5000 μm. In most samples, MPs smaller than 500 μm accounted for 50–100% of the total MPs, except in two samples from sites J and K (Fig. 4). The larger size proportion of MPs recorded in samples from sites J and K could be related to the higher proportion of fibres found, which have a higher length-to-diameter ratio. The size distribution of detected MPs across different sizes can also be attributed to the pretreatment procedures used to process the feedstock. For example, shredding, grinding, and sieving were carried out at all sampling sites except Site E to process batch feedstock (Table 1). These processes have been considered as a main factor

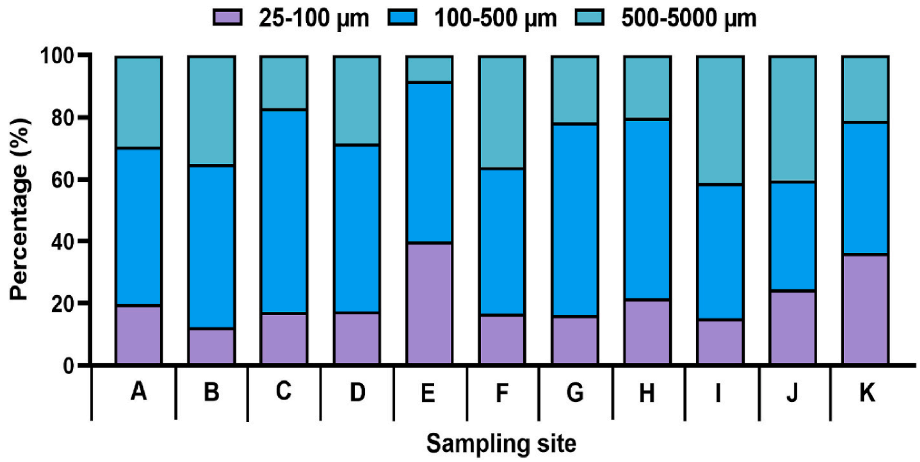

Fig. 4. Percentage of size ranges of microplastics detected in processed organic waste samples. Data is presented as average of replicates.

contributing to the fragmentation of MPs in compost samples which can mechanically break down plastics present in the compost into smaller particles, potentially leading to a higher concentration of MPs (Braun et al., 2023; Gui et al., 2021; Sholokhova et al., 2022). It has been shown that high temperatures (>60 °C) can cause strong degradation to a wide range of polymers (such as PET, PS, PE, PVC, PA) (Schrank et al., 2022). While temperature during industrial composting is often in the range of 55–60 °C, temperature during rapid dehydration may reach to over 100 °C. Thus, the lower size of MPs detected in site E could be attributed to feedstock treatment through rapid dehydration process as well employment of macerators, which may cause break down of plastics/MPs into smaller particles. Additionally, the concentration and polymers detected in this particular site may have been impacted by the dehydration process. For instance, some polymers such as PE with lower melting point (between 92 and 105 °C) may have been affected or removed during the processing.

The size distribution of MPs detected in the present study is consistent with studies reporting MPs in compost from China (Gui et al., 2021), Lithuania (Sholokhova et al., 2022) and Spain (Edo et al., 2022), where MPs smaller than 500 µm accounted for the majority of particles recorded. Concerns about smaller MPs were raised not only because of increasing bioavailability, but also potential toxicity to soil biota. Smaller MPs can be readily ingested by soil organisms and have a higher potential for uptake by plants (Liang et al., 2023). This can ultimately lead to toxic effects on soil biota (Shafea et al., 2023; Zhou et al., 2021). In addition, smaller MPs have larger surface areas, which increases the chances of sorption of other pollutants and microorganisms in the environment (Luo et al., 2022), eventually increasing the toxicity to exposed organisms.

3.4. *Potential transport of MPs from processed organics (composted materials) to soil through different applications*

In Australia, the composted materials are used in different applications primarily including agriculture, urban, land rehabilitation and environmental remediation. While only some activities may directly contribute to land or soil MP contamination, the amount of MPs transferred through composted materials was estimated based on the average concentration of MPs in compost samples, total organic waste processed in Victoria (2020–2021) (Victoria Government, 2022), and usage rate of composted materials across different sectors. For example, in Australia 26.2% of produced compost is used in intensive agriculture, while only 2.3% is used in land rehabilitation and 4% in environmental remediation.

According to Victoria's waste projection model and Australian Organics Recycling Industry Capacity Assessment (Australian Organics Recycling Association, 2021), approximately 1,490,000 tonnes of organic waste have been processed each year in Victoria. Therefore, based on this data it is estimated that between 5.9×10^{11} to 6.2×10^{12} MPs per year are likely to be released to agricultural lands from compost while 5.2×10^{10} to 5.4×10^{11} and 5.9×10^{11} to 9.5×10^{11} MPs/year could be transferred to land through rehabilitation and remediation activities. This is equivalent to the mass of 2.7–206 tonnes MPs/year for agriculture, 0.2–25.9 tonne MPs/year for land rehabilitation and 0.4–45.1 tonnes MPs/year for remediation sectors. A study in Switzerland investigated the flow of plastic (only plastic particles larger than 1 mm) from compost to soil and estimated that 50 tonnes of plastics/year can accumulate in agricultural soil from compost application (Kawecki et al., 2021).

It is very important to accurately estimate the transport of MPs from compost to soil as the majority of previous estimates are based on theoretical estimations rather than actual data. This information is critical for ecotoxicity studies and ultimately for any policy and decision making and implementation of effective MP source control approaches and strategies to protect soil and land environment.

3.5. *Limitations and future directions*

While the results of present study illustrate the ubiquitous presence of a range of MPs in all processed organic waste samples, particles smaller than 25 µm could not be analysed due to the detection limit of FTIR spectroscopy. Particles smaller than 25 µm can generally be analysed by Raman spectroscopy. While our methodology enabled us to isolate smaller MPs (down to 1 µm) from such complex samples, we were unable to identify the type of polymers using this technique due to the strong fluorescence interference caused by the naturally fluorescent colours/additives of particles affecting the accuracy of Raman measurement (Nava et al., 2021). This fluorescence masking has been identified in our previous work as one of the major limitations to identifying smaller MPs isolated from soil samples using Raman spectroscopy (Ziajahromi et al., 2024a).

Also, the physical and chemical properties of MPs could be significantly altered during the different composting and digestion processes which could affect the adsorption capacity of other pollutants (Zhang et al., 2024b). For example, MPs in composts have been reported to act as carriers of toxic chemicals, including metals (Vithanage et al., 2021). They may disrupt the carbon cycle, alter microbial distribution, and negatively impact soil biota. While compost has been reported to be beneficial to agro-ecosystems by improving soil quality and crop productivity (Ho et al., 2022), processed organic waste containing MPs could pose a risk when applied to agricultural land. More comprehensive research is warranted to investigate the environmental fate and behaviour of MPs during composting processes to determine the significance of this finding.

4. Conclusion

This study provides the first evidence of the occurrence of MPs in Australian processed organics. The results showed concentration varying from 1500 to 16,000 MP/kg dw which could be mainly linked to the types of feedstocks and processing. The majority of MPs detected across different sites were in the form of fragments and mainly comprised of PP and PE followed by PES. The FTIR spectra of some green fragments exhibited high similarity to the FTIR spectra of several compostable bags. However, further research is required to investigate the impact of compost processing on compostable plastics. Moreover, it is important to investigate the accumulation of MPs in soil with long-term application of processed organic waste. Our data shows that the majority of MPs across all samples were between 25 and 500 μm in size, highlighting the importance of detecting small-sized MPs in compost samples to provide more accurate data. The impact of compost processing on the size of MPs in the final compost needs to be further investigated in future research. Moreover, more research is required to investigate the fate of microplastics during composting and the leaching of plastic additives. Our findings confirm the presence of MPs in Australian processed organics, indicating a potential source of MPs in soil. Remediating MP pollution in soil environments is challenging, making effective source control crucial to prevent the transfer of MPs to agricultural ecosystems.

CRediT authorship contribution statement

Hsuan-Cheng Lu: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Winnie Cao:** Writing – review & editing, Conceptualization. **Scott Jones:** Writing – review & editing. **Frederic D.L. Leusch:** Writing – review & editing, Methodology, Conceptualization. **Nikol Slynkova:** Writing – review & editing, Methodology. **Raymond Trevorah:** Writing – review & editing, Methodology, Investigation. **Barry Warwick:** Writing – review & editing, Conceptualization. **Shima Ziajahromi:** Writing – review & editing, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

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

Acknowledgments

This study was funded by EPA Victoria and Sustainability Victoria through the Recycling Markets Acceleration Package. We thank Mr Ashley Locke at the Central Analytical Research Facility, Queensland University of Technology for assistance and helpful advice in interpreting FTIR spectra.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.124359.

Data availability

Data will be made available on request.

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