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RESEARCH ARTICLE

# Abundance and characteristics of microplastics in treated organic wastes of Kaunas and Alytus regional waste management centres, Lithuania

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**Abstract**
The widespread use of plastic without the sustainable management of the plastic waste has led to its accumulation in the environment. The presence of microplastics even in drinking water and food products is of immense concern. This situation is getting even more complicated due to the limited knowledge about the sources of microplastics and their impact on the environment and human health. This article focuses on a poorly understood but potentially significant source of microplastic-treated organic waste. Quantitative and qualitative analyses of microplastics down to 50 μm in the stabilised organic waste (SOW) output after mixed municipal solid waste (MSW) processing and green and food composts are presented in the article. Nile Red staining and FTIR analysis were adopted for the identification of microplastics. The highest average microplastic abundance was found in the SOW: 17407 ± 1739 particles $kg^{-1}$ in autumn and 15400 ± 1217 particles $kg^{-1}$ in winter. Nevertheless, even separately collected treated organic waste contained a significant amount of microplastics. Green compost contained 5733 ± 850 particles $kg^{-1}$ in autumn and 6433 ± 751 particles $kg^{-1}$ in winter, while food compost 3783 ± 351 particles $kg^{-1}$ in autumn and 4066 ± 658 particles $kg^{-1}$ in winter. Microplastics < 1 mm accounted for 83.8–94.9% of all microplastics, which reflects the need to control not only large but also small microplastics in organic waste fertilisers to prevent soil pollution. The dominant shape of microplastics in compost samples was films, while in the SOW, it was fragments. Based on morphological and FTIR analyses, the majority of microplastics in green and food composts were considered as the residuals of plastic bags and packaging materials.

**Keywords** Microplastics · Compost · SOW · Green waste · Food waste · Nile Red · FTIR

## Introduction

Plastics are in high demand in the modern world and are widely used in various sectors, especially in the packaging, building, and construction segments (PlasticsEurope 2020). However, the increase in plastic consumption without proper waste management has led to plastic and microplastic pollution. In 2018, 61.8 million tonnes of plastic was produced in Europe, while only 9.4 million tonnes of plastic post-consumer waste was recycled (PlasticsEurope 2020). Microplastics, synthetic polymer particles of 0.001–5 mm, have received considerable attention in recent decades. Understanding the sources and pathways through which microplastics enter the environment is essential for the control and prevention of microplastic pollution. The main sources of microplastics include abrasion from car tyres (Boucher and Friot 2017), washing of synthetic textile (Hernandez et al. 2017), city dust (Dehghani et al. 2017),

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plastic pellet production and fragmentation of plastic debris (Duis and Coors 2016), and personal hygiene products (Sun et al. 2020). Despite the large amount of existing research on microplastics, their sources are not comprehensively understood. Waste treatment, including organic waste treatment, has only recently begun to be identified as a source of microplastics. However, the initial calculations of German (Bertling et al. 2018) and Austrian (Meixner et al. 2020) researchers reveal that it can be one of the largest sources of microplastics.

Biological treatment of organic waste through composting, anaerobic treatment, or fermentation reduces the amount of biodegradable waste going to landfills and produces a nutrient-rich organic outputs (Weithmann et al. 2018). Application of such organic outputs to the land can return nutrients, trace elements, and humus to the soil and reduce chemical fertiliser and peat consumption (Sardarmehni et al. 2021; Weithmann et al. 2018). However, these organic outputs can contain significant amounts of microplastics and be a pathway for microplastics to enter the environment. Microplastic pollution in soil can have a significant impact on soil properties, terrestrial biota, ecosystems functioning, and human health (Boots et al. 2019).

The sources and amount of microplastics in the organic outputs depend on the raw materials used in their production. The biological treatment of organic waste from mixed municipal solid waste (MSW) at the mechanical-biological treatment (MBT) facilities produces a stabilised organic waste (SOW) output. In Europe, it is used in most cases for landfill covering or slope formation due to the high concentration of impurities (EC 2019). Most of the microplastics, in this case, are presumably formed at the pre-treatment stage due to the shredding of mixed MSW, of which plastic waste represents a significant part (Sundt et al. 2014). In Lithuania, plastic waste can represent up to 31% of total mixed MSW mass, depending on the season and the region (AAA 2020). After shredding, the waste is sieved, and a smaller fraction (usually less than 80–120 mm), including microplastics, is used for the biological treatment. Biological treatment can also affect the microplastic abundance as according to Gui et al. (2021) and Sintim et al. (2019), microplastics can also release from the macroplastic surface during aerobic waste treatment. After anaerobic and/or aerobic treatments, processed waste is sieved and microplastics finally concentrate in the SOW output.

Separately collected food and green wastes can be raw materials for compost production, which is used for agricultural purposes as fertiliser. However, even compost made of green or separately collected food waste can be contaminated with microplastics. In addition to food components, food waste may contain disposal bags and food packaging materials thrown into an organic waste bin (Sundt et al. 2014). Inputs of plastic in green compost could potentially include disposal bags and plastics accidentally trapped in green waste from the environment before waste collection. According to Markowicz and Szymańska-Pulikowska (2019), after composting biodegradable and oxo-biodegradable bags together with organic waste, their residues may remain in the produced compost.

Nowadays, there are only a few initial experimental studies on microplastics abundance in composts from separately collected organic wastes (Weithmann et al. 2018; Braun et al. 2020; Schwinghammer et al. 2020; Zafiu et al. 2020) and organic outputs made from mixed MSW (Carabassa et al. 2020; Schleiss 2017; Brinton 2005). A more detailed review of pre-existing studies on the amount of microplastics in organic outputs from the MBT facilities was presented in the previous article (Sholokhova et al. 2021). However, most authors in their work focused on the abundance of large visible microplastics (1–5 mm), while the small ones (< 1 mm) remain unexplored. The abundance of small microplastics in compost samples was only investigated by Meixner et al. (2020), Braun et al. (2020), and Gui et al. (2021), while in the SOW output, it was not investigated at all. In addition to a lack of research and a focus on large microplastics, an accurate assessment of treated organic waste as a source of microplastics is hampered by the use of different methodologies for the microplastic identification and quantification. Optical and spectroscopic methods provide information on the particles' number, as well as the shape, colour, and size of microplastics. Visual identification is the easiest and cheapest method, but it can lead to the overestimation of small microplastics (Braun et al. 2020; Meixner et al. 2020). FTIR and Raman spectroscopic imaging are the most accurate methods for quantification of microplastic particles' number, but they are expensive and time-consuming so they cannot always be used. In contrast, thermal extraction desorption gas chromatography mass spectrometry (TED-GC-MS) method is effective for the quantification of microplastic mass in environmental samples (Elert et al. 2017; Dümichen et al. 2017); however, it is destructive analytical method and does not provide information on the size and shape distribution of microplastics.

This article aims to investigate and compare the abundance of both large (1–5 mm) and small (< 1 mm) microplastics and their characteristics in different types of treated organic waste, such as SOW output from MBT facility and green and food composts. A comparison of different types of treated organic waste will show the relationship of raw materials with the amount of microplastics. The data on the abundance of small microplastics in compost samples will be useful for setting further limits on their concentration in organic waste fertilisers, since the new EU Fertilising Products Regulation covers only microplastics > 2 mm. In addition, investigation and comparison of the dominant sizes, shapes, and polymer types of microplastics from different treated organic waste will suggest their origins. Understanding the origins of microplastics is essential for developing recommendations to reduce the amount of microplastics. Methods for extraction and identification of microplastics were selected based on a literature review considering efficiency, accuracy, cost, and necessary laboratory equipment.

## Materials and methods

### Sampling points

Three different types of treated organic waste were taken to analyse the microplastic abundance. SOW output was obtained from Kaunas MBT facility. Food and green compost samples were obtained from Takniskes composting site of Alytus regional waste management centre. Kaunas MBT processes mixed MSW with average mass concentration of plastic waste from 10 to 31% depending on the region the waste comes from and the season (AAA 2020). Incoming mixed MSW is shredded and then screened into two main fractions: organic-rich fraction under 80 mm, which is used for aerobic biological treatment, and coarse fraction over 80 mm. Aerobic treatment is carried out in tunnels with oxygen, temperature, and moisture control. After the tunnel composting, the treated organic fraction is dried and sieved through a 15-mm sieve to remove the large non-compostable fraction. Then, the inert fraction, mostly glass, is separated using an air separator. Therefore, at the end of the mechanical post-treatment, three fractions are generated: a non-compostable fraction (15–80 mm), an inert fraction (0–15 mm), and the SOW output (0–15 mm). SOW output is left in an enclosed building for several additional weeks for the maturing phase. Considering the entire waste treatment scheme at Kaunas MBT and the sizes of the final fractions, most of the microplastics are concentrated in the SOW fraction. Three replicate samples of this fraction were taken for further analysis in September 2020 and February 2021.

Alytus region waste management centre is the only centre in Lithuania that processes separately collected food waste from households, supermarkets, canteens, and food factories. Incoming food waste includes fruit and vegetable residues, tea leaves and tea bags, coffee grounds and their filters, other food residues, food-coated paper, paper towels, and paper napkins. However, food waste can come to the composting site with packaging and residuals bags, which are not separated at the pre-treatment stage. Incoming food waste is first shredded, mixed with structural material (shredded branches), and then loaded into closed tunnels for anaerobic treatment with biogas production. After anaerobic treatment, the waste is treated aerobically, and at the end of the process, it is sieved through a 10-mm sieve to remove large non-compostable materials, including plastic bags. Ready compost is used as a fertiliser for non-agricultural soil. In addition, Alytus waste management centre produces certified compost for agricultural purposes from separately collected green waste. Green waste, such as branches, leaves, grass, and garden waste, comes from residents, utilities, small businesses, and institutions. Windrow composting is carried out with natural aeration and periodic reloading of the piles. For the current study, three replicate samples of food and green composts were taken from Takniskes composting site in October 2020 and February 2021. Basic information about the collected samples is presented in Supplementary Table 1.

### Microplastic extraction and identification

There are no standard operating protocols for sampling and detecting microplastics (Löder and Gerdts 2015; Vermeiren et al. 2020). Therefore, the protocol for the extraction and identification of microplastics from organic-rich samples was developed by authors of this article and it is based on the literature review of common methods (Sholokhova et al. 2021). The algorithm is presented in Fig. 1.

First, samples were dried at 80 °C for 24 h. For further analysis, 10–20 g of each sample was weighed. The dried samples were sieved through a 5-mm sieve to separate large particles, and then through a 1-mm sieve to divide samples into two granulometric fractions following the recommendations for European Union (EU) monitoring purposes (Hanke et al. 2013). Fractions 1–5 mm were examined visually. Particles were identified as plastics by their colour and shape. Presumptive microplastics were extracted with tweezers and then subjected for density separation to separate accidentally caught stones and glass. As a density solution, 1.5 g mL$^{-1}$ of potassium formate solution was chosen as it has several advantages over the commonly used sodium chloride, zinc chloride, and calcium chloride solutions. It is cheap and has low environmental impact and its density is enough to separate high-density microplastics, such as polyethylene terephthalate (PET). Floated microplastics were then dried overnight at 40 °C and weighed. FTIR analysis was used to confirm polymer nature of extracted 1–5-mm microplastics and to identify polymer composition. Polymer types of microplastics were identified in frame of SiMPle software by comparing obtained infrared spectra with reference database.

Since organic-rich samples were analysed in this study, the first step for the extraction of microplastics from fraction < 1 mm was the removal of organic matter using Fenton's reagent. This method is highly efficient and has the least effect on microplastics in comparison with other known methods (Hurley et al. 2018; Tagg et al. 2017; Vermeiren et al. 2020). Fenton's reagent was prepared based on the protocol described by The National Oceanic and Atmospheric Administration in 'Recommendations for quantifying synthetic particles in waters and sediments' (Masura et al. 2015). Samples with

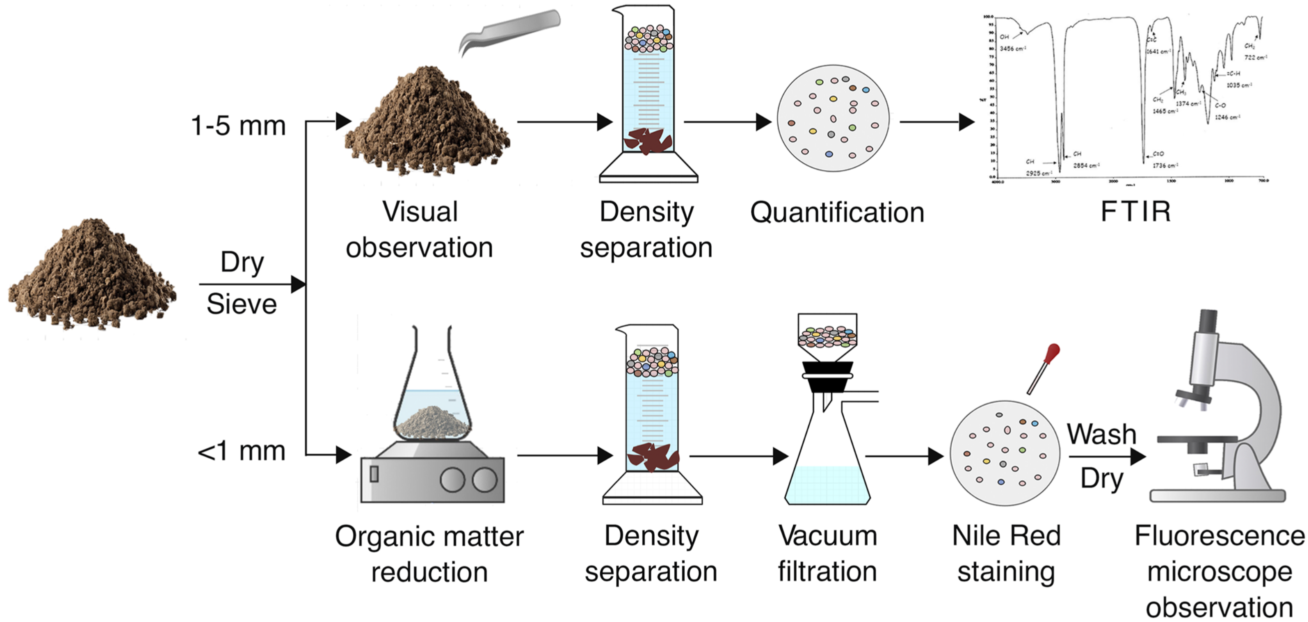



**Fig. 1** Protocol for microplastics extraction and identification

Fenton's reagent were heated at 60–70 °C and stirred until the reaction was completed. Next, samples were filtrated and subjected to density separation with potassium formate solution to separate plastics from denser inorganic components such as glass, sand, and stones. The samples with density solution were stirred for 15 min and were then allowed to settle overnight, as was proposed by Zhang et al. (2016). The supernatant was subsequently filtered through GF/F Whatman filters (47 mm ϕ) by vacuum filtration. The filters were transferred to Petri dishes and oven-dried at 60 °C for 24 h.

For microplastic identification and quantification, Nile Red (NR) dye staining was used. It is a fast, cheap, relatively rapid, and inexpensive quantification method (Maes et al. 2017; Shim et al. 2016). NR dye effectively stains the most common polymers such as polypropylene (PP), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polystyrene (PS), polycarbonate (PC), polyurethane (PUR), and nylon 6, while the effectiveness for PET, polyvinyl chloride (PVC), and rubber remains controversial (Shim et al. 2016; Erni-Cassola et al. 2017; Tamminga et al. 2017). Filter staining was done in accordance with Maes et al. (2017) and Vermeiren et al. (2020). NR solution was prepared by stirring 1 mg NR dye in 1 mL 99.5% acetone and diluted with 100 mL of distilled water to give a final concentration of 10 μg mL$^{-1}$. The filters were covered with NR solution and left in the dark for 30 min. Then, they were washed with distilled water and dried at 75 °C for 1 h (Maes et al. 2017). After the staining, filters were observed under a fluorescence microscope, in the blue excitation scale (peak wavelength 465 nm) under 40 times magnification. Fluorescent particles were photographed with a microscope camera and then measured and quantified in the ImageJ software.

### Quality assurance and quality control

Sampling and laboratory examination were carried out in such a way as to avoid the ingress of microplastics from the environment. All samples were collected with a stainless steel spatula, placed into clean glass jars, and stored at 4 °C until processing. During microplastic extraction, all laboratory instruments before and after use were washed with deionised water. The researchers used only cotton lab jackets.

Before microplastic identification in the samples, the most common polymers (PP, LDPE, HDPE, PS, and PET) were stained with Nile Red and observed under a fluorescence microscope to test the appropriateness of the chosen excitation scale for microplastic identification. Each type of polymer was represented by three microplastics: transparent, white, and other colours. Detailed information on the microplastics is presented in Supplementary Table 2. The results showed that all microplastics were fluorescent enough to be identifiable on the filter except for those of dark colours (black, blue, brown). Microplastic identification in all samples was conducted by the same person to avoid systematic errors, as suggested by Braun et al. (2020).

## Results

### Abundance of microplastics in treated organic waste

As showed in Fig. 2, the highest mean microplastics abundance was found in SOW samples: 17407 ± 1739 particles kg$^{-1}$ dry weight (mean±SD) in autumn and 15400 ± 1217 particles kg$^{-1}$ in winter. The difference in the microplastic concentration in the autumn and winter samples may be due to the variation in the mass content of plastic waste in the mixed MSW processed at the MBT. Considering the duration of the mechanical and biological treatments of waste, mixed MSW for the production of the autumn SOW output came to MBT in the summer of 2020, and for the winter SOW output came in the autumn of 2020. According to the results of the seasonal study of the mixed MSW morphological composition performed by Kaunas MBT, the mass content of plastic waste in summer (29.08%) was higher than that in autumn (23.13%) (AAA 2020). However, to confirm the influence of plastic content in the incoming waste on microplastic abundance in the SOW, more seasonal studies and correlation analysis between the plastic content and the mass rather than numerical concentration of microplastics are needed.

Food and green composts showed a significantly lower concentration of microplastics than SOW samples. Green compost samples contained 5733 ± 850 particles $kg^{-1}$ in autumn and 6433 ± 751 particles $kg^{-1}$ in winter, which is, respectively, 3.0 and 2.4 times less than SOW. The lowest concentration showed food compost samples: 3783 ± 351 particles $kg^{-1}$ in autumn and 4066 ± 658 particles $kg^{-1}$ in winter, which is, respectively, 4.6 and 3.8 times less than in SOW. High variation in microplastics abundance among some repeated samples and, consequently, large deviations were noted. Nevertheless, these deviations are acceptable since microplastics will never be homogeneously distributed in solid samples (Meixner et al. 2020). It should be noted that the treated organic waste outputs are different in granulometric composition (Supplementary Table 1). Green compost is finer than food compost and the weight percentage of the fraction < 1 mm is almost twice as large. Therefore, for comparison, the small microplastic abundance per 1 g of the fraction < 1 mm was also calculated by dividing the absolute values by the weight of the fraction < 1 mm. Recalculated abundance of small microplastics is presented in Fig. 2. According to the calculation results, the highest mean abundance of small microplastics was in the SOW output (62 ± 3 particles $g^{-1}$ in autumn and 46 ± 3 particles $g^{-1}$ in winter), while the lowest was in green compost samples (11 ± 1 particles $g^{-1}$ in autumn and 13 ± 2 particles $g^{-1}$ in winter). In this case, if the final composts are sieved through a 1-mm sieve at the post-treatment stage, there will be more microplastics in the food compost than in the green one.

Microplastics extracted from the 1–5-mm fractions were also calculated and weighed. The average for two seasons of mass concentration of large microplastics in SOW samples was 3.6315 g $kg^{-1}$, in green compost 0.237 g $kg^{-1}$, and in food compost 0.845 g $kg^{-1}$.

## Size, morphology, and polymer composition of microplastics

Considering the morphological classification of microplastics by different authors (Song et al. 2015; Su et al. 2019; Vianello et al. 2013; Weithmann et al. 2018), microplastics were categorised into classes such as fragments, fibres, films, and spheres. Examples for each class are illustrated in Fig. 3. The shapes of microplastics < 1 mm were determined based on fluorescent microscopic images. However, it was not always possible to determine shapes of the microplastics precisely; therefore, some particles have been classified as undefined.

The average for two seasons' shape distribution of microplastics in the organic outputs is presented in Fig. 4, and the distribution separately for each season is presented in Supplementary Fig. 1. The dominant shape of microplastics in green and compost samples was films (55.2% and 56.2%, respectively), followed by fragments. Conversely, most of the microplastics in SOW samples (almost 50%)

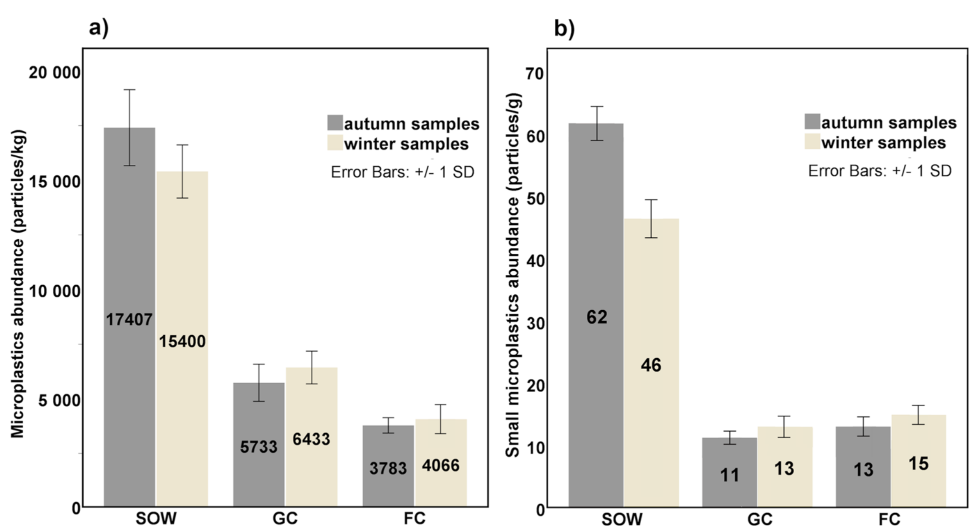



**Fig. 2** Total microplastic abundance (**a**) and small microplastic abundance in the fraction < 1 mm (**b**) of SOW, green compost (GC), and food compost (FC) samples

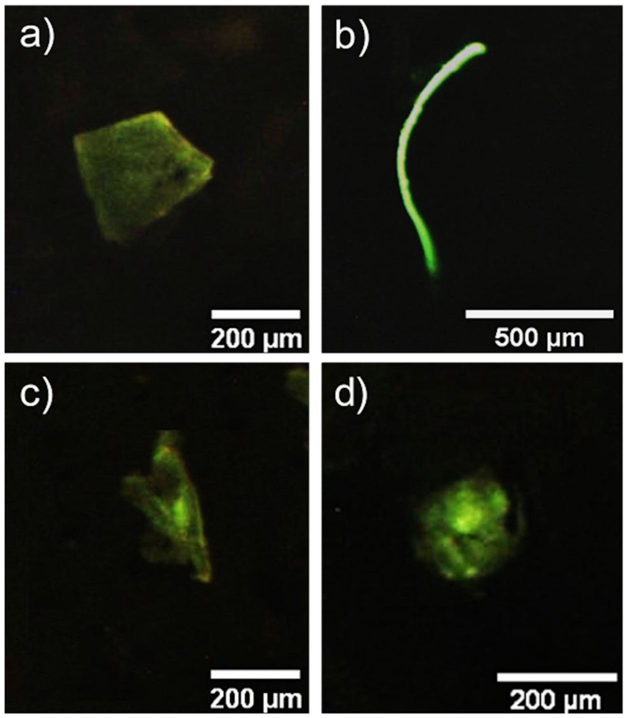



**Fig. 3** Main morphological classes of microplastics: **a** fragments, **b** fibres, **c** films, **d** spheres

were classified as fragments, followed by films (31.3%). Morphological analysis showed that spheres and fibres are less common shapes of microplastics for organic outputs and account for up to 14.3% in green compost samples.

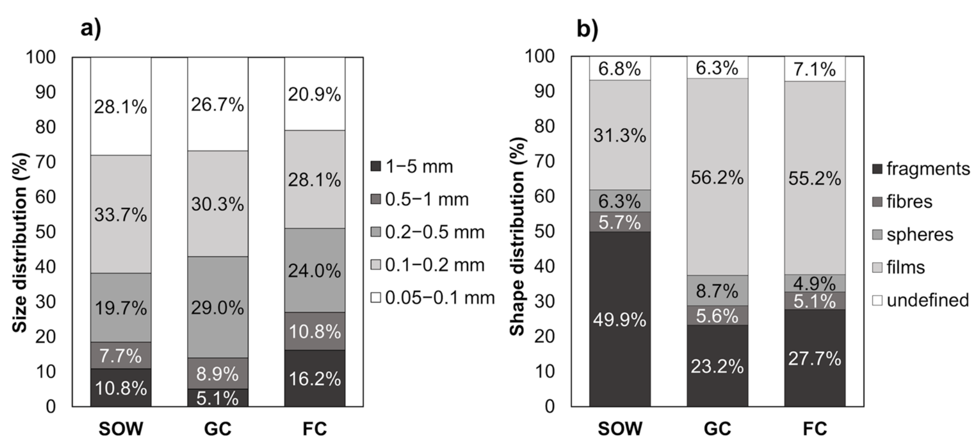
In general, the characterisation of microplastics size can be carried out in several ways. Renner et al. (2019) distinguished seven possible measurements: by spheres of same surface area, same minimum length, same maximum length, same weight, same sedimental rate, same volume, or passing same sieve aperture. In the current study, large microplastics (1–5 mm) were measured by passing the same sieve aperture and small microplastics (< 1 mm) were measured by particles of the longest axis lengths. All extracted microplastics were categorised by length into five categories: 1–5 mm, 0.5–1 mm, 0.2–0.5 mm, 0.1–0.2 mm, and 0.05–0.1 mm. Microplastics up to 50 µm were not investigated in this work since smaller particles are poorly identified using the fluorescent staining method (Vermeiren et al. 2020; Gui et al. 2021). The average for two seasons' size distributions of microplastics in different samples is shown in Fig. 4, and the distribution separately for each season is presented in Supplementary Fig. 2. Most microplastics in all samples were categorised into the size group of 0.1–0.2 mm. Microplastics less than 0.5 mm account for 73% of food compost microplastics, 81.5% of SOW microplastics, and 86% of green compost microplastics. Large microplastics (1–5 mm) were responsible for only 5.1–16.2% of the total number of microplastic particles.

The polymer composition of large microplastics was determined by FTIR spectroscopic analysis and the results are presented in Fig. 5. The FTIR results revealed that PP was a dominant class of microplastic in green compost, followed by LDPE and HDPE. These polymer types have the highest demand across Europe (PlasticsEurope 2019). PP is mainly used for food packaging, sweet and snack wrappers, hinged caps, and pipes. LDPE is a popular material for bags, film, trays, containers, and food packaging production, while HDPE is used for toys, bottles, pipes, and houseware production (PlasticsEurope 2019). In addition to common polymers, nitrile rubber (a synthetic rubber polymer), which is often used for glove production, was found in green compost.

PE and PS were the most abundant polymer types in food compost samples, accounting for 81% of the total amount of microplastics. The predominance of these polymer types can be explained by their widespread use as packaging materials for food products. In food compost samples, several microplastics were also identified as PET and PP.

PP, LDPE, HDPE, and PS polymers represented the majority of microplastics in the SOW samples and

**Fig. 4** Size (**a**) and shape (**b**) distributions of microplastics



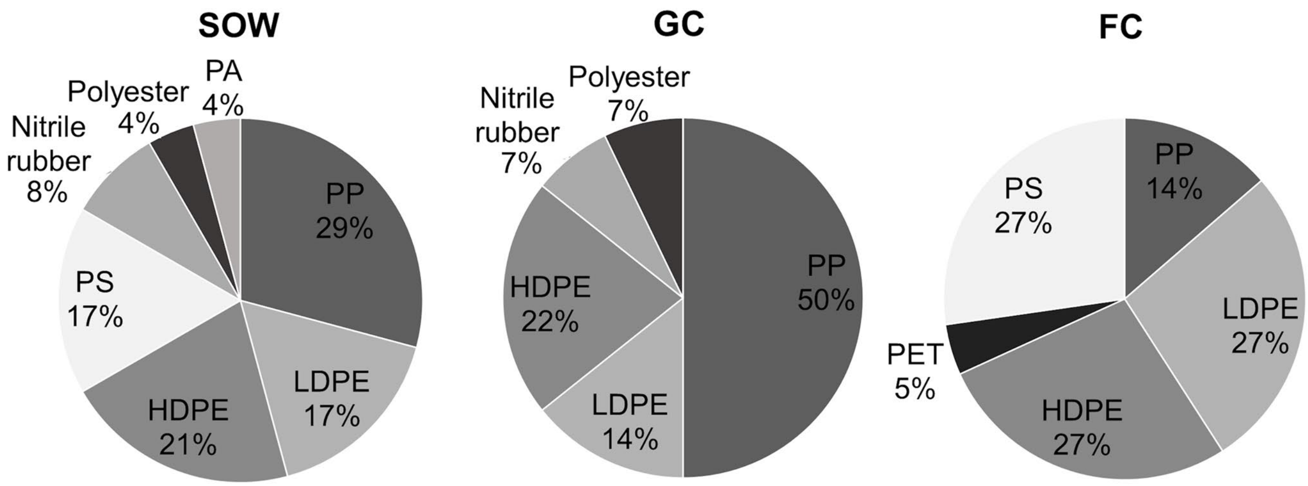



**Fig. 5** Percentages of different polymer types

constituted 84% of all microplastics. The FTIR analysis also showed the presence of polyester, polyamide (PA) fibres, and nitrile rubber in SOW samples. Polyester and PA fibres are widely used for synthetic textile production (Henry et al. 2019).

## Discussion

In Europe, until the 2019, the production of fertilisers from organic waste was not subject to existing legislation (EU 2003/2003), and there were no standards to control their quality. In 2019, a new European Fertilisers Regulation (EU 2019/1009) was adopted, setting clear standards for fertilisers made from organic waste streams. According to the new legislation, only separately collected organic waste can be used in the production of fertilisers. Therefore, organic waste from mixed MSW can be used only for the needs of landfills. Moreover, the regulation established additional safety criteria for compost and set limits on the content of inclusions above 2 mm, including plastic. Consequently, the concentration of microplastics of 2–5 mm in compost produced from separately collected organic waste now is covered by new European requirements. However, the new regulation does not cover the content of microplastics of < 2 mm. In the current study, the abundance of microplastics up to 50 μm was studied and, as was expected, compost samples had a lower numerical concentration of microplastics than the SOW output. This confirms that organic waste should be collected separately to produce compost with a lower abundance of microplastics. Nevertheless, green and food composts also contained a considerable amount of microplastics, up to 7200 particles $kg^{-1}$ for green compost samples. Moreover, it was found that small microplastics < 1 mm were responsible for 83.8–94.9% of the total number of microplastic particles. Therefore, to control soil contamination by microplastics, limits and safety criteria should be established for the concentration of not only large, but also small microplastics. One of the reasons for the still undefined limits for the small microplastic concentration in treated organic wastes is the limited number of studies and lack of uniform standards for the microplastic extraction, identification, and quantification. Researchers use various methods that differ in terms of recovery rate and the minimum size of microplastics that can be detected; therefore, it is hard to compare obtained results.

Meixner et al. (2020) investigated compost samples from different locations in Austria. The microplastics concentration found in this study was significantly lower than found by Meixner et al. (2020), at 15.4 Mil $g^{-1}$. The reason for such a large difference may be due to the different methods used for microplastics identification and quantification. Meixner et al. (2020) examined microplastics visually under a light microscope, while in this study, staining with Nile Red dye and further observation under a fluorescence microscope was used. This prevents the overestimation of the amount of microplastic in comparison with a light microscope observation. However, in this work, microplastics from 0–50 μm were not studied due to the limitations of this method, which also affects the estimation of final concentration of microplastics. The concentration of microplastics in food compost presented in this article can be compared with the results of Gui et al. (2021), who investigated the abundance of microplastics (0.05–5 mm) in rural domestic waste (RDW) compost made mostly from food waste. Gui et al. (2021) found that RDW compost contained 2400 ± 358 particles $kg^{-1}$, which is 1.5 times less than the microplastic concentration in food compost, determined in this article. A more accurate comparison would have been possible if there was a granulometric analysis of the samples taken by Gui et al. (2021). Hayany et al. (2020) quantified microplastics in the compost of green waste and dewatered sludge mixed in different proportions. Concentration of microplastic varied from 18.0 ± $3.2 \times 10^3$ particles $kg^{-1}$ in the mixture, which contained 1/3 of sewage sludge, to 26.0 ± $8.3 \times 10^3$ in the mixture, which contained 2/3 sludge. Our research indicates lower microplastic abundance in all organic outputs, although the difference with the concentration in SOW samples is not large.

Shapes and polymer types of microplastics are important characteristics for understanding microplastic origin. The origin of fibre material is commonly associated with the production, washing, and natural ageing of textiles (synthetic clothes and carpets) (Ballent et al. 2016; Mahon et al. 2017); microbeads and spheres – with production and use of personal care products (Eriksen et al. 2013); fragments – with the fragmentation of large plastics items, and films – with the fragmentation of plastic bags and packaging materials (Shim et al. 2018). The predominance of film shape with such polymer types as PP (green compost), PS (food compost) and PE (green and food composts) indicates that the majority of microplastics in composts was formed due to the incomplete decomposition of disposal bags and fragmentation of food packaging accidentally trapped in the organic waste. In addition, microplastics can release from the surface of macroplastics. Gui et al. (2021) confirmed the release of microplastics from PE, PP and expanded polystyrene (EPS) foam during lab-scale composting. The authors of this article are also planning to investigate the release of microplastics from the surface of the most popular packaging polymers, such as LDPE, HDPE, PP, PS, recycled PE, PET and PLA, in the real conditions of industrial composting.

Weithmann et al. (2018) studied polymer types in composts made from separately collected organic wastes and found that the most common types were styrene-based polymers, followed by PE. The authors indicated that, from theoretical point of view, separate organic waste collection from private households and commercial sources are suitable for compost production; however, in practice, it often contains plastics (mostly packaging) (Weithmann et al. 2018). Therefore, one of the recommendations for minimising microplastics in compost may be to conduct an information campaign among the population on the use of compostable bags for organic waste or not using bags at all. It is also important before biological treatment to separate organic waste from PE disposal bags if they do end up at the composting site.

In the SOW samples, fragments were the dominant shape; thus, most microplastics were formed due to the breaking down of large solid plastic waste from mixed MSW during waste treatment. Presumably, most of these fragments are formed at the pre-treatment stage, but there is no experimental data on it. Therefore, in the future, the authors of this article are planning to take samples at different stages of mixed MSW treatment and follow how the processes lead to the formation of microplastics.

## Conclusion

In this study, samples of SOW after the processing of mixed MSW, green, and food composts were analysed and compared for the abundance of microplastics and their characteristics. The SOW samples had the highest numerical concentration of microplastics, 2.4–3.0 times higher than green compost and 3.8–4.6 times higher than food cospost. Such findings prove that a separate collection of organic waste is necessary to reduce the amount of microplastics in organic waste fertilisers. However, even compost made from separately collected organic waste contains a significant amount of microplastics. Small microplastics < 1 mm were responsible for 83.8–94.9% of the total number of microplastic particles. Therefore, in order to control land pollution, it is necessary to update the existing European Fertilisers Regulation and set limits on the concentration of not only large, but also small microplastics. Considering FTIR and morphological analysis results, the main microplastic sources in food and green compost samples were plastic bags and food packaging. In addition, nitrile rubber was found in the green compost, the source of which is most likely medical gloves. Therefore, in order to reduce microplastics in such compost, it is necessary to conduct information campaigns among the population about the proper separation of organic waste, as well as to remove accidentally collected non-compostable plastic bags before composting. In the SOW samples, the dominant shape of microplastics was fragments, which means that most microplastics were formed due to large solid plastic waste fragmentation during waste treatment.

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**Data availability** The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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**Consent for publication** Not applicable.

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