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Mass Distribution of Nutrients, Trace Elements, and Heavy Metals Among Particle-Size Fractions of Municipal Solid Waste Compost from Different Regions of the Baltic States

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Abstract

This study assesses the distribution of nutrients, trace elements, and heavy metals across different granulometric fractions of municipal solid waste (MSW) compost from three regions: Kaunas and Alytus (Lithuania) and Daugavpils (Latvia). Samples were collected from mechanical biological treatment plants (MBTPs) and fractionated into six different granulometric fractions (>5 mm, 5–2.5 mm, 2.5–1 mm, 1–0.5 mm, 0.5–0.2 mm, and <0.2 mm). Each fraction was subjected to physicochemical characterization. Macronutrients (Ca, K, Mg, P), trace elements (Al, As, Co, Fe, Mn, Mo), and heavy metals (Cd, Cr, Cu, Ni, Pb, Zn) were analyzed using ICP-OES in triplicate. Results showed that essential nutrients and toxic metals were retained more in the finer fractions (<1 mm). In contrast, undesirable impurities, mainly glass, were retained in the coarse fractions across all the studied areas. All fractions in the compost samples of Kaunas, and coarse fractions (>5 mm, and 5–2.5 mm) of Alytus and Daugavpils are suitable to use as a soil amendment only if the undesirable impurities are removed to the acceptable limits in the coarse fractions. The fine fractions of Alytus have higher levels of heavy metals (Cd, Cr, Cu, Ni, Pb, Zn), while Daugavpils showed higher levels of Cd, Cu, Ni, and Zn, exceeding the EU limits. Regarding physical fractionation, results showed that nutrients and heavy metals increased in the compost as particle size decreased. Our findings suggest that removing particle sizes < 1 mm and large impurities from the coarse fractions can enhance compost quality. Overall, particle-size fractionation can improve the consistency and safety of MBT-derived MSW compost for reuse in circular waste management systems.

Keywords: MSW compost; particle size; impurities; nutrients; heavy metals
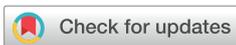
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1. Introduction

Municipal solid waste (MSW) has been steadily increasing in Europe over the past two decades [1]. This increase has been primarily driven by economic growth, industrial development, and urbanization [2]. The MSW is mainly disposed of worldwide through three main methods: landfilling, incineration, and composting. In the past, a large portion of residual MSW collected and transported as mixed waste was disposed of by incineration or landfilling without prior segregation, especially in regions that lack well-developed waste-sorting facilities [3]. Among these methods, composting is recognized as an effective and environmentally friendly way of reducing the amount of MSW significantly [4]. However, in Europe, mechanical–biological treatment plants (MBTPs) are now commonly used, in

which the organic fraction of MSW undergoes biological processing (e.g., composting) as a pre-treatment step before final disposal, such as landfilling or incineration, to stabilize the waste and reduce its environmental impacts [5].

Compost, as a soil amendment, plays a central role in soil health and nutrient cycling. However, its safe use depends on minimizing the contamination in it. Despite advanced policies on waste management and recycling facilities, a significant portion of MSW compost is still contaminated with heavy metals, which create huge environmental and public health issues [6]. Organic waste streams (mainly food scraps) are particularly got contaminated due to their frequent contact with household packaging materials, residual inorganic impurities, and plastic films with printing inks [7]. A study on the biowaste found that heavy metals such as cadmium (Cd), lead (Pb), copper (Cu), chromium (Cr), and zinc (Zn) can leach into the soil via printed plastics, metal parts, and unsorted inorganic waste fractions [8]. Achiba et al. [9] reported that soil organic matter, total nitrogen content, and electrical conductivity were significantly increased when MSW compost was applied over a period of five years. Additionally, this treatment with MSW compost also increased the overall heavy metal content in the soil. Therefore, the long-term and cumulative effects of these metals restrict the use of MSW compost in agriculture and require stricter quality monitoring.

The extent of contamination level across composting plants and compost batches, and their particle size, can vary, which reflects the complex interactions among feedstocks, operational conditions of composting plants, and local environmental factors [4,10]. Source separation of organic waste is widely used to reduce contamination in compost, but this is insufficient for the total removal of heavy metal content [11,12]. To produce sustainable and high-quality compost, it is essential to understand which factors contribute most to its contamination.

One of the most essential aspects in the regulation of the distribution of heavy metals in the compost is the particle size of the compost. Very little research has been conducted on compost fractionation and its importance in maintaining compost quality in the Baltic States. The content of organic matter and mineral elements in soils has been reported to be highly dependent on the size of the particles [13,14]. In another example, Lata Verma and Marschner [15] noted that the content of phosphorus changed with the size of particles of compost used in three different soils. As reported in many other studies, compost particles contain higher concentrations of heavy metals [16,17] and are also rich in essential nutrients [18], which pose a dual challenge to maintain the quality. This duality highlights the fact that special attention should be paid to compost fractionation strategies to maximize nutrient benefits while minimizing the risk of heavy metals.

In this paper, the distribution of nutrients, trace elements, and heavy metals in different fractions of MSW compost samples from three different MBT plants in the two Baltic States is examined. The objectives of this study include (i) characterizing the size distribution of the MSW composts produced by three MBT plants, (ii) analyzing the presence and distribution of nutrients, trace elements, and heavy metals among different size fractions of compost, and (iii) choosing particular compost size classes that could possess agronomic potential. These findings would contribute to improving the quality assessment of MSW compost and sustainable recycling of MSW for environmental benefits.

2. Materials and Methods

2.1. Sample Collection Sites and Granulometric Fractionation

Three mechanical–biological treatment plants (MBTPs) in two Baltic States, Kaunas and Alytus (Lithuania-LT), and Daugavpils (Latvia-LV), were selected to collect the samples (Figure 1). The composition of the received MSW and its treatment process at each MBT

plant are presented in Table 1. About 2 kg of well-mixed compost samples were obtained from the heap of each of the three plants in May 2024. Compost samples were obtained at each site from mature compost piles by mixing multiple sub-samples from various points within each pile to ensure homogeneity. After collection, the samples were brought to the laboratory in airtight plastic containers and later dried at room temperature. A 1000 g sample of air-dried compost was poured through a vertical column of five nested dry sieves with meshes of 5 mm, 2.5 mm, 1 mm, 0.5 mm, and 0.2 mm to obtain particle-size fractions and assess the influence of size distribution on the measured parameters. The compost sample was slowly poured onto the 5 mm sieve and spread thinly, with an almost uniform thickness over the entire surface. Upon mechanical shaking, residue on each sieve was collected, weighed, and stored again in airtight bags for further analysis.
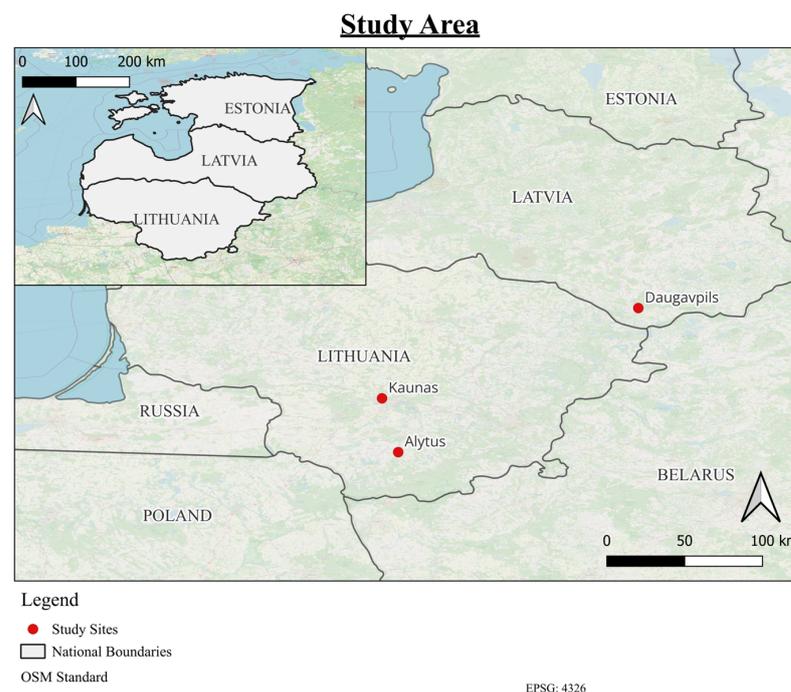
Study Area

Figure 1. Location of the study area sites.

Table 1. Composition of waste and treatment type in different MBT plants.

Region	Biodegradable Fraction in Treated Waste (%)	Treatment Type & Conditions	Intensive Phase Duration	Outdoor Maturation Duration
Kaunas (LT)	50–60	Aerobic (ventilated hall): Continuous mixing, aeration, moisture control; temperature rises to 65–72 °C	5–6 weeks	4–6 weeks
Alytus (LT)	30–35	Anaerobic (closed tunnel): Mesophilic (35 °C) or thermophilic (55 °C); biogas production	30 days	4–6 weeks
Daugavpils (LV)	30–35	Reverse aerobic–anaerobic (closed tunnel): Phase 1 thermophilic (55 °C), Phase 2 mesophilic (35 °C)	Multi-week (design-dependent)	4–8 weeks

2.2. Quantification of Physical Impurities in Compost

The MSW feedstock consisted of organic, inorganic, and recyclable wastes. The presence of physical impurities in the compost was established after a sequential quantification

and separation. Particles > 5 mm and 5–2.5 mm were considered for visual interpretation of undesirable contaminants. Plastic, glass, wood, paper, pebble, and metal were hand-separated from the compost samples in pre-weighted containers. These fractions were then measured, and the results expressed as a percentage of the total dry weight of the compost. Each fraction was stored in a labelled container before further analysis.

2.3. Determination of Proximate Analysis Methods for Compost Characterization

The oven-drying technique was used to measure the moisture content of the compost samples. Around 5 g of each sample fraction was precisely weighed in triplicate, transferred to pre-weighed, dried crucibles, and held at $105 \pm 2\,°C$ in an oven for 24 h [19]. The samples were cooled in a desiccator after drying, then reweighed. Moisture content was calculated as the percentage weight loss of the original wet weight of the sample [20].

Volatile matter content was determined by igniting a weighed sample of dried compost in a covered crucible in a muffle furnace at $950 \pm 20\,°C$ for 7 min, until total volatilization of organic matter [21]. The residue was cool-dried in a desiccator and weighed. Volatile matter percentage was expressed as percentage loss on ignition, excluding the removal of moisture content [22].

For ash content determination, about 2 g of oven-dried compost was placed in a crucible and heated in a muffle furnace at $550 \pm 20\,°C$ for 2 h to achieve total oxidation of organic matter [19,23]. The remaining inorganic material (ash) was measured after drying. Ash content, as a percentage of the original dry sample weight, was determined [20].

Fixed carbon content was then determined by applying the standard proximate analysis formula:

$$\text{Fixed Carbon (\%)} = 100 - (\text{Moisture content} + \text{Volatile matter} + \text{Ash content})$$

2.4. Analytical Method for Element Determination

Chemical analyses of nutrients, trace elements, and heavy metals in each granulometric fraction were determined by using inductively coupled plasma optical emission spectroscopy (ICP-OES). Visible impurities, such as glass and pebbles, were manually removed from each fraction to ensure that the elemental analysis reflected the compost matrix only. Approximately 1 g of oven-dried of each fraction was subjected to microwave-assisted acid digestion in triplicate using concentrated nitric and hydrochloric acids at a ratio of 5:1 [6,24,25]. Microwave digestion was conducted in a sealed-vessel setup (Multiwave GO Plus by Anton Paar, Graz, Austria) using the following procedure: samples were digested with ramping temperature to $180\,°C$ for 20 min, and then held for 10 min to achieve complete metal dissolution. Digested solutions were cooled, diluted to a fixed volume with deionized water, and filtered before ICP-OES analysis.

ICP-OES was analyzed on an Avio 220 Max by PerkinElmer (Waltham, MA, USA), which was calibrated using certified reference materials to ensure precision and accuracy. Analyses were performed on the macronutrient elements calcium (Ca), potassium (K), magnesium (Mg), and phosphorus (P); trace elements aluminum (Al), arsenic (As), cobalt (Co), iron (Fe), manganese (Mn), and molybdenum (Mo); and standard potential heavy metals cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn). Quality control measures involved procedural blanks, repeat analysis, and spike recoveries. Instrument specifications were used to determine the detection limits.

2.5. Statistical Analysis

Data were calculated for each element in each particle-size fraction and region. The two-way ANOVA was used to analyze the data, and significant differences between treat-

ments were determined using the Tukey HSD test at the 95% confidence level ($p \leq 0.05$) in Statistix 8.1.

3. Results and Discussion

3.1. Granulometric Fraction and Physical Impurities in Compost

The particle size mass fractionation of compost from three MBTPs in the Baltic region is shown in Figure 2. In Kaunas, compost particles with a size of 5–2.5 mm accounted for the highest percentage (30%), followed by 2.5–1 mm (28%) and >5 mm (20%). In Alytus, the most significant fraction was 2.5–1 mm and 0.5–0.2 mm (22%), followed by 1–0.5 mm (17%). Daugavpils had the highest percentage of large particles (>5 mm) at 43%, followed by 5–2.5 mm (20%) and 2.5–1 mm (18%). Size fractions < 0.2 mm accounted for only 2%, 9%, and 4% in Kaunas, Alytus, and Daugavpils, respectively. The predominance of mid-range fractions in MSW compost has been documented by Brťková et al. [26], who found that the most common 1.25–5 mm size fraction in the Czech Republic compost. These fractionation patterns also align with those of Sharifi and Renella [6], who noted that the lowest mass fractions were associated with the smallest particle sizes, regardless of preparation method.
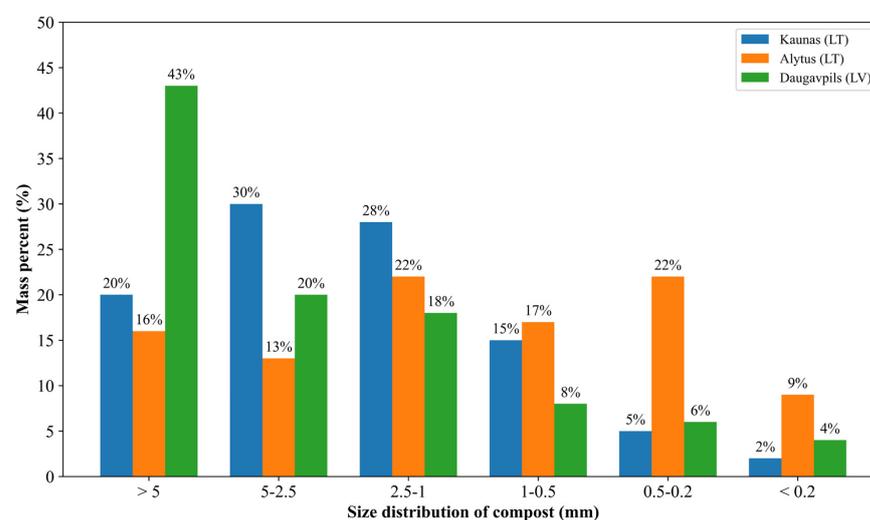

Figure 2. Size distribution of particles in different fractions of MSW compost.

The inert physical content of impurities (>5 mm and 5–2.5 mm) in Kaunas, Alytus, and Daugavpils compost had different differences between plants (Figure 3). Glass was the predominant impurity in Kaunas, taking up 50% of the >5 mm and 7% of the 5–2.5 mm content. The same was found in Alytus, where glass accounted for 54% and 34% of the >5 mm and 5–2.5 mm fractions, respectively, whereas in Daugavpils, glass accounted for 49% and 15% of the respective fractions. The contribution of other impurities, such as plastics, wood, pebbles, and metals, was lower. Plastics in Kaunas accounted for 6% (>5 mm) and 3% (5–2.5 mm), whereas they were significantly lower in Alytus (1% in both fractions) and Daugavpils (3% and 2%). Wood in Kaunas was 9% (>5 mm) and 11% (5–2.5 mm), whereas it was present only to the extent of 2% in Alytus and 5% and 2% in Daugavpils. Pebbles were a significant impurity in Daugavpils (23% and 13%), whereas they were <7% in Alytus and Kaunas. Paper was negligible, present only in Kaunas (>5 mm, 4%). Metals were scarce, making up 2% (>5 mm) in Alytus and 1% in Daugavpils, but not in Kaunas. In all three plants, the "other impurities" group accounted for a significant portion of the 5–2.5 mm fraction, at 76% in Kaunas, 60% in Alytus, and 66% in Daugavpils. This verifies that glass is the most significant inert impurity in Baltic composts, as has already been documented in other areas where heavy, dense impurities, like glass, dominate the

dry mass fraction in compost [6]. Haynes et al. [18] stated that mechanical shredding in the MBT plant often results in unintentional fractionation. For example, partially decomposed and easily degradable fragments are more readily broken down and are therefore likely to concentrate in the finer particle fractions. On the other hand, stronger materials, such as lignified wood and bark, require more mechanical energy to break apart and therefore tend to be retained in the coarser portions. As the shredded material is later piled up, further decomposition occurs mainly in the finer fractions, concentrating the labile material. These impurities indicate the inefficiency of mechanical or manual separation before composting, suggesting that composting with such plants would not meet the European regulatory limits on impurities in the dry weight of compost [7].

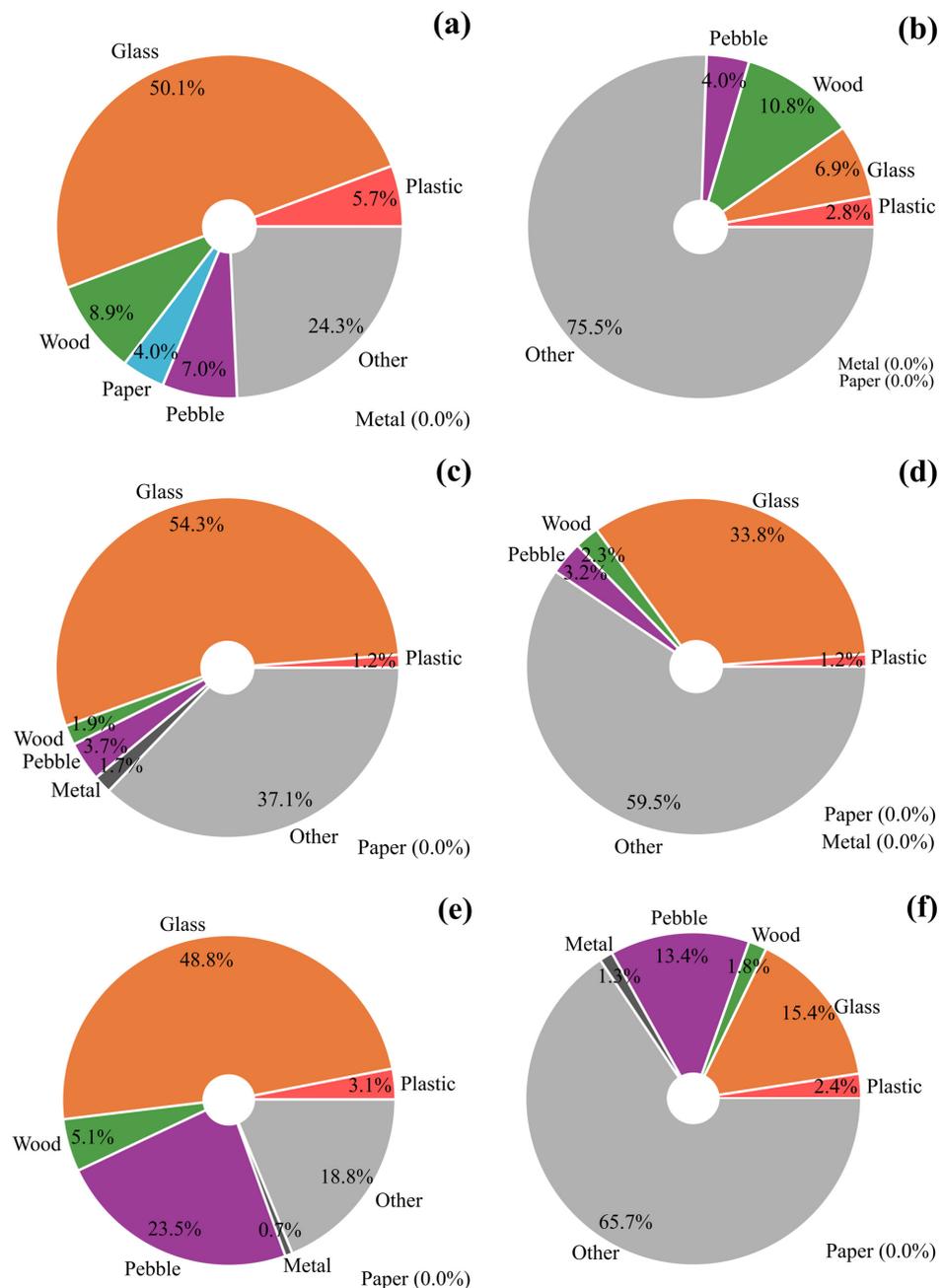**Figure 3.** Percentage of physical impurities in >5 mm and 5–2.5 mm fractions of MSW compost: (**a**,**b**) compost samples of >5 mm and 5–2.5 mm fractions from Kaunas (LT); (**c**,**d**) those from Alytus (LT); and (**e**,**f**) from Daugavpils (LV).

3.2. Proximate Analysis of Compost

The proximate analysis results are presented in Figure 4. In Kaunas compost samples, moisture content (MC) was recorded as higher in the 5–2.5 mm fraction (39.95%), >5 mm, and 2.5–1 mm fractions (20.12%), but then dropped to 3.26–3.41% in the 0.5–0.2 mm and <0.2 mm fractions. Alytus compost contained very homogeneous MC across all size fractions (18.61–21.87%), whereas Daugavpils material decreased from 10.79% (>5 mm) to 3.20% (<0.2 mm). Kaunas's high MC in coarse fractions is a sign of porous, water-retentive particle shape [27,28], while Alytus's consistency is an indication of homogeneous processing or material homogeneity as indicated by size distribution in Figure 2. Daugavpils's low overall MC (especially among its finer size classes) could be a result of proper drying practices or inherently less hygroscopic input material [29].
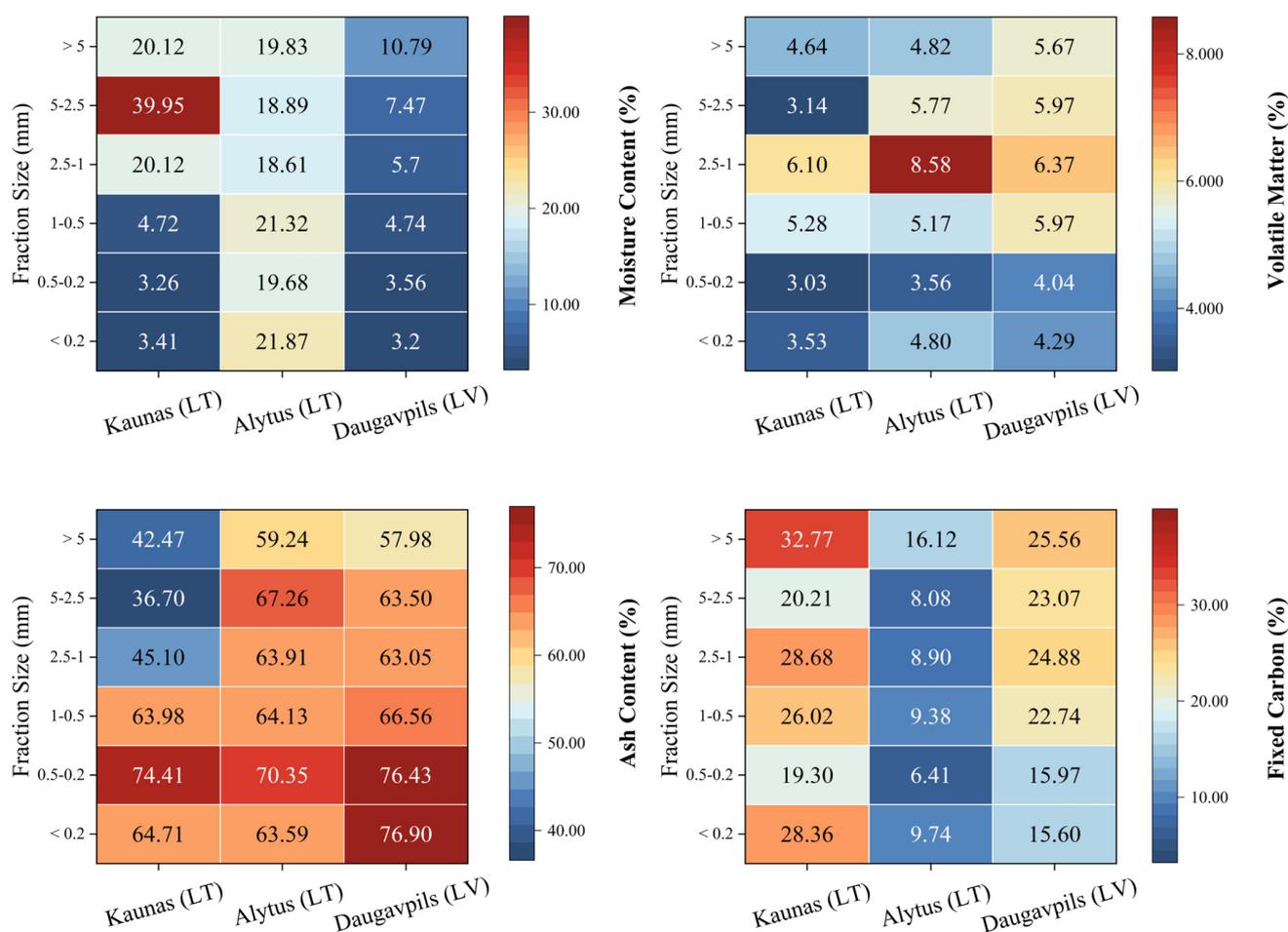

Figure 4. Heat maps of proximate analysis composition of different fractions of MSW compost.

Volatile matter (VM) was low in all ranges (3.03–8.58%) and highest in mid-size fractional peaks: Kaunas at 6.10% VM (2.5–1 mm), Alytus at 8.58% VM (2.5–1 mm), and Daugavpils at 6.37% VM (2.5–1 mm), with the lowest in <0.2 mm fractions below 5%. Low VM rates suggest high-level organic decomposition throughout; prominent mid-size peaks, relative to the small size of the rest of the spectrum, most likely indicate residual, partially decomposed plant material or slowly degrading bulking agents [30].

All three composts showed clear ash enrichment in the fine fractions. In Kaunas, ash content (AC) increased from 36.70% (5–2.5 mm) to 74.41% (0.5–0.2 mm), and then declined to 64.71% (<0.2 mm). Alytus increased from 59.24% (>5 mm) to 70.35% (0.5–0.2 mm) before decreasing slightly to 63.59% (<0.2 mm). Daugavpils exhibited the highest ash content

(up to 76.90%) in the fine fraction (<0.2 mm). The fine fractions contain more minerals and small inert particles because these materials naturally accumulate in the smallest sizes. In Alytus, the exceptionally high ash content even in the coarse fractions shows that the compost contains many fillers such as pebbles, wood chips, sand, or soil, as also shown in Figure 3. In contrast, the very high ash content in the fine fractions of Daugavpils suggests that too many mineral particles were carried over into the compost [18].

Fixed carbon (FC) decreased with ash content, inversely with a decreasing particle size. Kaunas reduced from 32.77% (>5 mm) to 19.30% (0.5–0.2 mm) and increased modestly to 28.36% (<0.2 mm). Alytus decreased from 16.12% to 6.41%, and then increased modestly to 9.74%. Daugavpils experienced a consistent decrease from 25.56% (>5 mm) to 15.60% (<0.2 mm). The inversely related correlation with ash ensures that fine fractions are mineral matter diluted rather than enriched in immobile carbon; thus, Kaunas coarse fractions (with maximum FC) have the most potential as long-term soil conditioners [31], while fine ash-rich fractions (particularly from Alytus and Daugavpils) would be used sparingly to prevent any change in soil pH or causing nutrient imbalance [20].

3.3. Distribution of Macronutrient Elements in Compost

The macronutrient composition (Ca, K, Mg, and P) in all regions showed significant variation across fractions (Table 2). Finer fractions, especially less than <1 mm, were richer in macronutrients of Alytus samples compared to the coarse fractions. Li et al. and Wang et al. [32,33] also found that major nutrients are concentrated in the finer size classes because they have a greater cation exchange capacity. This trend is typical of compost, since the fine fractions tend to contain more decomposed organic matter and minerals. In contrast, large particles tend to contain wood, plastic, glass, and other impurities (Figures 3 and 4), which do not hold nutrients, as reported in earlier studies [18,33].

Table 2. Macronutrients in different fractions (mm) of MSW compost (mg kg^{-1} dm).

Region	Fraction	Ca	K	Mg	P
Kaunas (LT)	>5	15,048 ± 1633 [d–f]	3444 ± 561 [ef]	18,566 ± 28,691 [ab]	653 ± 311 [j]
	5–2.5	13,727 ± 5461 [f]	2858 ± 1216 [f]	1946 ± 841 [b]	1109 ± 475 [ij]
	2.5–1	55,491 ± 19,066 [c–f]	4889 ± 1269 [d–f]	4670 ± 1652 [ab]	1651 ± 173 [h–j]
	1–0.5	41,059 ± 6569 [d–f]	3771 ± 646 [ef]	4992 ± 501 [ab]	1494 ± 205 [h–j]
	0.5–0.2	28,785 ± 12,510 [ef]	2761 ± 695 [f]	4986 ± 3733 [ab]	1496 ± 56 [h–j]
	<0.2	27,828 ± 1122 [ef]	3327 ± 202 [f]	4619 ± 580 [ab]	2135 ± 120 [g–j]
Alytus (LT)	>5	63,197 ± 59,343 [b–f]	5215 ± 1329 [d–f]	4732 ± 3393 [ab]	1721 ± 262 [h–j]
	5–2.5	40,352 ± 10,210 [d–f]	5302 ± 848 [d–f]	5283 ± 3190 [ab]	2738 ± 721 [f–i]
	2.5–1	164,838 ± 7678 [a]	13,861 ± 600 [b]	12,283 ± 2638 [ab]	5466 ± 658 [b–d]
	1–0.5	118,211 ± 6339 [a–c]	16,894 ± 1167 [ab]	12,939 ± 552 [ab]	6758 ± 311 [ab]
	0.5–0.2	90,200 ± 3148 [b–e]	14,142 ± 63 [b]	12,121 ± 67 [ab]	6166 ± 100 [a–c]
	<0.2	115,786 ± 2880 [a–c]	19,106 ± 456 [a]	16,957 ± 196 [ab]	7523 ± 76 [a]
Daugavpils (LV)	>5	72,344 ± 15,970 [b–f]	8699 ± 1091 [c]	12,367 ± 1486 [ab]	3178 ± 600 [e–h]
	5–2.5	132,247 ± 37,717 [ab]	9709 ± 873 [c]	24,490 ± 2094 [a]	3234 ± 1070 [e–h]
	2.5–1	106,637 ± 36,381 [a–d]	9330 ± 2043 [cd]	14,847 ± 4623 [ab]	4629 ± 1393 [c–e]
	1–0.5	101,818 ± 12,797 [a–d]	7622 ± 1942 [cd]	13,824 ± 2392 [ab]	3587 ± 936 [e–g]
	0.5–0.2	75,820 ± 9848 [b–f]	6669 ± 857 [c–e]	11,834 ± 1504 [ab]	3517 ± 392 [e–g]
	<0.2	90,842 ± 337 [b–e]	7995 ± 579 [cd]	14,984 ± 349 [ab]	4137 ± 140 [d–f]

The values in the column represent the average of three replicates ± standard deviation of each element. Different letters in the same column are significant at the 5% level according to Tukey's HSD test.

In Kaunas, nutrient values showed an inverse relation with particle size. For example, Ca was only 13,727 mg kg^{-1} in the 5–2.5 mm fraction but increased to more than 55,000 mg kg^{-1} in the 2.5–1 mm fraction. Similar increases in K, Mg, and P concentrations were observed. The highest *p* value (2135 mg kg^{-1}) was found in the <0.2 mm fraction.

However, Kaunas also had the highest impurity levels in the coarse fractions (Figure 3): more than 50% of glass and over 24% of other inert materials were found in the >5 mm fraction. The nutrient content in coarse fractions might be diluted by these impurities, as they do not add any organic matter or minerals.

The overall nutrient concentrations were highest in Alytus. The fine fractions from Alytus were very nutrient-rich, with Ca reaching 164,838 mg kg^{-1} and P up to 7523 mg kg^{-1}. These high values matched the pattern of proximate analysis results: fine fractions of Alytus contained high ash content and low moisture, i.e., they were more stable in nature and well-decomposed. Compost that is well stabilized is more likely to retain nutrients, since most of the easily decomposable organic matter has broken down, leaving behind concentrated, mineral-rich material.

Daugavpils showed intermediate nutrient levels but extremely high Mg concentrations (up to 24,490 mg kg^{-1}), particularly in the fine and medium fractions. The proximate analysis also showed very high ash content in the smallest fractions (up to 76.9%), suggesting that mineral particles accumulated in these fine sizes. This can be an indication of waste inputs with a higher proportion of soil material, as also found in coarse fractions (Figure 3), which might have reduced their nutrient value.

The regional comparison shows the differences in waste composition and processing. Alytus produced the most nutrient-rich and stable compost, which means that it has better waste sorting or more organic-rich feedstock. Daugavpils had a similar nutrient pattern but contained many pebbles and glass. The lowest nutrient levels were found in Kaunas because of very high levels of impurities and less stable compost.

While macronutrient enrichment in finer compost fractions is beneficial for soil amendment, it is accompanied by concerns about the co-concentration of heavy metals. Heavy metals like lead (Pb), zinc (Zn), cadmium (Cd), and copper (Cu) have been found in finer fractions and are thus potentially of concern regarding the use of this kind of compost in agricultural [8,34,35]. The simultaneous occurrence of pollutants and nutrients within the same granulometric fractions necessitates careful, fraction-specific monitoring and management to ensure the highest agronomic utility of compost while minimizing environmental and health hazards.

3.4. Distribution of Trace Elements in Compost

The trace elements (Al, As, Co, Fe, Mn, and Mo) distribution in the MSW compost showed clear differences between particle-size fractions across all regions, with a consistent pattern of higher enrichment of concentration in the fine fractions (<1 mm), as shown in Table 3. This behaviour is highly similar to the patterns observed for macronutrients, proximate analysis, and impurity distribution, which indicate that the extent of decomposition and mineral accumulation is strongly determinant of metal partitioning in compost.

In all three regions, the fine fraction was highly enriched with aluminum (Al) and iron (Fe). The highest values were exhibited by Alytus, where Al was 22,200 mg kg^{-1} at <0.2 mm and Fe was 41,256 mg kg^{-1} at 2.5–1 mm. The noticeable increases in Al and Fe with decreasing particle size were also observed in the Kaunas and Daugavpils samples. Other studies reported that the mineralogy of fine compost particles is the main cause of this enrichment of aluminium and iron oxides [6]. These fine fractions also contained the highest amount of ash (65–77%), and this is an indication that there are mineral residues. These oxides are highly susceptible to other trace metals and contribute significantly to their mobility to the environment, such as their possible leaching to soil and soil organisms [35].

Table 3. Trace elements in different fractions (mm) of MSW compost (mg kg^{-1} dm).

Region	Fraction	Al	As	Co	Fe	Mn	Mo
Kaunas (LT)	>5	2386 ± 568 [f]	0.11 ± 0.2 [a]	2 ± 0.4 [j]	2786 ± 1227 [c]	138 ± 47 [a]	1 ± 0.4 [b]
	5–2.5	2777 ± 1157 [f]	0.07 ± 0.1 [a]	3 ± 1 [ij]	3220 ± 1703 [c]	119 ± 39 [a]	2 ± 0.4 [b]
	2.5–1	6578 ± 1560 [ef]	1 ± 0.1 [a]	4 ± 1 [h–j]	11,211 ± 3112 [bc]	747 ± 1026 [a]	2 ± 1 [b]
	1–0.5	6696 ± 1111 [ef]	1 ± 0.2 [a]	4 ± 0.3 [g–j]	11,977 ± 1130 [bc]	196 ± 27 [a]	2 ± 0.2 [b]
	0.5–0.2	5511 ± 1205 [ef]	1 ± 0.2 [a]	6 ± 1 [f–i]	10,891 ± 2106 [bc]	292 ± 22 [a]	2 ± 0.4 [b]
	<0.2	7834 ± 593 [de]	3 ± 1 [a]	19 ± 2 [a]	12,168 ± 1743 [bc]	302 ± 22 [a]	3 ± 0.4 [b]
Alytus (LT)	>5	4870 ± 1536 [ef]	2 ± 1 [a]	4 ± 1 [h–j]	15,101 ± 13,469 [a–c]	250 ± 61 [a]	2 ± 1 [b]
	5–2.5	4818 ± 398 [ef]	1 ± 1 [a]	4 ± 1 [h–j]	14,575 ± 16,004 [bc]	229 ± 81 [a]	3 ± 1 [b]
	2.5–1	13,148 ± 1342 [c]	2 ± 1 [a]	8 ± 1 [d–f]	41,256 ± 23,405 [a]	503 ± 38 [a]	10 ± 4 [ab]
	1–0.5	18,332 ± 886 [ab]	5 ± 1 [a]	11 ± 1 [cd]	32,589 ± 4647 [ab]	1592 ± 1743 [a]	9 ± 3 [ab]
	0.5–0.2	16,152 ± 154 [bc]	4 ± 1 [a]	12 ± 1 [bc]	27,640 ± 459 [a–c]	622 ± 7 [a]	21 ± 17 [a]
	<0.2	22,200 ± 339 [a]	4 ± 0.2 [a]	15 ± 1 [b]	32,254 ± 139 [ab]	940 ± 9 [a]	10 ± 1 [ab]
Daugavpils (LV)	>5	11,672 ± 1969 [cd]	17 ± 22 [a]	8 ± 1 [d–f]	20,112 ± 1900 [a–c]	460 ± 22 [a]	8 ± 5 [ab]
	5–2.5	15,747 ± 3039 [bc]	39 ± 60 [a]	6 ± 1 [e–h]	24,258 ± 4679 [a–c]	563 ± 246 [a]	7 ± 5 [ab]
	2.5–1	13,097 ± 2938 [c]	5 ± 0.4 [a]	9 ± 1 [c–e]	31,902 ± 14,042 [ab]	622 ± 16 [a]	8 ± 4 [ab]
	1–0.5	12,193 ± 2489 [cd]	6 ± 2 [a]	8 ± 1 [e–g]	27,514 ± 2845 [a–c]	546 ± 101 [a]	7 ± 4 [ab]
	0.5–0.2	12,125 ± 952 [cd]	8 ± 2 [a]	7 ± 1 [e–h]	23,947 ± 2583 [a–c]	492 ± 60 [a]	4 ± 1 [ab]
	<0.2	15,312 ± 720 [bc]	7 ± 1 [a]	11 ± 1 [cd]	24,586 ± 42 [a–c]	590 ± 17 [a]	5 ± 1 [b]

The values in the column represent the average of three replicates ± standard deviation of each element. Different letters in the same column are significant at the 5% level according to Tukey's HSD test.

Manganese (Mn) also showed a trend of granulometric enrichment. Alytus had the highest Mn concentration at 1592 mg kg^{-1} in the 1–0.5 mm fraction, while Kaunas and Daugavpils had lower but similar particle-size behaviour. The strong correlation between Mn and Fe suggests processes such as co-precipitation or lattice substitution, which result in uneven distribution among size fractions [34].

Arsenic (As) did not have statistically significant differences between regions or fractions, but the particle-size distribution of arsenic had some interesting patterns. In Kaunas, no As was found in the coarse fractions, but its concentration suddenly increased to 3 mg kg^{-1} in the finest fraction (<0.2 mm). Alytus and Daugavpils had higher As levels, even in coarser fractions, with the former showing an exceptional peak at 5–2.5 mm (39 mg kg^{-1}), suggesting local sources of pollution or non-homogeneous contributions of As waste. Arsenic accumulation in fine particles is in line with the high sorption capacity of organics and iron oxides. Therefore, this fact brings the possibility of As mobilization by means of fine compost fractions when used as soil amendments [35].

The levels of Co were significantly higher in the fine fractions as well, with 19 mg kg^{-1} in the <0.2 mm fraction in samples from Kaunas and 15 mg kg^{-1} in the <0.2 mm fraction in samples from Alytus, compared to their coarse fractions. Since Co is considered a micronutrient for plants, it is important to maintain its level in fine compost particles by ensuring that it is not accumulated excessively in soils [34]. The findings can be explained by the earlier studies of heavy metal distribution in compost, whereby the ability of cobalt to form complexes with organic ligands causes the mineral to be concentrated in the smaller particles with the high humic content [18].

The findings indicated that there were substantial variations throughout the region, which is an indication of the influence of feedstock composition. The elevated trace metal levels in Alytus, particularly in the fine fractions, indicate either more contaminated feedstocks or poorer removal/separation in the composting process. The trace metal levels were also lower in Kaunas than in other areas, and it may be a sign of greater control over feedstock inputs.

A granulometric fractionation of compost gives useful information that is essential to achieve maximum safety and regulatory compliance. Trace metals in the fine fractions of compost contain considerable amounts of nutrients that are essential for soil fertility, and they increase the risk of heavy metal contamination in crops and soils if they are not

managed properly. This duality demands modifications to the waste treatment process, such as selective sieving of compost [6].

3.5. Distribution of Standard Potential Heavy Metals in Compost

The granulometric distribution of potentially toxic elements in compost (Cd, Cr, Cu, Ni, Pb, and Zn) also showed a clear size-dependent pattern across all three regions, with consistent enrichment in the fine fractions (<1 mm), as shown in Table 4. This trend is the same as that of macronutrients and other trace elements and is closely associated with the chemical properties of non-volatile components, as reflected by their higher ash content (Figure 5).

Table 4. Standard potential heavy metals in different fractions (mm) of MSW compost (mg kg^{-1} dm).

Region	Fraction	Cd	Cr	Cu	Ni	Pb	Zn
Kaunas (LT)	>5	1 ± 0.1 [f]	14 ± 10 [e]	63 ± 19 [g]	11 ± 4 [d]	26 ± 10 [a]	183 ± 64 [c]
	5–2.5	1 ± 0.3 [ef]	20 ± 6 [e]	105 ± 15 [fg]	15 ± 3 [d]	50 ± 14 [a]	282 ± 47 [bc]
	2.5–1	1 ± 0.2 [d–f]	29 ± 5 [e]	107 ± 19 [fg]	18 ± 3 [d]	80 ± 18 [a]	396 ± 65 [bc]
	1–0.5	1 ± 0.1 [d–f]	42 ± 11 [c–e]	119 ± 30 [e–g]	24 ± 6 [cd]	109 ± 66 [a]	392 ± 73 [bc]
	0.5–0.2	1 ± 0.1 [c–f]	36 ± 8 [de]	109 ± 4 [fg]	24 ± 2 [cd]	88 ± 20 [a]	387 ± 15 [bc]
	<0.2	2 ± 0.04 [b–f]	71 ± 10 [b–e]	224 ± 15 [d–g]	46 ± 6 [b–d]	121 ± 17 [a]	587 ± 45 [a–c]
Alytus (LT)	>5	1 ± 0.1 [d–f]	42 ± 14 [c–e]	198 ± 6 [d–g]	28 ± 5 [cd]	53 ± 11 [a]	374 ± 0.2 [bc]
	5–2.5	1 ± 0.3 [b–f]	39 ± 13 [c–e]	190 ± 51 [d–g]	23 ± 10 [cd]	56 ± 13 [a]	360 ± 64 [bc]
	2.5–1	3 ± 0.1 [a–f]	107 ± 34 [a–e]	507 ± 37 [bc]	75 ± 25 [a–d]	1264 ± 1928 [a]	778 ± 45 [a–c]
	1–0.5	4 ± 0.3 [a–d]	159 ± 47 [a–c]	630 ± 37 [b]	87 ± 17 [a–c]	179 ± 8 [a]	1029 ± 98 [a–c]
	0.5–0.2	4 ± 1 [ab]	207 ± 50 [a]	617 ± 12 [b]	134 ± 60 [a]	181 ± 14 [a]	974 ± 19 [a–c]
	<0.2	5 ± 0.2 [a]	173 ± 7 [ab]	870 ± 14 [a]	98 ± 2 [ab]	241 ± 6 [a]	1312 ± 40 [ab]
Daugavpils (LV)	>5	3 ± 1 [a–f]	108 ± 58 [a–e]	298 ± 53 [c–f]	42 ± 22 [b–d]	154 ± 103 [a]	1585 ± 1172 [a]
	5–2.5	3 ± 3 [a–f]	151 ± 116 [a–d]	334 ± 174 [c–e]	40 ± 17 [b–d]	106 ± 64 [a]	679 ± 135 [a–c]
	2.5–1	4 ± 2 [a–c]	114 ± 54 [a–e]	392 ± 40 [cd]	74 ± 48 [a–d]	102 ± 61 [a]	1327 ± 851 [ab]
	1–0.5	3 ± 0.3 [a–f]	73 ± 21 [b–e]	308 ± 46 [c–f]	38 ± 7 [b–d]	76 ± 16 [a]	1019 ± 260 [a–c]
	0.5–0.2	5 ± 1 [a]	86 ± 8 [b–e]	450 ± 197 [bc]	62 ± 4 [b–d]	69 ± 8 [a]	890 ± 142 [a–c]
	<0.2	4 ± 0.1 [a–e]	108 ± 6 [a–e]	620 ± 61 [b]	86 ± 6 [a–c]	99 ± 9 [a]	846 ± 30 [a–c]

The values in the column represent the average of three replicates ± standard deviation of each element. Different letters in the same column are significant at the 5% level according to Tukey's HSD test.

In all three regions, fine fractions had higher concentrations of most of the heavy metals due to their greater content of decomposed organic matter, mineral-bound residues, and Fe/Al oxides that provide numerous adsorption sites [6]. In Kaunas, Cd increased from 1 mg kg^{-1} in the >5 mm fraction to 2 mg kg^{-1} in the <0.2 mm fraction. Chromium (Cr) rose sharply from 14 mg kg^{-1} in the coarse fraction to 71 mg kg^{-1} in the finest fraction, while Cu increased from 63 to 224 mg kg^{-1}. Both Ni and Pb approximately doubled to quadrupled in concentration with decreasing particle size, and Zn increased from 183 mg kg^{-1} to 587 mg kg^{-1} in the <0.2 mm fraction. These trends validate the fact that fine particles have a greater adsorption and metal-complexing potential, which is consistent with earlier studies that have found the enrichment of metals in humified, fine particulate compost fractions [34].

The samples from Alytus had the highest heavy metal concentrations in almost all the fractions compared to other regions, which is a clear indication of more contaminated feedstock or weaker pre-sorting efficiency. Cd reached 5 mg kg^{-1}, Cr increased to 207 mg kg^{-1}, and Cu and Ni rose sharply, reaching 870 mg kg^{-1} and 134 mg kg^{-1}, respectively, in the fine fractions. Most notably, Pb levels peaked at 241 mg kg^{-1} in <0.2 mm, which is significantly greater than that in Kaunas and Daugavpils. The highest zinc level was also found at 1300 mg kg^{-1} in the finest fraction, which is consistent with the presence of Zn-bearing packaging waste, galvanized materials, printed plastics, and other urban waste streams [8]. The high concentrations of metals in the finest fractions of Alytus have far-reaching conse-

quences, as fine particles are more mobile and bioavailable and can transfer metals into soils and crops upon application of this compost [32,34].
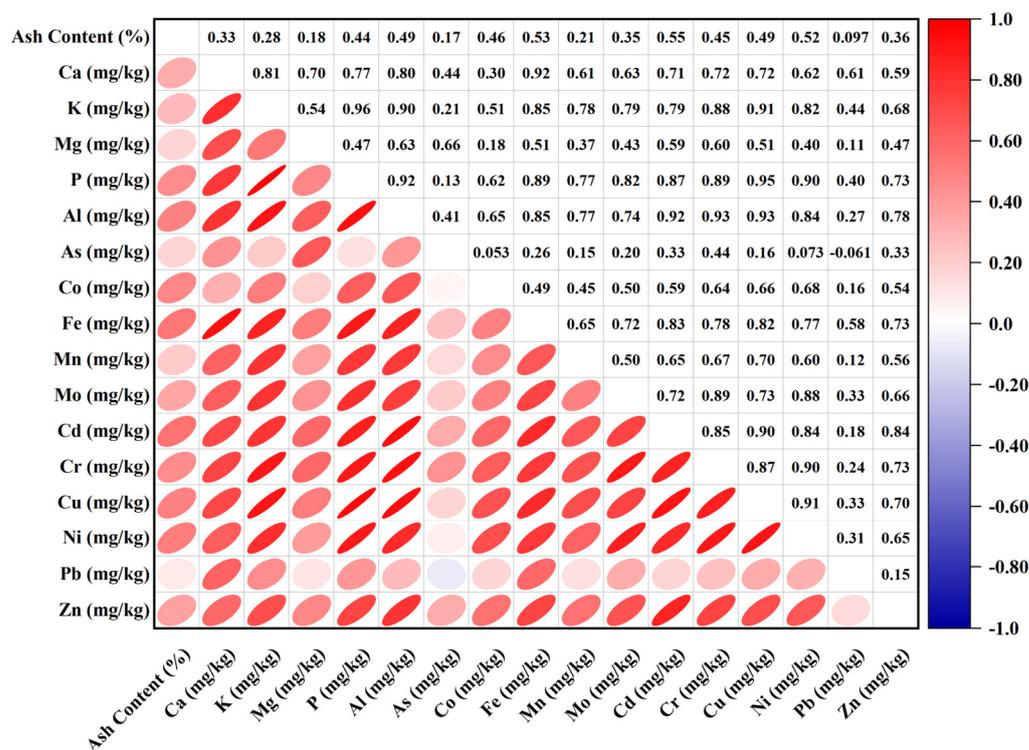

Figure 5. Correlation heatmap showing relationships among ash content and elemental concentrations in MSW compost. Ellipses and numbers denote the direction and magnitude of correlation coefficients (r), highlighting positive associations between ash content and elements.

The distribution of metals was more irregular in Daugavpils samples, which means that the inputs of waste were highly heterogeneous. The highest concentration of Zn was in the coarse fractions (>5 mm) with 1585 mg kg^{-1}, probably because of certain metal-containing debris like coated materials or processed metal waste pieces, as shown in Figure 3. Pb was detected in coarse fractions as well (154 mg kg^{-1}). Cu, Ni and Cr, on the other hand, were concentrated in the mid-range or fine fractions. This pattern of contamination is a sign of multi-source contamination, non-uniform input of the minerals, and non-uniform composition of feedstock. However, the Daugavpils samples also had a general enrichment of the metals in the particles < 1 mm, as was the case in Kaunas and Alytus.

The physical impurity profile, as well as proximate analysis of the same compost samples, also explains the high correlation between metal enrichment and the size of the particles. Coarse fractions (>5 mm) contained very high levels of glass, stones, and wood, which cause a dilution of the metals because these impurities do not contribute to metal content themselves. These fractions also had a high fixed carbon and less volatile matter, which are typical of undecomposed or inert waste pieces. Comparatively, the fine fractions (<1 mm) contained fewer contaminants, a greater quantity of ash (up to 76.9%), and more humified organic matter that had a greater quantity of metal-binding capacity. This combination naturally led to higher concentrations of heavy metals in the fine granulometric classes [36].

Overall, the results clearly demonstrate that fine particles are the pollution hot spots in MSW compost. They contain the highest concentrations of potentially toxic elements and therefore require careful management. Although these fractions contain nutrients and

other useful organic matter, their high content of heavy metals makes them more prone to contaminating the soil, plant uptake, and biomagnification in the food chain when not controlled. These results underline the necessity of fraction-specific regulations, better selective sieving, and better pre-treatment of MSW to make the compost use in agriculture safe and sustainable. These are necessary steps to building a circular economy where organic waste can be recycled without affecting the environment or human health [6].

3.6. Interrelations and Regional Insights

The coexistence of macronutrients, trace elements, and heavy metals within the same granulometric fractions of compost reveals their physicochemical affinity for organic matter and mineral surfaces. Fine particles of compost are characterized by high surface area and their capability to make complexes with humic substances, which contain a considerable number of binding sites for cations, such as agronomically essential elements (Ca, Mg, K, P) and heavy metals (Pb, Cd, Cu, Zn) [8,35,37]. This co-accumulation of nutrients and heavy metals in the same fraction is a major issue for compost regulations, as agronomically applicable nutrient loadings coexist with high concentrations of potentially toxic elements. The co-contamination phenomenon in MSW compost leads to the accumulation of heavy metals in crops and soil, food security risks, and environmental risks [38,39].

Our results reveal substantial variability among regions, with consistently higher nutrient and heavy metal concentrations in the fine fractions of compost samples from Alytus (compared to those from Kaunas and Daugavpils). This is consistent with European Commission evaluations indicating that variability in feedstock is reflected in variability in municipal waste composition and source separation rate, and that local urban or industrial contamination significantly impacts the quality of compost [40]. For example, the high levels of heavy metals in Alytus may reflect contamination from unsorted or poorly sorted MSW feedstocks, as noted previously in relation to high heavy metal levels in MBT composts from mixed wastes [41].

Furthermore, when compared with maximum limit values of heavy metals in compost set by the EU, all fractions in the compost samples of Kaunas and coarse fractions (>5 mm, and 5–2.5 mm) of Alytus and Daugavpils are suitable to use as a soil amendment only if the undesirable impurities are removed to the acceptable limits in the coarse fractions. The fine fractions of Alytus have higher values of heavy metals (Cd, Cr, Cu, Ni, Pb, Zn), while Daugavpils is found to have higher values of Cd, Cu, Ni, and Zn [42]. These findings emphasize that compost quality cannot be assumed, as it depends on feedstock characteristics in the particular local environment and treatment processes. Fine-scale studies in the literature show that physical and chemical heterogeneity within compost fractions strongly affects the partitioning and bioavailability of both nutrients and contaminants [32]. This indicates that regional screening and granulometric fractionation help to provide relevant information on quality control efforts. Such results were similar to those reported in previous studies, which suggested that mechanical fractionation was effective in reducing heavy metal pollution in MSW compost to meet regulatory quality standards and achieve safe recycling of organic waste residues [34,35].

This is the reason why the quality of the compost depends on the local characteristics, such as the materials used to produce the compost and the treatment processes undergone for composting. Such awareness can serve the goals of the circular economy through improvement in MSW compost quality. This also increases the reuse of MSW to a safe level. Therefore, policies should be made on the level of contaminants in specific particle sizes of compost. Such measures are likely to have positive impacts on consumer confidence, market acceptance, and sustainable recycling of waste, while ensuring protection of the environment and resource recovery.

4. Conclusions

This study shows that particle-size fractionation is a useful method to characterize the physical composition and chemical behaviour of MSW compost. The coarse fractions (>5 mm and 5–2.5 mm) mainly consisted of inert materials such as glass, pebbles, wood, plastics, and other impurities, and had comparatively low concentrations of nutrients and heavy metals. The fine fractions (<1 mm), on the other hand, were mainly composed of humified organic matter, silt, clay-sized particles, and mineral residues.

The concentrations of macronutrients (Ca, K, Mg, and P) were always highest in the fine fractions compared to coarse fractions of all studied regions, which indicates their strong affinity with organic matter and mineral surfaces. Enrichment of heavy metals also carries the same fraction-based pattern, and Cd, Cu, Ni, and Zn exceeded the EU legal threshold limits in fine fractions of both Alytus and Daugavpils samples. This means that the fractions with the greatest agronomic value also have the greatest contamination load. These trends emphasize the significance of the basic composition of MSW feedstock and pre-sorting efficiency, as the observed level of metals depends largely on the characteristics of input waste.

Overall, these findings demonstrate that understanding the composition and behaviour of coarse and fine fractions is essential for managing the dual role of MSW compost: fine fractions act as concentrated reservoirs of nutrients but also as hotspots of heavy metals. Selective handling or controlled use of these fractions may therefore improve the environmental safety and agronomic reliability of MSW compost. Such an approach could support more effective regulatory frameworks and contribute to safer circular use of organic waste in agriculture systems.

Author Contributions: B.T.: Conceptualisation, Methodology, Formal Analysis, Data Curation; Investigation, Writing—Original Draft, Visualization; G.D.: Conceptualisation, Validation, Resources, Writing—review and editing, Supervision, Project Administration; K.B.: Resources, Formal analysis, Validation, Writing—review and editing; S.U.: Formal analysis, Validation, Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement: Data will be made available on request.

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

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