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Particulate matter concentrations and size distributions during different stages of municipal solid waste biostabilization

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Abstract. Particulate matter (PM) is released during waste management operations as a result of various mechanical and chemical processes. The emission of specific chemical compounds is influenced by transformations occurring during the phases of aerobic waste biodegradation. This study provides a thorough analysis of particle number concentrations (PNC) and PM concentrations measured at a composting facility handling organic waste, with a focus on the detailed fractionation of PM to identify which fractions predominate in different areas of the composting site. PNC measurements were conducted using an Optical Particle Sizer, which detects the number of particles within the 0.3 – 10 μm size range through single-particle counting. Differences in PNC observed between the compost piles and other areas of the facility were minimal. The average mass concentrations of PM_1, $PM_{2.5}$, and PM_{10} on the waste piles were 1.71 μg/m³, 4.5 μg/m³, and 19.77 μg/m³, respectively. Similar to PNC, higher PM concentrations were observed for fresh and maturing compost piles, with increases of up to 86% compared to mature piles at the end of the process. These findings provide critical insights into the distribution of airborne particles within a biodegradable waste composting facility, an environment with significant implications for environmental monitoring and public health.

Introduction

Literature review

Composting processes lead to the creation of products with high fertilizing quality, which can be classified as organic fertilizer or stabilized compost (Sidełko and Boruszko, 2024). Their primary objectives include resource recovery, organic recycling, loss of waste status, and compost production. Models for managing solid waste often strive to incorporate the sustainability principles by addressing the three pillars of the triple bottom line: environmental, economic, and social factors (Singh 2023). However, ineffective, fragile, and flawed systems can significantly endanger both society and the environment (Singh 2014). Despite the key advantage of minimizing the environmental impact of biodegradable waste, composting processes are associated with the emission of various air pollutants. Considering the air pollution issues associated with biological waste processing, it is essential to consider the emission of various chemical compounds. These emissions may result from substances present in the raw waste, their formation during the composting process, or their persistence in the final stage of biodegradation.

As a consequence of both aerobic and anaerobic processes during waste processing in composting facilities, massive amounts of air pollutants, including ammonia, polycyclic aromatic hydrocarbons (PAHs), particulate matter (PM), volatile organic compounds (VOCs), and bioaerosols, are released into the ambient air, indirectly affecting human health (Pileco Cappelleti et al. 2023, Ibor et al. 2023, Singh and Raj 2018). Composting plants are recognized as primary sources of PM, which can act as carriers of PAHs and trace elements. Additionally, secondary PM can form in the atmosphere from ammonia and VOCs (Viegas et al. 2014).

Particulate matter (PM) is a complex mixture of airborne pollutants that poses significant risks to human health. Exposure to PM has been associated with a range of adverse health outcomes, including asthma exacerbation, cardiac arrhythmias, nonfatal myocardial infarction, and premature mortality due to cardiovascular or respiratory diseases (Ghobakhloo et al. 2024, Yang et al. 2022). The chemical composition of PM can exhibit significant variability across different regions, influenced by primary emission sources, atmospheric dispersion conditions, season, and chemical reactions occurring in the atmosphere (Reizer et al., 2025, Wong et al. 2024, Bounakhla et al. 2023).

Additionally, the impact of air masses transported from both adjacent and distant areas further contributes to this variability (Juda-Rezler et al. 2020, 2011).

PM is emitted during waste management operations through various mechanical and chemical processes. The generated particles include those from vehicular movement (as well as diesel exhaust emissions, tire and brake wear) and biologically derived particles associated with biomass processing (bioaerosols) (Pascale et al. 2022, Chalvatzaki et al. 2013). Windblown dust emissions from open storage piles are linked to several factors: wind erosion of the piles accounts for 30%, compost loading activities contribute 40%, and vehicle movement within the facility is responsible for the remaining 30% (Chalvatzaki et al. 2012). Several variables affect the wind erosion process from piles, including the bulk density of the stored material, the presence of a surface crust, moisture content, pile geometry, the kinetic energy of turbulent wind flow, and the availability of erodible particles (Chalvatzaki et al. 2012).

Specifically, exposure to organic PM among compost workers leads to several health issues, including inflammation of the upper airways, eye irritation, toxic pneumonitis, and both acute and chronic lung function impairments, such as bronchitis, as well as increased cardiovascular risk (Urbanowicz et al. 2024, Huang 2023). A strong association has also been identified between the concentrations of heavy metals in $PM_{2.5}$ – whose elevated levels can have carcinogenic effects – from personal exposure and the corresponding levels detected in the urine and blood of recyclers (Khoshakhlagh al. 2024a; Khoshakhlagh et al., 2024b; Ghobakhloo et al., 2025). To evaluate the impact of aerosols on human health, it is crucial to estimate both PM exposure and the dose received by individuals. Equally important is assessing the effective internal dose, which involves understanding how particles are

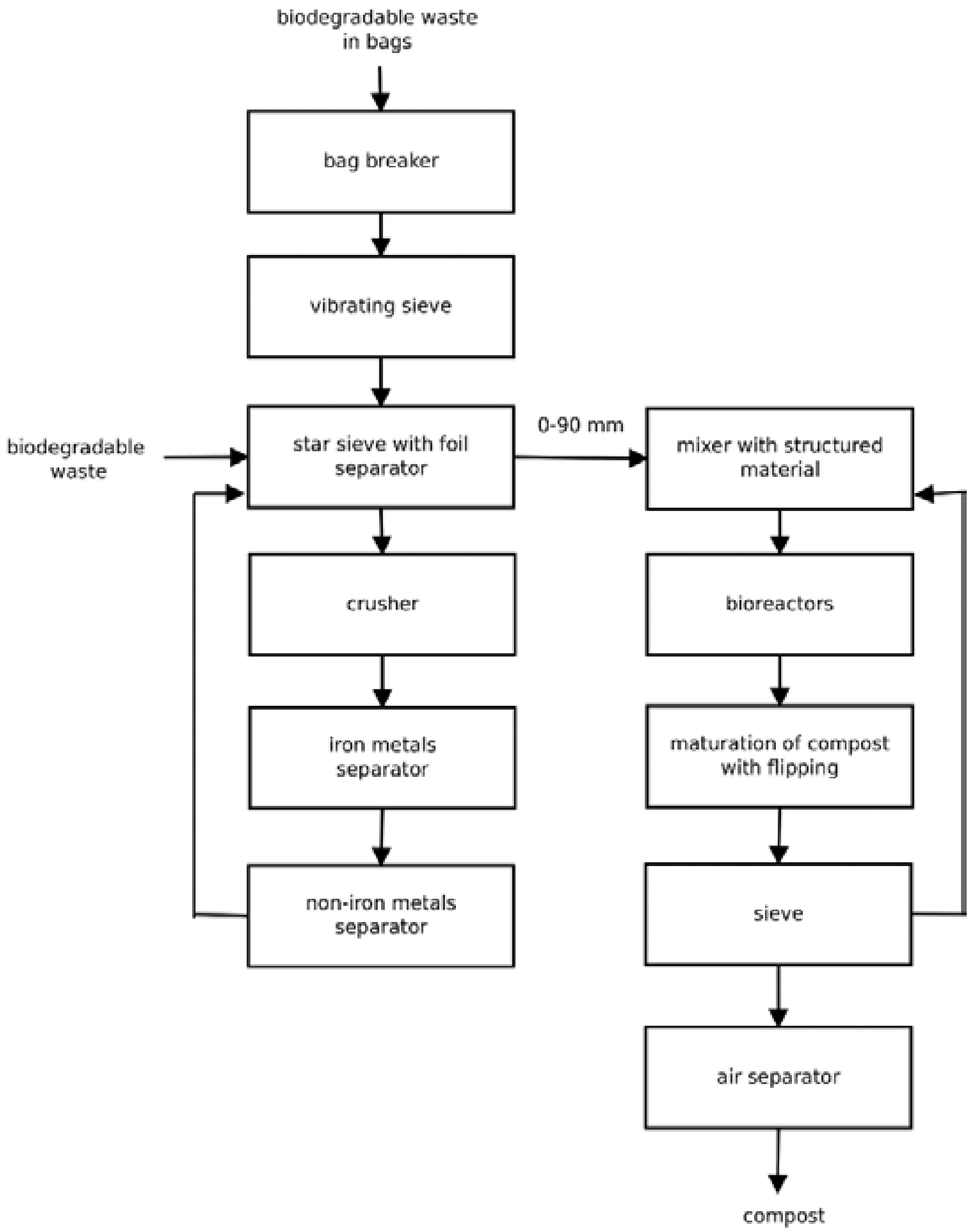

Figure 1. Schematic block diagram of biodegradable waste processing within the composting facility.

deposited in the lungs, transported within the body, and cleared from the respiratory system (Chalvatzaki et al. 2012).

The individual stages of the process are closely linked to changes in gas composition, leading to modifications to both the quality and quantity of emitted substances. Furthermore, the emission of specific groups of chemical compounds is influenced by the transformations occurring during the four phases of aerobic waste biodegradation: mesophilic, thermophilic, cooling, and maturation. As the waste stream progresses and reaches the parameters characteristic of the subsequent phase, both the amount and composition of the emitted compounds change accordingly (Szyłak-Szydłowski and Kos 2024).

Aim of the study

The aim of the current study is to examine the particulate matter emissions from municipal solid waste compost piles, with the highest possible fractionation of PM to identify which fraction is most prevalent in different areas of the composting site. A secondary objective is to determine whether - and to what extent - the PM emissions from individual compost piles vary based on the degree of waste bio stabilization. This is particularly important to ensure the safety of composting facility workers. Furthermore, the results may contribute to modifying operational protocols at the composting facility by incorporating measures aimed at intensifying PM reduction on piles with specific stages of maturity.

The study focused not only on the smallest size ranges of particulate matter but also placed particular emphasis on the $PM_{2.5}$ and PM_{10} fractions, as these are the most representative in terms of hazardous air pollution risks to human health. Special attention was also given to PM_1 (particles with an aerodynamic diameter of less than 1 micrometer), being the most harmful variant of fine particles, as they can penetrate deep into the lungs, enter the bloodstream, and disperse to various organs.

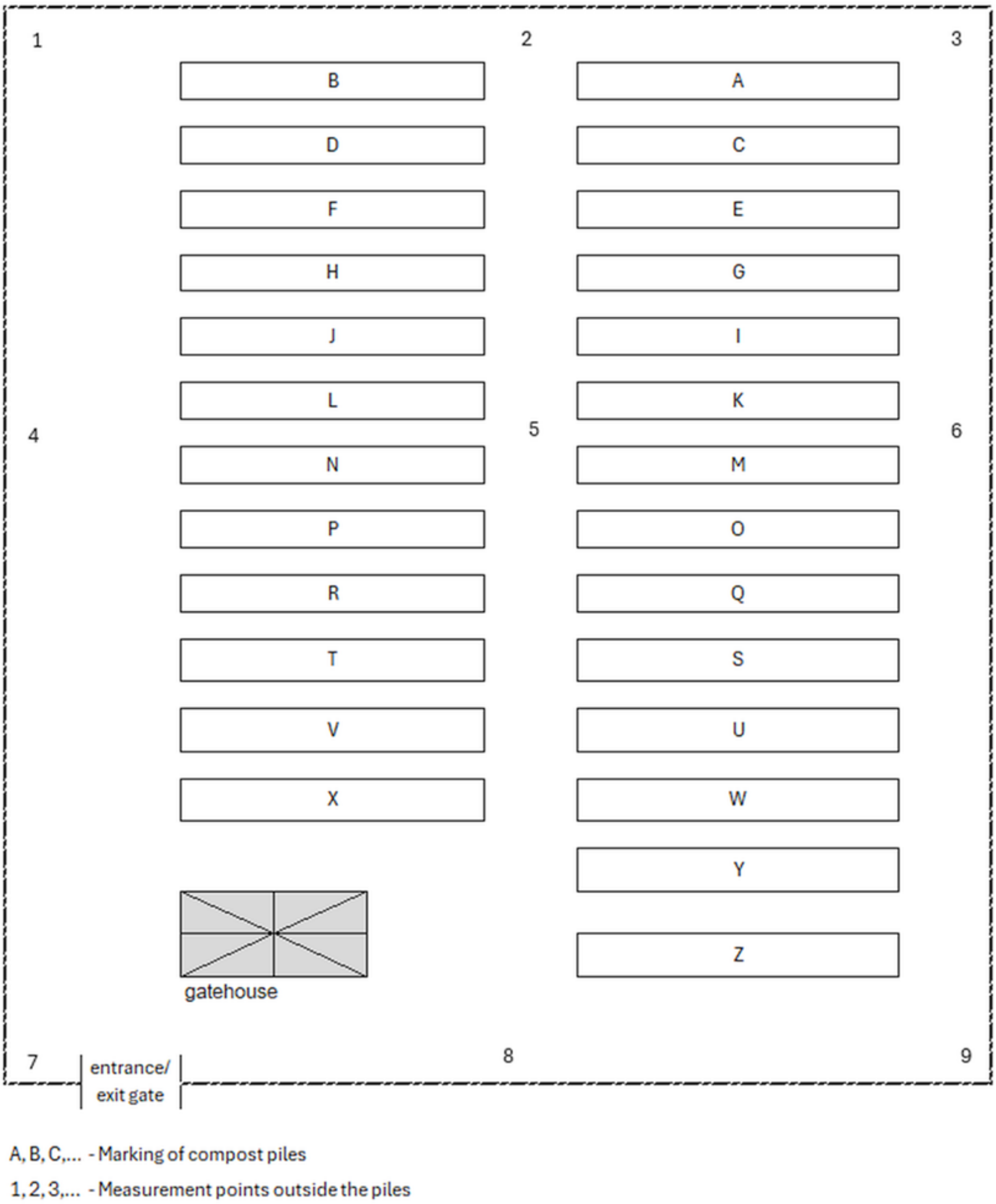

Figure 2. Scheme of the composting plant. Letters (A–Z) indicate compost piles; numbers (1–9) refer to sampling locations outside the piles.

Although composting plants release multiple types of air pollutants, this study focused exclusively on PM due to its dual role as both a physical pollutant and a carrier of health-relevant contaminants. PM is widely recognized in air quality and occupational safety policy, and its size-dependent behavior plays a crucial role in determining exposure risk.

Materials and methods

Research objective and scope

The primary objective of this study was to investigate particle number concentrations (PNC), particle number size distributions (PNSD), and mass concentrations of particulate matter (PM_1, $PM_{2.5}$ and PM_{10}) across different stages of municipal waste composting under real operating conditions. The study aimed to identify concentration hotspots, characterize particle size profiles, and assess their implications for environmental monitoring and occupational exposure risk.

The study was carried out at a full-scale composting facility dedicated to the treatment of biodegradable waste, including dried leaves, grass clippings, shredded branches, and plant residues. The facility's processing line consists of several technological stages, including a shredding unit, vibrating and star screens, a crushing system, and metal separation devices. Additionally, the process involves material blending, internal transport, and the use of an air separator for fractionation and sorting (Figure 1).

The composting process was conducted in an open composting area, where biodegradable material was arranged into trapezoidal piles representing different stages of the stabilization cycle. Each pile measured approximately 7 meters in width, 17 meters in length, and 3.5 meters in height, with an estimated mass of 300 to 350 metric tons. Mechanical equipment, such as wheel loaders, was used to aerate the material by facilitating air exchange throughout the pile volume. The composting process included a maturation phase lasting approximately 10 to 14 weeks (Szyłak-Szydłowski and Kos, 2024).

Beyond the facility, in the direction of the prevailing winds, the surrounding environment mainly consisted of wooded areas, grasslands, and an infrequently used road.

Methodology

The research was conducted within the compost yard (internal roads and points located in the immediate vicinity of the fence of the composting plant) and on the compost heaps (Figure 2).

Measurement points within the composting yard were marked with numbers 1 through 9 and located as follows:

1 - at the south-east corner of the composting plant
2 - along the southern fence of the composting plant
3 - at the south-west corner of the composting plant
4 - along the eastern fence of the composting plant
5 - on the internal road, at the central point of the composting plant
6 - along the western fence of the composting plant
7 - at the north-east corner of the composting plant
8 - along the northern fence of the composting plant
9 - at the north-west corner of the composting plant.

The 24 compost prisms were labeled A through Z. Prism A represented the freshest material (time '0'), where waste was deposited immediately after sieving, before the composting process began. The oldest prisms (Y-Z) were 13-14 weeks old and considered fully composted.

Samples were collected from three locations on the top (plateau) of each pile (the two corners and the geometric center). Four measurement series were carried out, each spaced a week apart.

During the measurement campaign, temperature and humidity data were recorded directly on-site using a multifunctional Testo 440 meters equipped with a thermal probe. To ensure full compliance of meteorological data with actual on-site conditions during sampling, supplementary weather information, such as atmospheric pressure and wind speed, was gathered from the Institute of Meteorology and Water Management. Table 1 presents the values of the meteorological parameters in each series.

Measurement of particulate matter

Particle number concentrations were measured using an Optical Particle Sizer (OPS 3330, TSI Inc., Minnesota, USA). This instrument detects the number of particles in the size range of 0.3 – 10 μm based on the principle of single-particle counting. It uses a laser with a wavelength of 660 nm and collects scattered light at 90° ± 60° using a wide-angle spherical mirror. Particle pulses are counted individually and binned into 16 user-adjustable size channels. In this study, the sampling time resolution was 30 seconds, with a flow rate ~1 L/min ±5%. The dead-time correction was applied during OPS operation. The OPS was calibrated with Polystyrene Latex (PSL) spheres by the manufacturer according to ISO 12501-1/4.

The measurements were conducted during summer in morning hours, typically lasting from 2 to 3 hours. At each measurement point, the exact start and end times of the sampling were recorded and assigned to particle number concentration data. Measurements were taken outside the compost piles, at a height of about 1.5 m above the surface of the piles and the surface of the area. This approach provides representative

Table 1. Meteorological parameters recorded during each measurement campaign.

Series	Wind speed (m/s)	Wind direction	Temperature (°C)	Humidity (%)	Cloudness
1	2.5-3.0	S	30.2-32.5	54-61	0/8
2	2.7-5.2	S	24.6-28.2	44-55	1/8
3	2.1-3.5	S	24.0-28.7	42-52	6/8
4	1.1-1.6	E	20.1-20.9	75-80	0/8

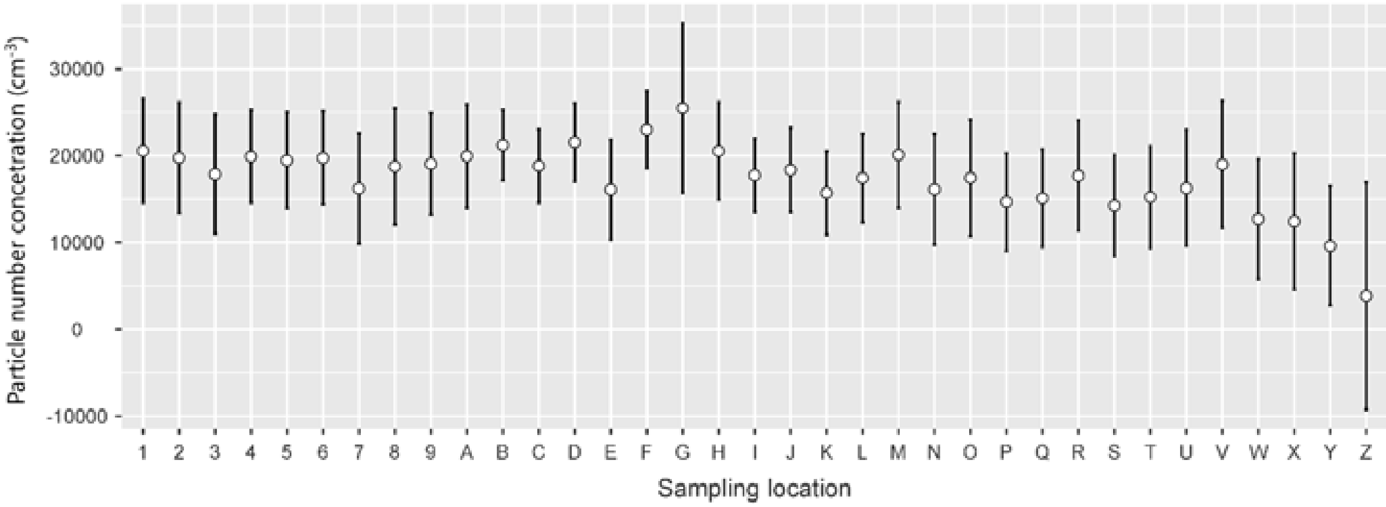

Figure 3. Estimated boundary averages for particle number concentration (PNC) for particle sized 0.3-10 μm, expressed as particles per cubic centimeter [cm^{-3}], at different sampling locations. The bars represent 95% confidence interval.

results regarding PM emissions from the pile surfaces and the composting area, while also avoiding disturbances caused by direct contact between the probe and the compost material.

Mass concentrations of all PM fractions were calculated assuming that all the particles are spheres with a density of 1.0 g/cm^3.

Statistical methods

To evaluate differences among datasets and identify which group deviated most significantly, analysis of variance (ANOVA) was applied. Prior to conducting ANOVA, the assumptions of normality and homogeneity of variances were verified using the Shapiro-Wilk and Levene's tests, respectively. When these assumptions were violated, the non-parametric Kruskal-Wallis test was used as an alternative. Post hoc pairwise comparisons were subsequently conducted using Dunnett's C Simultaneous Confidence Formula (DSCF), which is specifically designed for multiple comparisons in one-way analysis of variance. This method enables the assessment of statistically significant differences between each group and a selected reference category, typically a control. To assess whether two independent samples originated from populations with different distributions, the Mann-Whitney U test was employed. Prior to its application, the Shapiro–Wilk and Levene's tests were used to evaluate the normality and homogeneity of the data. The Mann-Whitney U test, which operates on rank-transformed data, is particularly suitable for variables that do not follow a normal distribution.

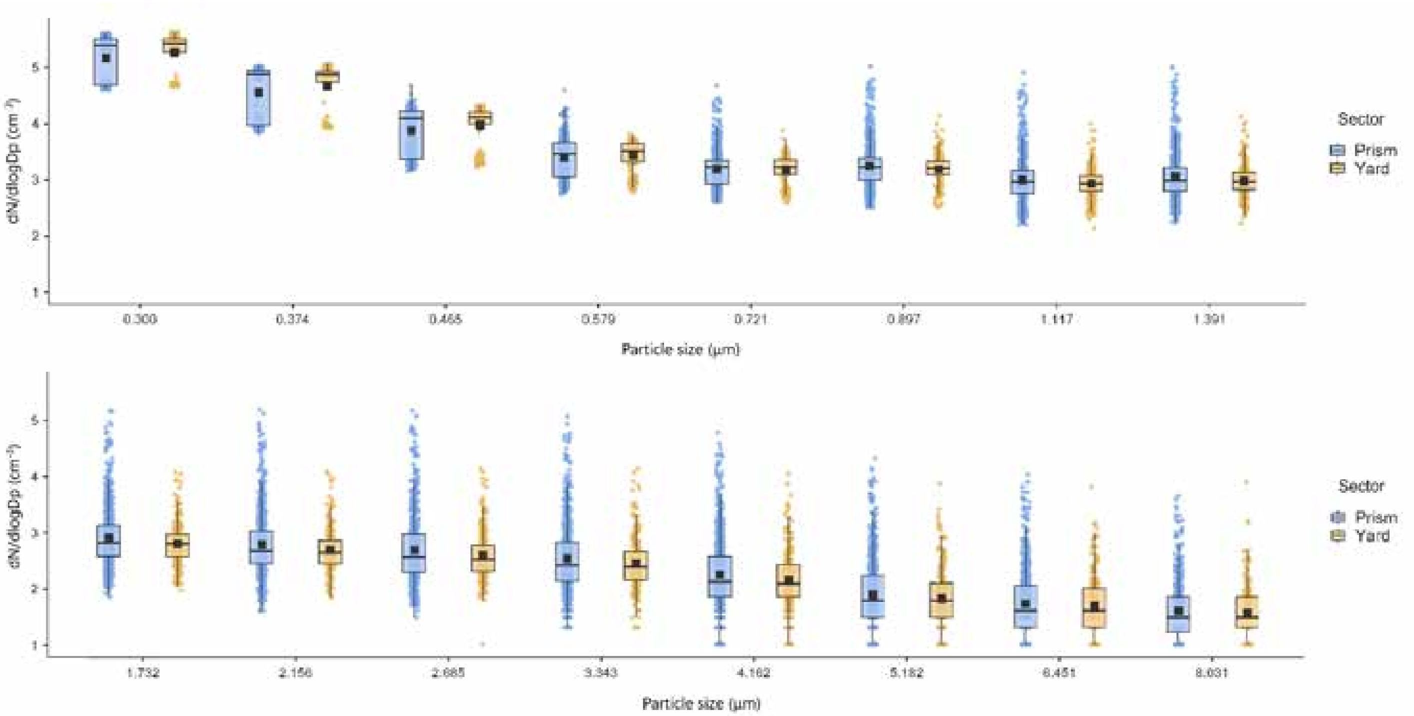

Figure 4. Particle number size distribution (logarithmic scale), expressed as dN/dlogDp [cm^3], by sampling sector. a) Particles sized 0.300-1.391 μm; b) Particles sized 1.732-8.031 μm.

Results and discussion

Particle number concentration

Particle number concentration depending on sampling location

The datasets obtained did not meet the assumptions required for ANOVA test. Both Levene's homogeneity test and the Shapiro-Wilk normality test yielded $p < 0.001$. Therefore, the Kruskal-Wallis test was applied, as it does not require homogeneity of variance. The grouping variable was the sampling location, while the dependent variable was particle number concentration (PNC), expressed in cm^{-3} (number of particles per cubic centimeter). Plots of the estimated boundary averages of PNCby sampling location are presented in Figure 3.

The highest PNC value was found at pile G (maturing compost, week 4), with an average result of 25 491 cm^{-3} and median of 1,018 cm^{-3}. The lowest values were observed on the mature piles toward the end of the composting process. On pile Z, the mean PNC was 3,836 cm^{-3}, and the median was 189 cm^{-3}.

Across the composting site, the overall mean PNC was 18,107 cm^{-3}, with a median of 819 cm^{-3}. Slight differences were recorded between the piles and the yard: the mean PNC at the piles was 17,785 cm^{-3} and 18,155 cm^{-3} in the yard, with corresponding medians of 830 cm^{-3} and 778 cm^{-3} respectively. Outside the composting facility, in the direction of the prevailing wind, PNC ranged between 500 and 700 cm^{-3}. These background levels indicate a negligible influence on the PM concentrations measured directly at the compost piles. Therefore, the background environment had a negligible influence on the PM concentrations measured directly at the compost piles.

Particle number size distribution

Table 2 presents basic descriptive statistics for the particle number size distribution (PNSD), expressed as dN/dlogDp, i.e., the number of particles per logarithmic diameter interval per cubic centimeter (cm^{-3}), and sampling sector - yard (points 1-9) or prism (points A-Z).

Particle number decreased with increasing particle diameter. The median number of particles with a diameter of less than 0.3 µm was 246,412 cm^{-3}. For particles with a diameter between 0.3 µm and 0.374 µm, the median was 75,522 cm^{-3}, while for those between 8.031 µm and 10 µm, it was only 21 cm^{-3}.

Figure 4 presents basic descriptive statistics for the PNSD and sampling sector - yard (points 1-9) or prism (points A-Z).

PNSD values depending on sampling sector were similar within each particle diameter range. Differences between the prism and yard sectors ranged from 0% (identical PNSD values) to 13%. The outlier was a difference of 17% for particles with diameters between 5.182 and6.451 µm, where the median value was 63.1 cm^{-3} at the prism and 52.6 cm^{-3} at the yard.

Figure 5 presents PNSD at selected sampling locations – point 1 (the yard), point A ("fresh" waste), point G (maturing compost), and point Z (mature compost).

The median values of the PNSD decrease with increasing particle diameter. The lowest median values (0-48,334 cm^{-3}) across

Table 2. Basic descriptive statistics for the particle number size distribution, expressed as dN/dlogDp [cm^{-3}], across measured diameter bins (0.3–8.031 μm).

Particle size [μg]	dN/dlogDp [cm^{-3}]				
	Min	Mean	Median	Max	SD
0.3	39 352.3	209 023.7	246 411.6	435 727	127 174
0.374	6 629.2	56 945.6	75 522.3	114 631	36 149
0.465	1 428.2	10 946.5	12 328.6	47 435	6 811
0.579	556.4	3 236.3	2 981.4	39 367	2 535
0.721	379.5	2 142.1	1 697.3	47 145	3 030
0.897	325.4	2 908.7	1 658.6	104 734	6 439
1.117	136.4	1 907.4	871.2	79 770	4 921
1.391	168	2 457.6	955.7	99 317	7 383
1.732	73.6	2 506.6	662.5	150 977	9 922
2.156	42	2 343.1	472.2	157 321	9 969
2.685	10.5	207.25	367.7	151 714	9 203
3.343	21	1 571.9	252.2	118 688	6 997
4.162	0	813.6	126.1	61 631	3 494
5.182	0	322.2	52.6	21 392	1 299
6.451	0	181.5	31.5	11 026	708
8.031	0	96.4	21	7 991	410
10	-	-	-	-	-

all particle size ranges were observed for mature compost (prism Z), while the highest values (21-294,714 cm^{-3}) were recorded for maturing compost (prism G). The median particle size distribution for pile G was 78-100% higher than that of pile Z, and 1-21% higher than that of the "fresh" compost (pile A) in the particle size range of 0-1.732 µm. In contrast, for particles between 1.732 and 8.031 µm, the median PNSD in pile G was 4-50% lower than in pile A.

The median PNSD values in the yard were like those on heap G in the diameter range of 0.3 µm, to 5.182 µm, with differences ranging from 0.5% to 18% and increasing with particle size). For diameters ranging from 2.165 µm to 8.031 µm, the differences between yard and prism G were from 25% to 69% - the yard values were higher than the prism values.

During the measurements, there was typically no vehicle activity in the yard, but when a sweeper passed through the yard, an increased particle number concentration was noted (Figure 6).

For particle sizes between 0.3 µm and 0.374 µm, the median values were comparable – 46,318 cm^{-3} during no vehicle traffic and 46,736 cm^{-3} during sweeper operation. However, for particles between 0.374 µm and 0.465 µm, the difference increased to 30%, with median values of 10,309 cm^{-3} and 11,552 cm^{-3}, respectively. For particles ranging from 0.897 µm to 10 µm, the particle count was 74% higher during vehicle traffic.

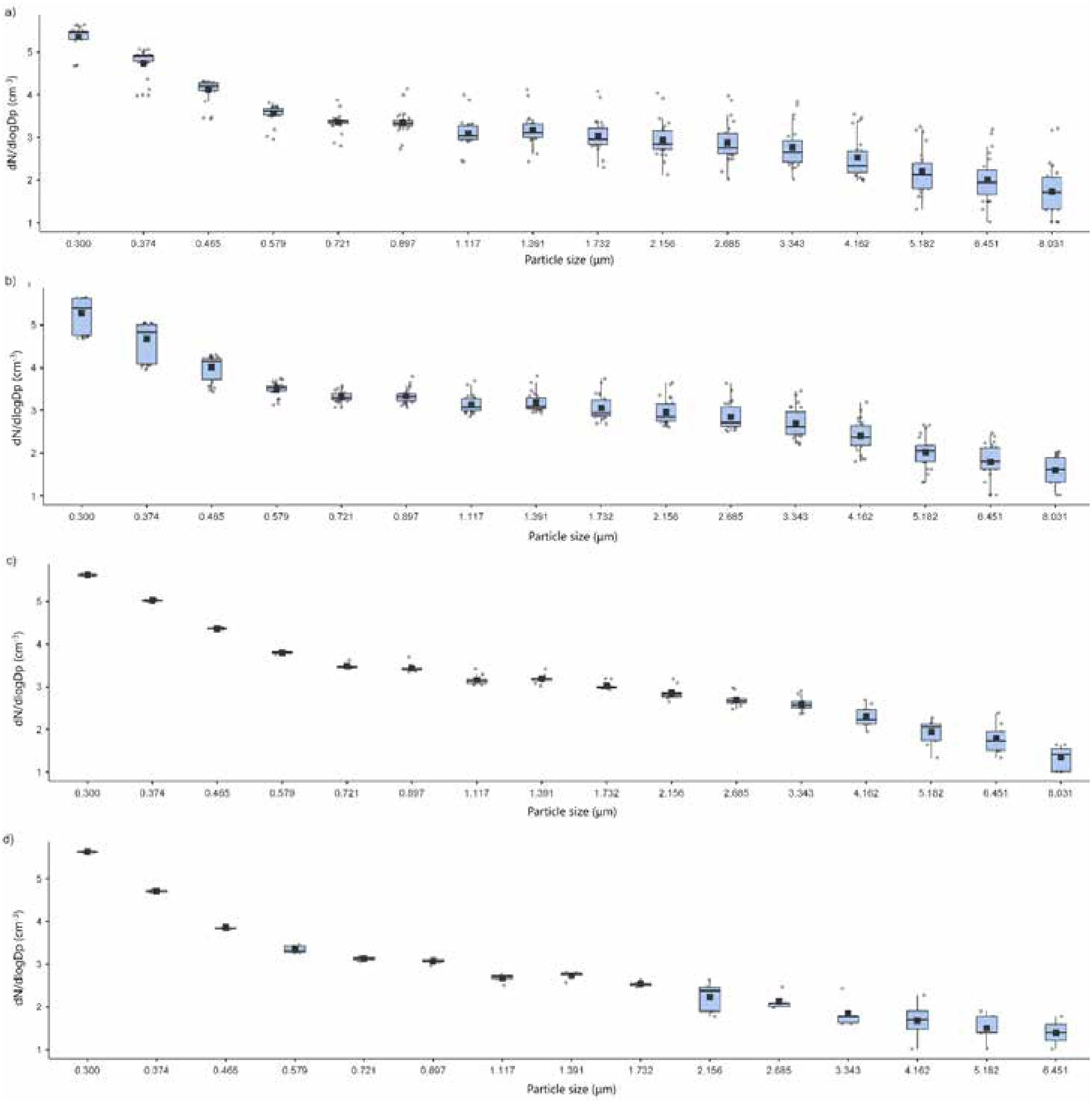

Figure 5. Particle number size distribution (logarithmic scale), expressed as dN/dlogDp [cm^3], at selected sampling points: a) Point 1 - yard, b) Point A - "fresh" waste pile, c) Point G - maturing compost, d) Point Z - mature compost.

Table 3. Basic descriptive statistics of PM_1, $PM_{2.5}$ and PM_{10} concentrations [µg/m³] in two composting sectors: piles and the surrounding yard area.

Sector	Particles	Concentration [µg/m³]				
		Min	Mean	Median	Max	SD
Piles	PM_1	0.317	1.71	2.18	4.25	1.003
	$PM_{2.5}$	0.662	4.50	3.81	35.77	3.941
	PM_{10}	1.353	19.77	10.31	161.66	24.709
Yard	PM_1	0.353	1.85	2.26	3.22	0.876
	$PM_{2.5}$	0.686	3.94	3.76	15.47	2.390
	PM_{10}	1.722	17.89	10.49	147.41	21.774

PM_1, $PM_{2.5}$, PM_{10} concentration

PM_1, $PM_{2.5}$ and PM_{10} concentrations depending on sampling location

Table 3 presents descriptive statistics of PM_1, $PM_{2.5}$ and PM_{10} concentrations in different sectors: yard and prisms.

PM_{10} concentration values in the groups: yard and prism are characterized by homogeneity of variance (p-value of Levene's test is 0.059). As the results obtained do not meet the criterion of normality of distribution (p-value of the Shapiro-Wilk test is less than 0.001), so, instead of a t-test, the Mann-Whitney U-test was used. For PM_1, $PM_{2.5}$ and PM_{10}, the p-value of this test was 0.376, 0.454 and 0.916, respectively, which leads us to accept the hypothesis of equality of variance in each of these cases. The PM_{10} concentration values for the yard and prism groups exhibited homogeneity of variance, as indicated by Levene's test ($p = 0.059$). However, the results did not meet the assumption of normality (Shapiro–Wilk test, $p < 0.001$). Therefore, instead of a t-test, the non-parametric Mann–Whitney U test was applied. For PM_1, $PM_{2.5}$, and PM_{10}, the p-values obtained from the Mann–Whitney U test were 0.376, 0.454, and 0.916, respectively. These results indicate no statistically significant differences between the yard and prism groups for any of the PM fractions.

Figures 7-9 show plots of PM_1, $PM_{2.5}$ and PM_{10} concentrations, depending on sampling location.

The average concentration of $PM_{2.5}$ on the waste prisms was 4.5 µg/m³, while PM_1 and PM_{10} averaged 1.71 and 19.77 µg/m³ respectively. Similar values were obtained by Viegas et al. at composting plant prisms in Portugal (Viegas et al. 2014). These values are 10 times lower than those obtained by Priyanka et al. at the landfill site in Central India, although minor renovation work near the site may have influenced their results (Priyanka et al. 2023). In comparison, Madhwal et al. (2020) reported $PM_{2.5}$ concentrations ranging from 60 to 224 µg/m³ at a landfill

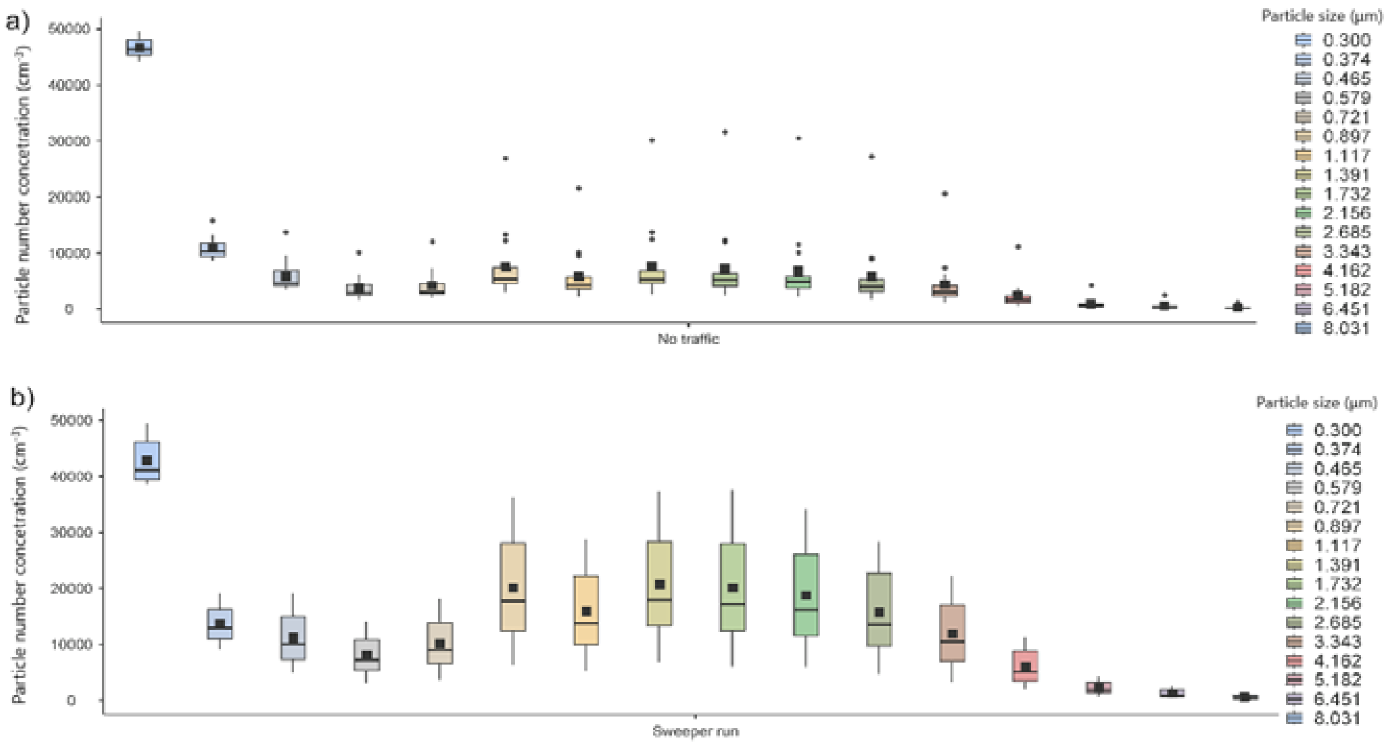

Figure 6. Comparison of particle number concentrations, expressed as particles per cubic centimeter [cm⁻³], under different operational conditions: a) no vehicle traffic; b) during sweeper vehicle run. Line inside frame – median, rectangle inside *frame – mean.*

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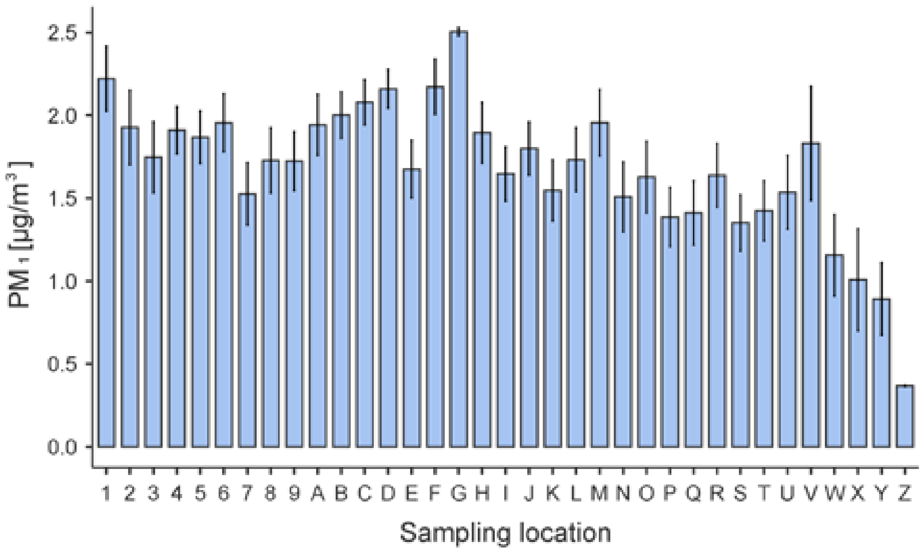

Figure 7. PM_1 concentrations [µg/m³] across sampling locations.

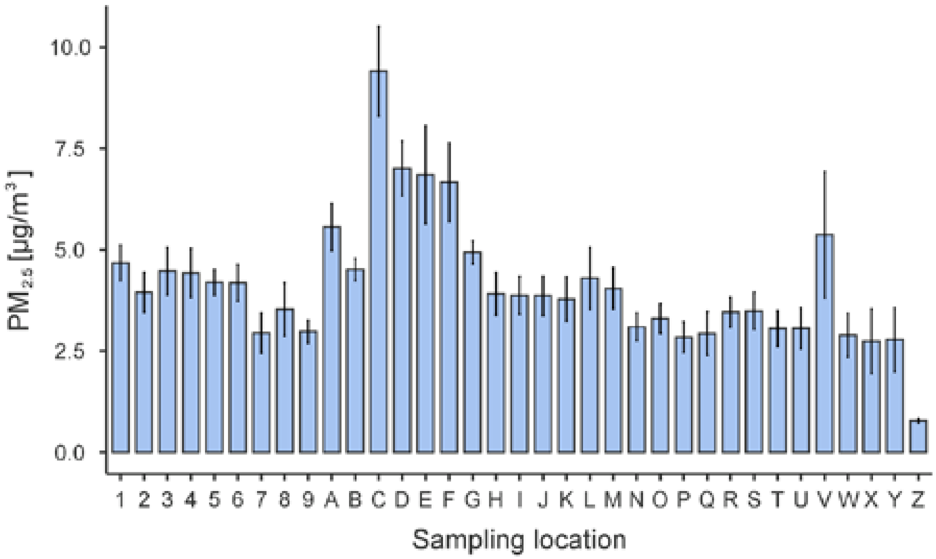

Figure 8. $PM_{2.5}$ concentrations [µg/m³] across sampling locations.

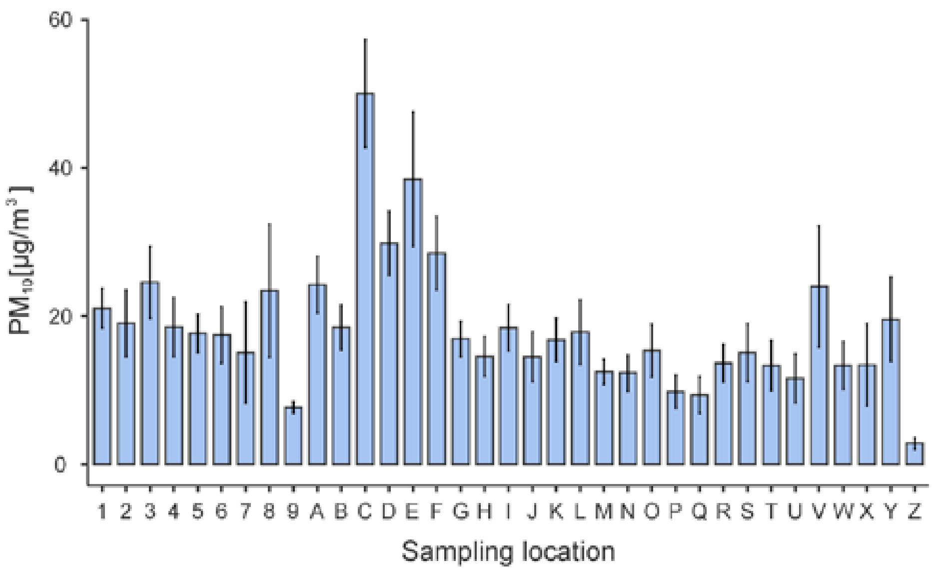

Figure 9. PM_{10} concentrations [µg/m³] across sampling locations

in Dehradun, India. Chalvatzaki at al. (2010) found that outdoor PM_{10} concentrations at a landfill site in Crete, Greece, ranged from 42 and 601 µg/m³, primarily due to dust generated during waste covering operations and vehicle movement. The highest indoor PM levels were observed in areas where manual waste sorting occurred (Chalvatzaki et al. 2010).

In Teheran, Kermani et al. (2018) recorded highly variable $PM_{2.5}$ levels across three composting facility sites, which ranged between 33 and 1 552 µg/m³. The mean concentration of $PM_{2.5}$ particles was 479 µg/m³ at the primary processing site, 59 µg/m³ at the aerated site, and 1,037 µg/m3 at the final processing site. The high concentrations were attributed to equipment emissions, incomplete diesel combustion, and resuspension of particles by vehicles and machinery (Kermani et al. 2018). Mahato et al. (2023) conducted continuous monitoring during waste burning periods and reported extremely high $PM_{2.5}$ levels: 1,391 ± 358 µg/m³ at industrial sites, 998 ± 319 µg/m³ at urban sites, and 957 ± 313 µg/m³ at rural locations. Chalvatzaki et al. (2013) reported outdoor PM_{10} concentrations ranging from 84 to 140 µg/m³ (107 µg/m³ average value) during working hours. In comparison, the maximum PM_{10} concentration in the present study was 167 µg/m³. Barkhordari et al. (2022) found the highest average PM concentrations at the hand-picking area of a waste sorting plant: PM_1= 8.49 (±0.49) µg/m³, $PM_{2.5}$ = 36.5 (±3.45) µg/m³, and PM_{10} = 830.23 (±109.2) µg/m³. Finally, Purdy et al. (2009) observed seasonal variation in PM_{10} levels at compost fields, reporting a mean of 108.2 µg/m³ in summer and 57.6 µg/m³ in winter.

Table 4 shows the descriptive statistics of the fractional composition of PM_{10} and $PM_{2.5}$, in different areas of the composting site, specifically the yard and prism sectors.

The share of $PM2_{.5}$ in the PM_{10} fraction ranges from 3.59% to 71.88%, with median values ranging from 29.19% (prisms) to 30.68% (yard). The average share varies from 31.26% (prisms) to 31.86% (yard). The share of PM_1 in PM_{10} fraction is between 0.51% (prisms) 50.55% (yard) with median from 13.41% (prisms) to 15.14% (yard), while the share of the PM_1 in $PM_{2.5}$ ranges from 6.36% (prisms) to 72.52% (prisms) with median from 45.94 (prisms) to 52.25% (yard).

For comparison, Vega et al. (2001) investigated the resuspension of surface dust at the Mexico City landfill and analyzed PM_{10} and $PM_{2.5}$ fractions for their physico-chemical properties. Their findings revealed that $PM_{2.5}$ constituted 20–26% of the PM_{10} fraction at the landfill site (Vega et al. 2001).

The observed predominance of fine particulate fractions (PM_1 and $PM_{2.5}$) across various composting stages raises important concerns regarding occupational exposure. Fine and ultrafine particles can bypass the upper respiratory tract and penetrate deep into the alveolar region, where they may trigger inflammatory responses, aggravate pre=existing respiratory conditions, or contribute to cardiovascular effects (e.g., Huang 2023). This is particularly relevant for workers involved in high-exposure tasks such as turning, screening, or transporting compost piles. Ghobakhloo (2023) reported that dismantlers experienced the highest PM2.5 exposure levels, with an average concentration of 2,148 ± 1,257 µg/m³, while sorters and collectors were exposed to lower mean concentrations of 1,864 ± 965 µg/m³ and 1,782 ± 876 µg/m³, respectively. Although this study did not include toxicological or chemical characterization of PM, the elevated concentrations detected during early composting stages and operational activities (e.g., sweeper runs) suggest a significant potential for acute worker exposure.

These findings underscore the importance of identifying critical emission phases and high-risk facility areas to implement targeted mitigation strategies, such as dust suppression systems and appropriate personal protective equipment. Future studies should include health-based risk assessments, bioaerosol quantification, and long-term exposure modeling to better define safety thresholds in composting operations.

Conclusions

This study provides a comprehensive analysis of particle number concentrations (PNC), particle number size distribution (PNSD) and particulate matter (PM) concentrations measured at a full-scale composting facility managing organic waste.

Table 4. Descriptive statistics of the share [%] of PM_1 in $PM_{2.5}$ and PM_{10}, and $PM_{2.5}$ in PM_{10}, for the entire composting facility and separately for the yard and pile areas.

Sector	PM	PM share [%]				
		Min	Mean	Median	Max	SD
Compost plant	PM 1 in PM_{10}	0.51	15.97	13.70	50.55	11.13
	$PM_{2.5}$ in PM_{10}	3.59	31.40	29.68	71.88	14.39
	PM_1 in $PM_{2.5}$	6.36	45.04	48.28	72.52	16.95
Piles	PM 1 in PM_{10}	0.51	15.55	13.41	44.84	11.03
	$PM_{2.5}$ in PM_{10}	3.59	31.26	29.19	68.35	14.16
	PM_1 in $PM_{2.5}$	6.36	43.76	45.94	72.52	17.47
Yard	PM 1 in PM_{10}	0.99	17.29	15.14	50.55	11.38
	$PM_{2.5}$ in PM_{10}	5.30	31.86	30.68	71.88	15.11
	PM_1 in $PM_{2.5}$	7.31	49.12	52.25	71.05	14.50

Particle number concentrations varied across different areas of the composting facility. The highest PNC were recorded on fresh compost piles (average: 19,953 cm^{-3}, median: 1,160 cm^{-3}) and 4-week maturing compost piles (average: 25,491 cm^{-3}, median: 1,018 cm^{-3}), while the lowest PNC values were observed on the mature pile at the end of the process (average: 3,836 cm^{-3}, median: 189 cm^{-3}). Only slight differences were noted between PNC levels on compost piles and yards of the composting facility. Elevated PNC values were typically associated with periods of increased operational activities, such as sweepers run across the yard. These events contributed to significant short-term increases in particle counts (PNC increased by up to 30% and 70% for particle sizes 0.374 – 0.465 μm and 0.897 – 10 μm, respectively). The data revealed a trimodal particle number size distribution, with peaks at 0.3 μm, 0.897 μm and 1.732 μm. The first two peaks correspond to accumulation mode particles (aerodynamic diameter from 0.1 μm to 1 μm), typically formed through coagulation or vapor adsorption from smaller particles in the nucleation mode: (aerodynamic diameter < 0.01 μm) and Aitken mode (aerodynamic diameter 0.01 – 0.1 μm). Further growth of these mode particles is inefficient, and their gravitational settling is slow, thus they can remain suspended in the air for several days.

Overall, the analysis revealed that 98% of particles had aerodynamic diameters below 2.5 μm, while particles smaller than ≤ 1 μm constituted 95% of the total particle number concentration.

The average mass concentration of PM_1, $PM_{2.5}$ and PM_{10} measured on the waste prisms were 1.71 μg/m³, 4.5 μg/m³ and 19.77 μg/m³, respectively. Similar to PNC, higher PM levels were observed for fresh and maturing compost piles, with increases of up to 86% compared to the mature pile at the end of the process. On average, PM_1 and $PM_{2.5}$ accounted for approximately 16% and 30% of the PM_{10} mass concentration, respectively. Additionally, PM_1 made up about 45% of the $PM_{2.5}$ mass. Slightly higher contributions of PM_1 and $PM_{2.5}$ to PM_{10} , as well as PM_1 to $PM_{2.5}$,were noted on the yards. The highest proportions of PM_1 within $PM_{2.5}$ (above 70%) were recorded in the maturing heaps (week 5-6) and in the two-week compost pile.

The results provide valuable insights into the distribution of airborne particles in a biodegradable waste composting facility, which constitutes a unique environment with significant implications for environmental monitoring and public health. However, the scope of the study was limited by its temporal coverage; measurements were carried out only on selected days during the summer and therefore do not capture air quality variations across different seasons. During warmer periods, atmospheric turbulence is a key factor, contributing to the resuspension of both soil particles and composting material from piles. Thermally induced turbulence also contributes to the dispersion and temporary stabilization of particle concentrations. To better understand these dynamics, future research should incorporate long-term, multi-seasonal monitoring of PNC and PM concentrations across different months and landfill management practices. Seasonal factors (temperature, humidity, wind dynamics, and microbial activity) and long-term trends should be considered to capture a comprehensive picture of particle behavior and exposure risks.

In addition to particle number and mass concentrations, other particle characteristics, such as chemical composition and biologically active compounds (e.g., VOCs, PAHs, trace elements, and endotoxins) were not studied in this research but are essential for evaluating potential health impacts of atmospheric PM. Despite these limitations, the present findings offer high-resolution, spatially and process-resolved data across various composting stages and activity zones. This provides a strong foundation for future investigations and environmental planning.

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Stężenia i wielkości rozkładów cząstek stałych podczas różnych etapów biostabilizacji odpadów komunalnych: ocena terenowa w wysokiej rozdzielczości

Streszczenie. Niniejsze badanie oferuje dogłębną analizę stężeń liczby cząstek (PNC) i stężeń PM mierzonych w kompostowni przetwarzającej odpady organiczne, z naciskiem na szczegółowe frakcjonowanie PM w celu określenia, które frakcje dominują w różnych obszarach kompostowni. Pomiary PNC przeprowadzono przy użyciu urządzenia Optical Particle Sizer, które wykrywa liczbę cząstek w zakresie wielkości 0,3 - 10 µm poprzez zliczanie pojedynczych cząstek. Różnice w PNC zaobserwowane między stosami kompostu a innymi obszarami zakładu były minimalne. Średnie stężenia masowe PM1, PM2,5 i PM10 na pryzmach odpadów wynosiły odpowiednio 1,71 $\mu g/m^3$, 4,5 $\mu g/m^3$ i 19,77 $\mu g/m^3$. Podobnie jak w przypadku PNC, wyższe stężenia PM zaobserwowano dla świeżych i dojrzewających pryzm kompostu, ze wzrostem do 86% w porównaniu do dojrzałych pryzm na końcu procesu. Wyniki zapewniają krytyczny wgląd w dystrybucję cząstek zawieszonych w powietrzu w zakładzie kompostowania odpadów biodegradowalnych, środowisku o znaczących konsekwencjach dla monitorowania środowiska i zdrowia publicznego.