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OCCUPATIONAL EXPOSURE TO SIZE-SEGREGATED PARTICULATE MATTER IN SOLID WASTE HANDLING: A MULTI-ANALYTICAL AND DOSIMETRIC STUDY

Urban solid waste management in developing countries often exposes the frontline workers to airborne particulate matter (PM), which poses serious health risks. This study was conducted among the waste workers in Peruntholuvu village in Tirupur district, India. Using a personal cascade impactor operating at a flow rate of 9.3 dm³/min, exposure assessments were performed at four operational stages, namely, residential collection, street-to-street collection, transport, and dump yard operations. Analytical characterization of the collected PM samples was performed using inductively coupled plasma mass spectrometry (ICP-MS), Fourier transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM). The chemical analysis revealed the presence of heavy metals, including lead, nickel, and mercury, at trace levels. FTIR confirmed hazardous functional groups like amines, aromatic hydrocarbons, and organophosphates. SEM micrographs showed 0.25 µm diameter fibrous and porous PM structures, indicating deeper lung penetration. The multiple-path particle dosimetry (MPPD) model indicated that for ultrafine particles < 0.25 µm, the fractional deposition in the pulmonary region reached 0.285 (28.5%) for workers in the dump yard and a fraction of 0.232 (23.2%) for residential collectors, implying deep lung deposition. Study confirms the increased risk of chronic respiratory conditions due to unprotected exposure, including non-mechanised and comingled waste handling.

1. INTRODUCTION

Increased municipal solid waste (MSW) due to rapid industrialization and urbanization has increased the demand for effective and sustainable waste management techniques, especially in developing nations [1]. Garbage waste handling starts from the collection of waste from the source, transportation, treatment, and disposal [2]. Workers in

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the domestic waste collection industry are among the most highly exposed groups in terms of personal exposure due to their longer working hours, less job control, and the physically demanding nature of work. Particulate matter (PM) is a complex mixture of solid and liquid particles suspended in the air that is produced by the various components of MSW, such as organic matter, plastics, metals, and other materials. These particles can cause respiratory and cardiovascular issues, among other harmful health effects, when inhaled. Seriousness of the risks is determined by several variables, such as the type of waste, the workplace, and the length of exposure [3–5]. Significantly, waste discharged for collection in developing nations is dropped straight onto the ground, shovelled manually, and stored in an open container rather than a closed one [6]. Burning MSW, a common way to dispose of waste in some areas, releases several dangerous pollutants which are harmful to human health due to the release of carbon monoxide, greenhouse gases, polycyclic aromatic hydrocarbons, and toxic dioxins [7–10]. The degree of these health risks varies according to the kind and concentration of contaminants that the workers are exposed to, and they can include respiratory infections, allergies, and chronic illnesses [11, 12]. Furthermore, waste collectors are more prone to injuries and illnesses, including lung diseases, than the general population, largely because of exposure to hazardous waste and unsafe working conditions [13]. Additionally, the hazards faced by waste handlers are increased by inadequate housing, poor working conditions, and restricted access to healthcare facilities [14, 15].

While numerous studies have addressed the environmental impact and regulatory aspects of waste disposal, less attention has been paid to the occupational hazards faced by waste workers. The need for further investigation into the health risks is necessary for improving worker health and safety. The global premature mortality rate among adults attributed to long-term exposure to fine particles from open waste incineration is estimated at 270,000 per year [16, 17]. Although there is growing evidence that waste workers face health risks, there is a lack of information on the specific health risks in different municipalities. It is also inferred that $PM_{2.5}$ is the significant size fraction in lung deposition [18]. The analysis of $PM_{2.5}$ samples can be done by attenuated total reflection-Fourier transform infrared spectroscopy (ATR-FTIR) and scanning electron microscopy (SEM), which will reveal important details about the inorganic and organic groups of the airborne particles present in the sample [19].

This study aims to address these gaps by providing evidence-based suggestions to improve the occupational safety of waste management workers. The primary objectives of the research are to assess personal occupational exposure to PM during different stages of the waste handling processes, characterize the composition of PM particles, and develop respiratory deposition models to assess the health risks associated with exposure. By increasing the understanding of these occupation-related health hazards, this study seeks to ensure better safety for workers in the waste management sector and contribute to their overall well-being.

2. STUDY AREA AND METHODOLOGY

The Tirupur District, with a total of 5,187 km² consisting of nearly 297 villages, known for its textile industry, is one of the industrial hubs in Tamil Nadu that is expanding quickly and is home to several apparel manufacturing facilities. Because of its large population and active economy, the city produces a large volume of domestic solid waste, putting additional pressure on the existing waste management infrastructure. Based on statistics, Tirupur stands next to Chennai, with a daily average of 1700 tonnes of waste generation. The study area considered is Pongalur Block in Tirupur district, shown in Fig. 1, which contains the village of Peruntholuvu, which produces nearly 10–20 tonnes of household garbage daily during 2019–2020. This data is based on the reports submitted by the local urban bodies in the district. Manual waste handling is predominant, with minimal mechanization or protective infrastructure.

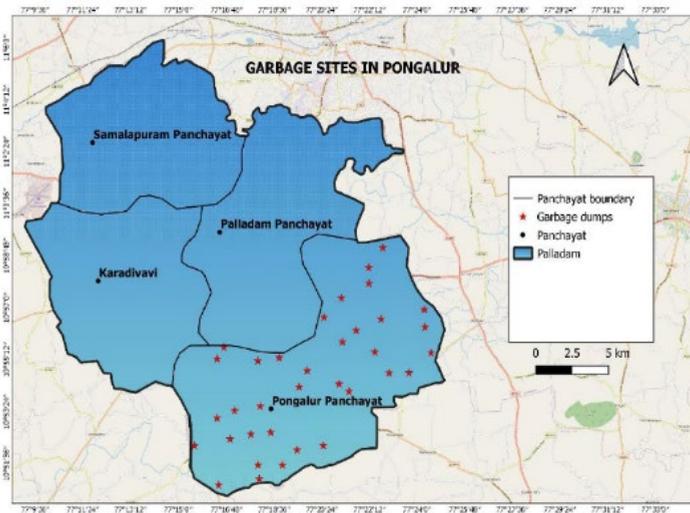


Fig. 1. Pongalur town map

Four waste management tasks, namely, residential waste collection (house-to-house), street-level collection, transportation, and disposal at the dump yard, were selected based on their operational distinctiveness and exposure potential. Workers were selected for each task based on the following inclusion criteria:

- ≥ 5 years of occupational experience.
- No pre-existing diagnosed respiratory illness.
- Willingness to participate with informed consent.

Each worker underwent 2 h of personal exposure monitoring during routine morning operations. Ambient temperature and humidity were also recorded during the sampling periods.

Sampling using a personal cascade impactor and gravimetric analysis. PM samples were collected from 35 locations (12 residential, 10 street-level, 15 transportation hubs, and 13 dump yards) over 3 months (December 2024–February 2025). One sample was taken from each site once a week during the collection times. Personal exposure to airborne particulate matter was measured using a five-stage personal cascade impactor (Fig. 2) connected to a portable vacuum sampling pump calibrated to a flow rate of $9.3 \text{ dm}^3/\text{min} \pm 2\%$. The impactor possesses the subsequent aerodynamic size fractions: > 2.5 , $2.5\text{--}1.0$, $1.0\text{--}0.5$, $0.5\text{--}0.25$, and $< 0.25 \mu\text{m}$, collected on a 37 mm diameter polytetrafluoroethylene (PTFE) filter after each filtration stage. The PTFE membrane-based filters have a pore size of $0.2 \mu\text{m}$ and are pre-weighed using a microbalance with $\pm 1 \mu\text{g}$ precision. After sampling, filters were sealed, transported under desiccated conditions, and stored at $4 \text{ }^\circ\text{C}$ until analysis. The mass of PM deposited on each filter was determined by gravimetric analysis under identical conditions.

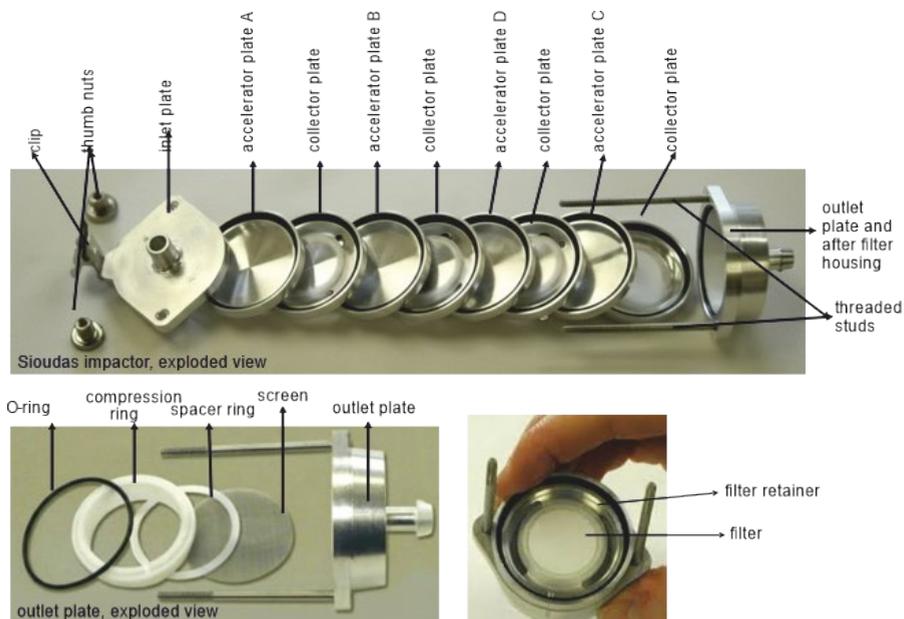


Fig. 2. Personal cascade impactor

Experimental. Data samples for analyzing particulate matter (PM) exposure and associated worker characteristics were systematically collected across four major municipal waste-handling activities: residential waste collection, street waste collection, transportation, and dump yard operations. A structured sampling framework was adopted to ensure consistent temporal coverage and standardized monitoring conditions. Table 1 summarises the operational characteristics, sampling frequency, PM filter collection details, and environmental conditions recorded during field monitoring.

Table 1

PM sampling parameters across waste handling operations

Parameter	Waste collection		Transportation	Dump yard
	Residential	Street		
Activity	residential areas	sweeping, transportation (vehicles), garbage	transportation (vehicles)	waste segregation and disposal
Type of waste	packaging materials, yard debris, food scraps, household items	Household waste, street litter	organic and inorganic waste, e-waste, medical waste	organic and inorganic waste, e-waste, medical waste
Number of sites	10	10	8	7
Duration of study	3 months			
Frequency of sampling	once per week			
PM filter samples collected	144	120	180	156
Number of PM size fractions analysed	5			
Total number of PM fraction measurements	3000 measurements with 600 filter samples			
Average temperature	23 °C	25 °C	28 °C	26 °C
PM sampling duration	7 AM–9 PM	7 AM–9 AM	8 AM–10 AM	11 AM–1 PM
Filter weight measurement protocol	standard protocol (5-digit microbalance)			

Table 2

Worker demographics and occupational exposure characteristics

Parameter	Waste collection		Transportation	Dump yard
	Residential	Street		
Breathing zone height ^a , cm	145	130	137	160
Number of workers	12	10	15	13
Average years age of workers	53	65	38	27
Average years of employment	20	30	7	6
Health effects reported	sneezing, eye irritation, skin and grass allergies, cuts and bruises	bacterial skin infection, skin allergies, eye irritation, hypertension, neurological pain	respiratory issues, wheezing, skin allergies, eye irritation, inflammation, cuts	dried/cracked feet, inflammation, skin allergies, asthma

^aBreathing-zone height: vertical distance from ground to the nostrils in a natural standing posture, used to position personal air samplers for inhalation exposure assessment.

Additionally, worker-related demographics and other exposure monitoring samples characteristics, including breathing-zone height, age, employment duration, and self-reported health symptoms, were documented to contextualise exposure variability and occupational risk in Table 2. This information provides a comprehensive foundation for understanding how activity type, environmental conditions, and waste composition influence inhalation exposure to size-segregated particulate matter and associated chemical constituents.

Three different analytical techniques were utilized to evaluate the chemical composition of particulate matter measured from various waste-handling operations. The employed methods facilitated the assessment of (i) elemental concentrations, (ii) functional groups of organic constituents, and (iii) particle morphology and surface characteristics. The following section outlines the instrumentation and the specific parameters that were quantified in this study.

Inductively coupled plasma mass spectrometry (ICP-MS). The elemental composition of PM samples, comprising both major and trace metals, was quantified utilizing the Agilent 7900 ICP-MS system. The PM filters that were collected underwent acid digestion before the analysis was conducted. The ICP-MS quantified the levels of metals including Na, Mg, Al, P, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Cd, Zn, Pb, Cs, Cd, Mo, Ag, Sn, Mn, etc., which were utilized to evaluate the contributions from handling waste, transportation, and disposal processes. Thorough atomisation and ionisation of the digested sample permitted accurate quantification of metal ions even at trace-level concentrations.

Fourier transform infrared spectroscopy (FTIR). Organic and inorganic functional groups present in PM were identified using an FTIR spectrometer. Three PM_{2.5} filter samples were analysed for each sampling category. The spectra were acquired by averaging 200 absorbance scans within the range of 600–4000 cm⁻¹, utilizing a resolution of 4 cm⁻¹. FTIR was specifically used to identify functional groups associated with organic pollutants and waste-related emissions, including: C–H stretching (alkanes), C=C aromatic bands, P–O stretching (phosphates), O–H groups (hydroxyl compounds). These results provided detailed insight into the contribution of household waste, street debris, and mixed refuse to PM composition.

Scanning electron microscopy (SEM). SEM imaging resulted in detailed visualization of PM particles to determine: Particle morphology, Surface characteristics and the estimated size distribution. The morphological characteristics identified were useful in distinguishing particulate matter arising from different waste handling activities. High-resolution images provided more evidence to reinforce the results of ICP-MS and FTIR analyses for source identification and characterization.

Respiratory deposition modeling. The multiple-path particle dosimetry (MPPD), an algorithmic model, forecasts the deposition and movement of airborne particles in the human respiratory system. It calculates the percentage of inhaled particles that go to various

respiratory system areas and the dosage that is subsequently administered to these locations. The MPPD model version 3.04 (<https://www.ara.com/products/multiple-path-particledosimetry-model-mppd-v-304>), was used to analyse the risk assessment of PM among waste management workers. The model inputs included the following: particle size distribution from cascade impactor data, exposure time: 2 h, breathing rate: 20 dm³/min (light activity), tidal volume: 0.75 dm³ particle density: 1.6 g/cm³ (average assumed). The output provided deposition fractions by region and allowed estimation of total deposited mass (μg) over the exposure period.

3. RESULTS

3.1. AVERAGE PM EXPOSURE LEVELS DURING WASTE HANDLING ACTIVITIES

Table 3 shows the results of particulate matter with fine to ultrafine fraction, and Fig. 3 shows the particle deposition profile by size fraction from the type of waste handling activity.

Table 3

Average PM deposition rates \pm SD [$\mu\text{g}/\text{min}$]

Particle size [μm]	Waste collection		Transportation	Dump yard
	Residential	Street		
2.5	1.85 \pm 0.20	5.25 \pm 0.66	2.25 \pm 0.19	0.68 \pm 0.18
1.0	0.25 \pm 0.005	1.83 \pm 0.25	0.65 \pm 0.08	1.18 \pm 0.12
0.5	0.25 \pm 0.04	1.75 \pm 0.22	0.87 \pm 0.16	0.77 \pm 0.11
0.25	1.57 \pm 0.18	2.08 \pm 0.25	0.32 \pm 0.09	1.20 \pm 0.17
< 0.25	1.33 \pm 0.16	3.50 \pm 0.45	2.58 \pm 0.34	0.72 \pm 0.11

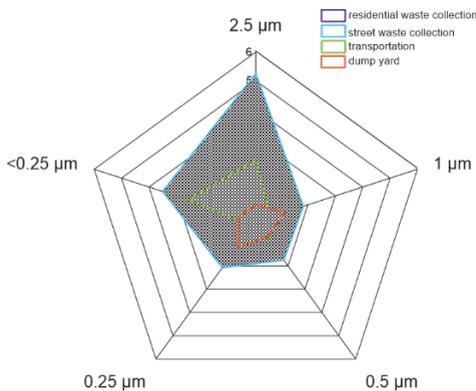


Fig. 3. Deposition rates by particle size fraction and the type of activity

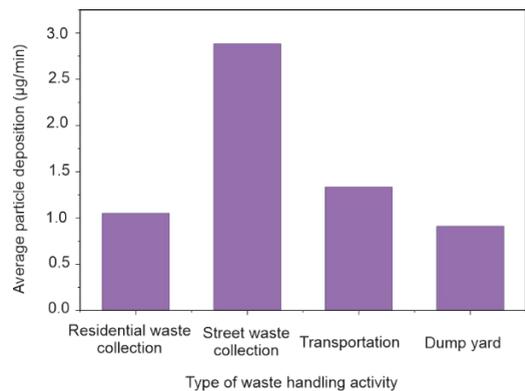


Fig. 4. Activity-specific average particle deposition across all particle size fractions

Figure 4 illustrates the activity-specific average particle deposition across all particle size fractions, which clearly captures a peak value being identified during the street waste collection activity compared to all other activities involved during the waste handling processes. Residential waste collection illustrates moderately high levels of ultrafine particles ($PM < 0.25 \mu m$), whereas this value is very high during street waste collection and the transportation process. The garbage collectors and the workers at a dump yard show a high level of fine particles, namely, $PM_{2.5} \mu m$ and $PM_{0.25} \mu m$, respectively. The observed trend in exposure is identified in the following sequence: street waste collection > transportation > residential waste collection > dump yard.

These microscopic airborne particles may be extremely harmful to human health if inhaled. As a result, there may be an increase in air pollution at nearby areas and respiratory issues for both employees and locals, impacting adjacent ecosystems and the quality of the soil. Several studies [20–23] also confirm that municipal solid waste handling workers are affected by various health effects due to exposure to particulate matter.

Table 4

Tukey's HSD multiple comparison results for mean particle deposition rates

Subject	Mean difference	SEM	<i>q</i> -value	<i>p</i> -value	α	Sig	LCL	UCL
Street waste collection residential waste collection	1.8188	0.0122	210.395	< 0.0001	0.05	1	1.787	1.850
Transportation residential street waste collection	0.2922	0.0110	37.5216	< 0.0001	0.05	1	0.263	0.320
Street waste collection transportation	1.5265	0.0118	181.945	< 0.0001	0.05	1	1.557	1.496
Dump yard residential waste collection	-0.1482	0.0114	18.391	< 0.0001	0.05	1	-0.177	-0.118
Street waste collection dump yard	1.9670	0.0122	227.545	< 0.0001	0.05	1	1.998	1.935
Dump yard transportation	-0.4404	0.0110	56.558	< 0.0001	0.05	1	-0.468	-0.412

SEM – standard error of the mean, *q*-value – Tukey's HSD statistic, α – significance threshold, Sig – significance indicator, LCL and UCL – lower and upper limits of the 95% confidence interval.

Pairwise comparison among operational categories was evaluated using Tukey's HSD (honestly significant difference) post hoc test (Table 4). The Tukey's HSD analysis showed statistical significance ($p < 0.0001$ for all possible pairwise comparisons) hierarchy of deposition rates across the different activities handled by solid waste workers. Most importantly, waste collectors were exposed to 1.97 particles per minute more than dump

yard workers (95% confidence interval (CI): 1.935–1.998). The confidence interval indicates the actual difference in exposure between the two groups will likely be between 1.935 and 1.998 particles per minute, with an accuracy rate of 95%. The dump yard operations were linked to the lowest deposition rates, which were much lower than those of the residential waste collection control group (Mean Diff = -0.148 , 95% CI: -0.177 – 0.118). The perceived risk associated with a static disposal site might be lower than the immediate exposure encountered during the active processes of handling, lifting, and compacting waste at this location. This lower level of exposure could be because the dump site is farther away from the pollutant source and the dispersal of the pollutant by wind. Low standard errors (SEMs < 0.013) and significant q -statistics (18.4–227.5) indicate reliable results that align with epidemiological studies that showed a higher incidence of bronchitis and impaired lung function among waste collectors [24–26].

3.2. ELEMENTAL COMPOSITION ANALYSIS USING ICP-MS

The presence of heavy metals detected in the size-segregated particulate matter collected from the four waste-handling activities was examined using inductively coupled plasma mass spectrometry (ICP-MS). The results are summarized in Table 5, provide the detailed summary of the ICP-MS elemental characterization, categorizing elements as acceptable, trace, or not detected. Table 6 outlines the detected concentrations of heavy metals that exceed the international regulatory guideline values. Identification of these elements helps to mitigate environmental risks and safeguard human health. The results detected the presence of 23 elements, including heavy metals exceeding the permissible limit.

Table 5

ICP-MS elemental characterization showing not-detected, acceptable and elements present at trace levels

Status	Residential waste collection	Street waste collection	Transportation	Dump yard
Acceptable (within permissible exposure limits)	Nil	Mo	Nil	Nil
Not detected	Li, Be, B, As, Cd, Sb, Cs	B, Al, Ni, As, Cd, Sn, Sb, Cs, Hg, Te	Li, Be, P, B, As, Cd, Sb, Cs	
Present at trace levels	Al, Cr, Co, Cu, Fe, Mg, Mn, Mo, K, Ag, Na, Ti, Sn, P	Cr, Co, Cu, Fe, Mg, Mn, K, Ag, Na, Ti, V, Zn, P, Be, Li	Al, Cr, Co, Cu, Fe, Mg, Mn, Mo, K, Ag, Na, Ti, V, Zn, Hg, Sn	Al, Cr, Co, Gu, Fe, Mg, Mn, Mo, K, Ag, Na, Ti, V, Zn, Hg, Sn

Most elements were detected at trace levels in all four levels of operations (Table 5), reflecting the natural mineral and particulate composition of mixed municipal waste. Residential waste collection, transportation, and dump yard samples showed no elements

within the acceptable range, whereas street waste collection showed molybdenum as the only element falling within permissible limits. A substantial number of elements, including B, As, Cd, Sb, and Cs, were not detected even at trace levels in all the activities. Street waste collection additionally showed the absence of Ni, Sn, Te, and Hg, indicating distinct waste compositions compared to other operations. Trace-level elements such as Cr, Co, Cu, Fe, Mg, Mn, K, Ag, Na, Ti, V, and Zn were consistently observed across the activities, reflecting dust re-suspension, mechanical abrasion, and handling of mixed waste.

Table 6

ICP-MS elemental characterization for detecting heavy metal concentrations exceeding regulatory guideline values

Element	Residential waste collection [$\mu\text{g}/\text{m}^3$]	Street waste collection [$\mu\text{g}/\text{m}^3$]	Transportation [$\mu\text{g}/\text{m}^3$]	Dump yard [$\mu\text{g}/\text{m}^3$]	Reference standard and limit
Pb	0.6	0.9	0.8	1	0.50 $\mu\text{g}/\text{m}^3$ (EU)
Ni	0.03	below detectable limits	0.05	0.07	0.02 $\mu\text{g}/\text{m}^3$ (EU)

Table 6 presents the concentrations of two heavy metals that may pose health risks from prolonged exposure. Lead levels ranged from 0.6 to 1.0 $\mu\text{g}/\text{m}^3$ across all four waste-handling activities, exceeding the European Union (EU) limit of 0.50 $\mu\text{g}/\text{m}^3$ in every instance. The highest concentrations were observed in the dump yard (1.0 $\mu\text{g}/\text{m}^3$) and street waste collection (0.9 $\mu\text{g}/\text{m}^3$), in which these operations are characterised by intensive manual handling, mixed waste handling, vehicular movement, and dust re-suspension. The consistent exceedance of Pb across all waste handling operations suggests widespread contamination from sources such as battery residues, metal scrap, vehicular exhaust, and combustion by-products. Nickel concentrations also exceeded the EU annual guideline value of 0.02 $\mu\text{g}/\text{m}^3$ in the residential waste collection (0.03 $\mu\text{g}/\text{m}^3$), transportation (0.05 $\mu\text{g}/\text{m}^3$), and dump yard (0.07 $\mu\text{g}/\text{m}^3$) activities. These elevated levels can be attributed to the exposure from stainless steel fragments, e-waste components, and catalytic or fuel combustion particles commonly encountered in waste-handling operations. Only the street waste collection recorded Ni levels below detectable limits, likely illustrating the differences in waste composition and the dominance of road dust rather than mixed metal-rich materials.

3.3. CHEMICAL BOND IDENTIFICATION USING FTIR SPECTROSCOPY

FTIR spectra (Fig. 5) identified multiple hazardous organic functional groups from the collected PM samples. Chloroalkane C–X bond appearance spans from weak to medium, and it is reflected in the fingerprint region's absorption peak at 635–640 cm^{-1} .

Phosphorus oxide P–O bond with a strong appearance is implied by the absorption peak 1201–1203 cm^{-1} of the fingerprint region.

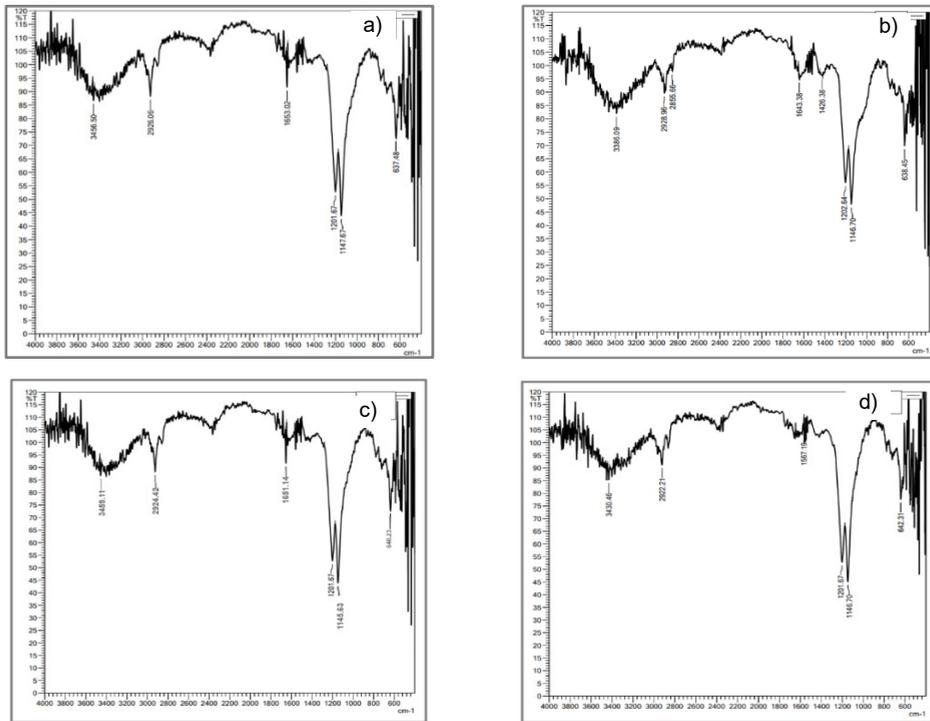


Fig. 5. FTIR bonding results of: a) residential waste collection, b) street waste collection, c) transportation, and d) dump yard

It is a representation of the stretching and bending vibrations connected to the phosphorus and oxygen atom connection. The medium-appearing P–C bond of an organo-phosphorus molecule is implied by the absorption peak at 1426 cm^{-1} of the fingerprint region. It represents the existence of phosphorus molecules that are directly bound to carbon atoms, or organic phosphorus compounds. The absorption peak with the double bond region 1500–1700 cm^{-1} with C=C bond with medium appearance depicting the presence of aromatic compounds and alkenes. After conjugated alkenes, absorption usually takes place between 1600 and 1680 cm^{-1} and after isolated alkenes, between 1500 and 1600 cm^{-1} . The phosphate compounds are indicative of the presence of detergents and fertilizers in the waste sample. The C–H alkyl single bond with medium to strong appearance having the absorption peak in the region 2850–2950 cm^{-1} which is identified in aromatic compounds, alkanes, alkenes, and alkynes which might be due to the presence of hydrocarbons and degradation of plastics. The wide appearance of the hydroxyl groups denoted by O–H alcohol and phenol bonds is shown by the absorption peak with a single bond area 3385–

3387 cm^{-1} representing the presence of compounds like water, carboxylic acids, alcohols, and phenols. Strongly visible N–H primary amines are seen in the absorption peak with the single bond area between 3430 and 3460 cm^{-1} . O–H and N–H stretches are strongly associated with alcohols, amines, or amide functional groups. These compounds are often volatile signs for photochemical smog and secondary organic aerosol formation, affecting both indoor and outdoor air quality. Their identification confirms the organic toxicity potential of waste-related PM.

3.4. PARTICLE MORPHOLOGY USING SEM IMAGING

Particle morphology was depicted using scanning electron microscope images (Fig. 6), showing particulate matter deposited during sampling for each activity. The images have different diameters at the microscopic level and provide expanded views of the structures. With a high aspect ratio, it resembles the nanofibers or the nanorods. A variety of materials, including polymers, carbon nanotubes, and inorganic substances, might make up these nanofibers or nanorods. Physical interactions between individual particles, such as electrostatic attraction or van der Waals forces, might be causing the aggregation.

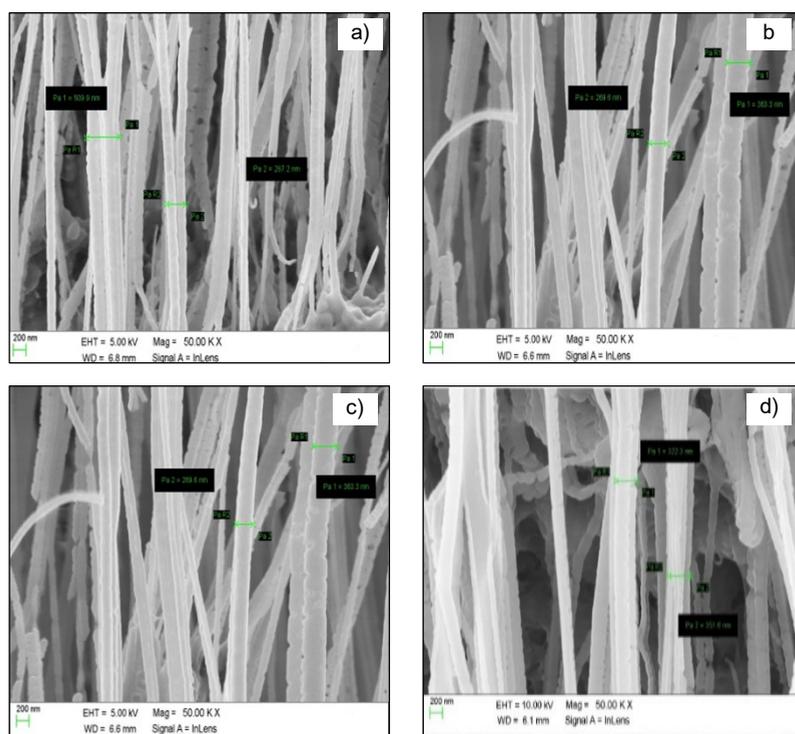


Fig. 6. Particle morphology using SEM for various types of waste handling activities: a) residential waste collection, b) street waste collection, c) transportation, and d) dump yard

Agglomerated particles can influence the dispersion and deposition of PM in the environment, which has consequences for human health and air quality. Different textures, such as smooth, rough, porous, and irregular characteristics, are present on the particle surface, impacting the particles' mechanical, adsorption, and chemical properties. Porous designs can improve surface area and particle interactions, whereas rough surfaces could offer additional sites for adsorption or chemical reactions. As the waste composition is heterogeneous, with several sorts of particles contributing to the total waste mixture, as suggested by the two different particle sizes, PA₁ and PA₂. SEM analysis revealed that these particles exhibited irregular, porous, and agglomerated morphologies, and they have fibrous structures with sharp edges, increasing potential for mucosal irritation and tissue damage. Particle diameters ranged from 287.2 nm (PA₁) to 509.9 nm (PA₂) confirm the inhalability of ultrafine particles. The porous structure increases the surface-to-volume ratio, increasing the ability of PM to carry adsorbed heavy metals and organic compounds deep into the respiratory system. Differential particle sizes indicate that these waste particles may have come from a variety of sources or processes.

3.5. RESPIRATORY DEPOSITION MODELING USING MULTIPLE-PATH PARTICLE DOSIMETRY (MPPD)

Potential health effects are illustrated by the graphs (Fig. 7) that depicts the deposition proportion of inhaled particles in various lung areas.

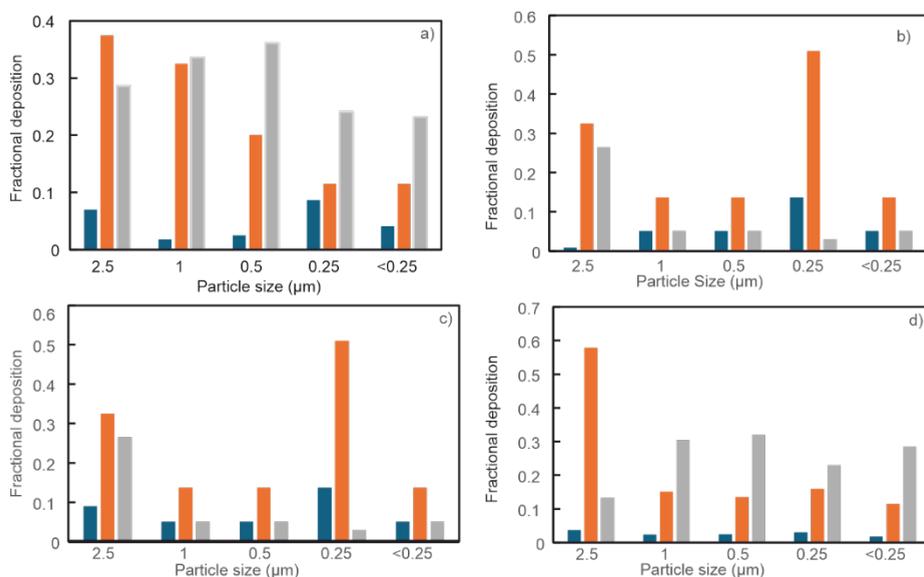


Fig. 7. Whole lung fractional deposition for different types of waste handling activities

Using field-derived PM size distribution, the MPPD model estimated deposition fractions [24] in different respiratory regions. The output revealed evident patterns of particle-size-dependent deposition in the respiratory tract across various waste management stages. In all activities, particles $> 2.5 \mu\text{m}$ predominantly deposited in the tracheobronchial region (0.374 for residential collection and 0.579 for dump yard), while the particles in the range $0.5\text{--}2.5 \mu\text{m}$ showed increased pulmonary penetration. For the particles $< 0.25 \mu\text{m}$, the deposition reached 0.285 in the pulmonary region for workers working in the dump yard workers and a fraction of 0.232 for residential collectors, implying deep lung exposure. For garbage collectors and transporters, tracheobronchial deposition peaked at 0.51 for $0.25 \mu\text{m}$ particles. Deposition in the head region was minimal for all tasks and particle sizes. Pulmonary deposition seemed to be highest for ultrafine particles ($< 0.25 \mu\text{m}$), while tracheobronchial deposition peaked for PM $0.25\text{--}2.5 \mu\text{m}$ across all waste handling activities, indicating critical zones of respiratory risk.

4. DISCUSSION

The elevated levels of PM_{2.5} worsen the surrounding area's air quality by increasing environmental pollution and causing breathing issues for residents living near waste disposal sites. The buildup of dust and debris produced during the disposal process might lead to increased PM levels in dump yards. The high levels of fine and ultrafine PM in transportation and street waste collection might be attributed to mechanical abrasion from vehicle tyres and road dust resuspension. Additionally, inadequate source segregation and open-air collection without containment measures lead to high particulate dispersion due to the presence of comingled waste.

Municipal waste-handling operations detected the presence of several elements and segregated them into different categories, namely, acceptable, present at trace levels, not detected, and exceeding the permissible exposure limits based on ambient air guidelines set by the EU. The measured concentrations of metals, particularly lead and nickel, were found to exceed the permissible exposure limits, indicating the possible occupational exposure risk for waste handling workers due to the exceedance of occupational exposure limits (OELs) when these exposures occur repeatedly over long durations. These risks pose significant health effects to workers involved in street waste collection, transportation, and dump yard operations, who experience prolonged contact with airborne particulates during physical handling, sorting, and movement of mixed waste. Chronic inhalation of Pb above $0.5 \mu\text{g}/\text{m}^3$ heightened the risk for neurocognitive impairment, hypertension, renal dysfunction, and reproductive toxicity. presents a significant neurotoxic and cardiovascular hazard. The Occupational Safety and Health Administration (OSHA) identifies lead as a systemic toxin that accumulates in bone and soft tissue. Nickel is a recognized respiratory toxicant and is classified as a human carcinogen (IARC Group 1 for certain

compounds). Concentrations observed in residential, transportation, and dump yard zones exceeded the EU value of $0.02 \mu\text{g}/\text{m}^3$. Chronic exposure at these levels may increase the risk of nasal inflammation, pulmonary irritation, chronic bronchitis, and long-term carcinogenicity. In this study, mercury (Hg) is detected at trace levels in workers handling residential waste collection, transportation, and in dump yard activities, but persistent inhalation exposure can cause subtle neurological disturbances, impaired motor coordination, tremors, and mood or memory alterations. Other metals like Mn, Cr, Cu, Co, Fe, Al, Zn, Ti, and V are found to be consistently at elevated levels across all activities suggest frequent dust re-suspension, mechanical abrasion, and combustion events. These metals may aggravate respiratory discomfort, wheezing, skin irritation, and allergic symptoms, particularly among workers with long service durations (> 10 years), who experience cumulative exposure.

Potential health effects are illustrated by the MPPD model graphs displaying the deposition proportion of inhaled particles in various lung areas. Inflammation, decreased lung function, and respiratory disorders, including asthma and chronic obstructive pulmonary disease (COPD), can result from higher deposition fractions in the pulmonary (P) region, which represent enhanced particle penetration deep into the lungs. Fewer particles may deposit in the upper airways and lessen the risk of upper respiratory tract infections if there are lower deposition fractions in the head and tracheobronchial (TB) regions. There may be a greater chance of exposure to hazardous particulate matter while engaging in activities linked to heightened P deposition fractions, including working at dump yards. These results support the frontline garbage workers' increased risk of long-term bronchial and alveolar exposure resulting in shortness of breath, persistent coughing, eye irritation, fatigue, and neurological complaints amongst workers exposed to high Pb levels, particularly in a non-mechanized work environment.

Higher levels of ultrafine particles ($\text{PM} < 0.25 \mu\text{m}$) imply that there may be less-than-ideal air quality around the waste disposal facility, which might put the health of the locals and employees at risk. These particles readily enter the respiratory system through circulation, both of which can hurt health. Elevated levels of ultrafine particles have been associated with cardiovascular disorders, respiratory disorders, and even early mortality, while long-term exposure to fine particulate matter inhalation leads to cardiovascular and pulmonary problems, resulting in long-term health problems.

5. CONCLUSIONS

This study establishes an integral approach to assess the occupational exposure to particulate matter amongst the waste management workers in an urban area. Exposure levels of PM were monitored in real time using a personal cascade impactor, and the analysed results clearly revealed the elevated levels of exposure risk during the municipal waste handling operations, particularly during street waste collection and transportation

activities. PM emissions were also increased by using conventional trash management techniques, including hand sorting. The sample data revealed significant deposition rates of fine (PM_{2.5}) and ultrafine (< 0.25 µm) particles. This causes critical concern because of their intense lung penetration, causing potential health risks due to continuous exposure and concentration levels.

The ICP-MS analysis identified several elements, including lead and nickel exceeding the permissible exposure limits, and mercury present at the trace level, while FTIR and SEM confirmed the presence of reactive organic compounds and the inhalable fibrous structure of the particles being present in the waste. The SEM study specifically identified that the waste composition may be heterogeneous, with several sorts of particles contributing to the total waste mixture, as suggested by the two different particle sizes, PA1 and PA2. These variations in particle sizes might result from different waste material sources, production methods, or phases of decomposition.

The health symptoms reported by workers across the four waste-handling activities are consistent with the identified elemental exposure patterns. Workers in residential waste collection and street waste collection, who frequently reported sneezing, eye irritation, skin allergies, and cuts, operate in environments where trace-level metals such as Cr, Mn, Fe, Cu, and Zn were consistently detected. These metals are known to aggravate mucosal irritation and dermal sensitivity, particularly when combined with coarse particulate dust generated during sweeping and manual waste collection. In street waste collection, additional complaints such as bacterial skin infection, hypertension, and neurological pain align with elevated levels of Pb and the complex mix of organic–inorganic residues characteristic of street litter and mixed municipal debris. Workers in the transportation activity, who reported respiratory issues, wheezing, and inflammation, were exposed to elevated concentrations of Ni and trace metals associated with vehicular emissions and mechanical abrasion.

These elements are linked to airway irritation and inflammatory responses, supporting the respiratory symptoms observed. Similarly, dump yard workers reported cracked skin, inflammation, allergies, and asthma, symptoms that reflect continuous contact with mixed waste and inhalation of metal-rich particulates, including elevated levels of Pb, Ni, and Hg as well as prolonged exposure to abrasive particulates and bioaerosols from decomposing waste at landfill sites [27, 28]. The correlation between reported symptoms and estimated pollutant levels indicates that persistent exposure to different-size segregated particulate matter pollutants, either at elevated or even at trace levels, is found to significantly affect the health of all the waste handling workers.

The MPPD dosimetry model is used to assess the risk of waste management personnel's exposure to PM and bioaerosols. The model output further confirmed the high deposition fractions in the alveolar and tracheobronchial regions, stressing the internal exposure problems faced by workers. It reveals that inhaled particles can deposit in the respiratory system, potentially leading to respiratory or neurological issues. In residential

waste collection and dump yards, particles like dust, pollen, and mold spores can cause respiratory problems.

Therefore, this study serves as a warning that immediate action is required to control the occupational-related PM exposures for frontline waste handling workers. There are ongoing and preventable health risks associated with manual handling without filtration, ventilation, or any mechanical assistance. This study aids in the creation of evidence-based plans for exposure mitigation, occupational safety measures, and pollution source control. To reduce exposure levels and safeguard employees' health, employers should set policies to mechanize waste handling processes, maintain proper ventilation systems in vehicles and enclosed transport of wastes, ensure the use of personal protective equipment (PPE) like N95, P100 masks, gloves and shoes for those who handle metal scrap, e-waste, mixed residual waste, adapt dust suppression practices, worker rotation and establish routine health monitoring (lung function testing, neurological screening, blood metal levels) for waste handling workers who are at higher risk for exposure to the pollutants and comprehensive training programs on safe waste-handling practices. To conclude, this study highlights a critical need for strengthening the exposure control levels and systematic occupational safeguard action to be planned to protect the health and well-being of waste-handling workers.

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