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Preliminary study of air emission in Sarimukti open dumpsite, Indonesia

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ABSTRACT

Open dumpsites have been identified as significant sources of air emissions. This study analyzed the spatial and temporal variations of multicomponents in the Sarimukti dumpsite, Indonesia, and the health profiles of landfill workers. The analysis revealed that benzene, $PM_{2.5}$, and NH_3 levels exceeded the permissible threshold, with average value of 0.41 ppm, 103.2 μg/m^3, and 1.26 ppm, respectively. H_2S concentrations showed strong negative correlation with temperature (ρ = -0.77), wind speed (ρ = -0.55), pressure (ρ = -0.62), and a positive correlation with humidity (ρ = 0.72). The absence of daily soil cover and vehicle activity at the dumpsite contributed to the ambient air quality issues at the Sarimukti dumpsite. Further studies are necessary to assess the long-term health risks to dumpsite workers.

Keywords: air emissions, ambient air, open dumpsite, worker health.

INTRODUCTION

Mixed waste disposed of at the dumpsite undergoes degradation through various physico-chemical processes in the waste pile (Chugh et al., 1999). Landfill gas (LFG) emissions are by-products of this degradation process (Erdogdu, 2025). LFG compounds can be formed even before waste is piled up in landfills, and their composition varies depending on the period of degradation (Frank et al., 2016). Landfill waste piles typically consist of 45–60% CH_4, 40–90% CO_2, 2–5% nitrogen, 0.1–1% oxygen, 0.1–1% ammonia, 0.01–0.6% non-methane organic compounds (NMOCs), 0–1% sulfides, 0–0.2% hydrogen, and 0–0.2% carbon monoxide (Manheim et al., 2021).

Once formed, LFG is transported to ambient air through several processes, such as diffusion, advection, dilution, volatilization, adsorption, conversion, and degradation. The transport process is influenced by the physical and chemical characteristics of the compound, the cover soil, landfill design, and meteorological conditions (Yilmaz et al., 2021). In landfills, these processes occur when waste is transported, unloaded, and stacked (Duan et al., 2021).

Air emissions from landfills can adversely affect human health and the environment (Ghobakhloo et al., 2023; Opara et al., 2021; Palmiotto et al., 2014; Siddiqua et al., 2022; Tian et al., 2013; Yu et al., 2018). Improperly managed landfills exacerbate these issues by forming more pollutants that subsequently disperse into ambient air (Chukwuemeka et al., 2021; Shoddo, 2024). Landfill workers face a higher prevalence of respiratory disease symptoms, respiratory tract inflammation, decreased lung function, and other health issues (Ray et al., 2005). Additionally, odor nuisances can affect residents living within a 3 (three) km radius of the landfill. Studies have shown that increased odors are associated with heightened disease symptoms reported by people living near landfill sites (Zhang et al., 2021; Hoang et al., 2022). Children in these areas may experience health problems such as immune deficiency and reduced lung function (Yu et al., 2017).

Monitoring LFG emission concentrations is essential for determining its composition. Previous studies have assessed the impact of LFG exposure on landfill workers' welfare and evaluated their history of disease symptoms (Olu and Iyere, 2020; Wang et al., 2021; Zhang et al., 2021). A foundation for controlling LFG exposure among local workers and the surrounding communities was also established. Zhang et al. (2021) monitored LFG emissions on waste pile surfaces using a wind tunnel system (Li et al., 2023). Other methods involve identifying LFG compound concentrations in the ambient air using active or passive samplers placed approximately 1.5–2 m above the ground or waste pile. These monitoring activities were conducted at multiple points across the landfill during a specific period, providing insights into the spatial variations in air emission concentrations (Ighodaro et al., 2020; Uche, 2021). Previous studies revealed the variation of trace gas levels in different monitoring times, and landfill zones (Duan et al., 2021; Slominska et al., 2014; Lakhouit et al., 2016; Lakhouit and Al Rashed, 2022). Spatial data analysis, such as spatial interpolation and dispersion modelling was performed using landfill gas emission concentrations based on monitoring results. However, the study did not model the time variation in a day for the pollution spatial distribution (Daramola and Makinde, 2024).

This study builds on multiple components by monitoring additional compounds in tracing ambient air quality in landfills, many of which align with WHO recommendations for ambient air quality (World Health Organization, 2021). The monitored parameter included SO_2, NO_2, CO, CO_2, $PM_{2.5}$, Pb, H_2S, NH_3, and BTEX (Benzene, Toluene, Ethylbenzene, and Xylene). This approach addresses the gaps in previous studies for a comprehensive ambient air quality monitoring in dumpsite and an identification on landfill workers' health symptoms simultaneously. Therefore, the objectives of this study were to identify priority pollutants at Sarimukti dumpsite and compare them with landfills in other locations. Correlation analysis was conducted to assess the effects of meteorological factors on pollutant concentrations. Considering the risk of diseases caused by exposure to landfill air emissions, this study examined the demographic conditions and health symptoms of landfill workers.

METHODOLOGY

Study area

The Sarimukti dumpsite is located in Cipatat District, West Bandung Regency, covering a total area of 43.44 ha, with 16.5 ha currently in use. By 2023, the landfill area received 1.816 tons/day of waste with composting facilities received 4 tons/day, and the total waste recovered by illegal workers accounted for 10 tons/day. The dumpsite area is divided into three main zones, as shown in Figure 1. The active zone includes Zone A (4.00 ha) and Zone D (3.75 ha), which currently receive waste from Bandung City, Cimahi City, Bandung Regency, and West Bandung Regency. These zones are the main operational areas for daily waste disposal and also the main areas where scavengers collect valuable materials. While, the inactive zone in Zone C (3.75 ha), is no longer receiving waste. The waste piles in this zone have been compacted and covered with

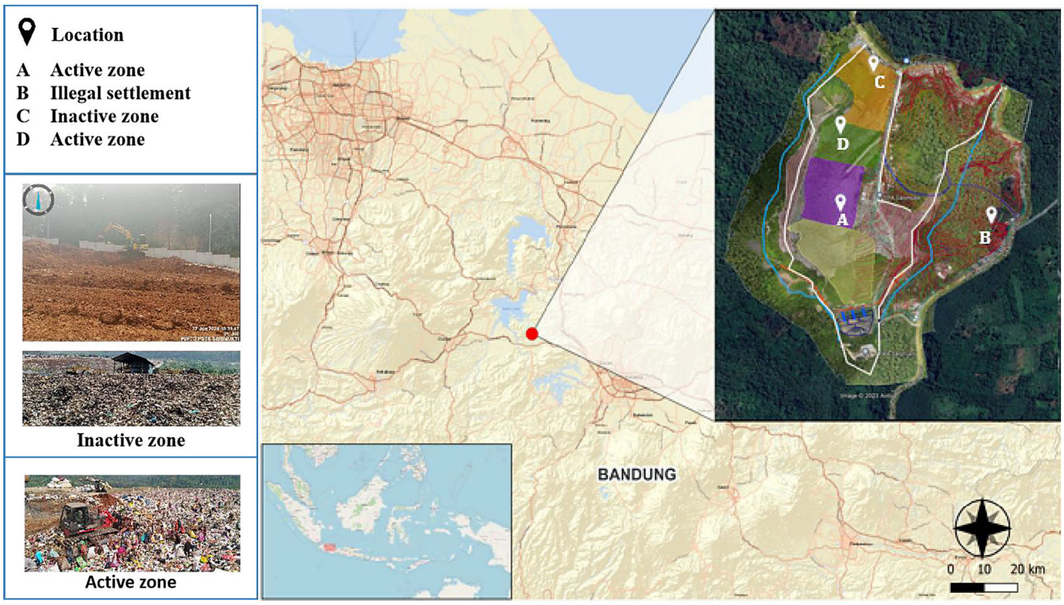

Figure 1. Study area in Sarimukti Open Dumpsite: Zone A (active zone), Point B (illegal settlement), Zone C (inactive zone) and Zone D (active zone) (modified from UPTD PSTR Sarimukti (2024))

a 30 cm layer of topsoil for every 5 meters of pile height to minimize environmental impact. The illegal settlement area, labeled as point B, is located less than 500 meters from Zone A and along the roadside leading to the dumpsite. This area is inhabited by scavengers who regularly access the active zone for informal waste collection activities. The dumpsite is also supported by essential infrastructure, including a wastewater treatment plant, composting area, heavy equipment area, office building, internal roads and embankments, which operated by UPTD PSTR Sarimukti (UPTD PSTR Sarimukti, 2024).

Sampling method

BTEX, SO_2, NO_2, NH_3, and H_2S were monitored during the dry season (July 31–August 1, 2024) due to higher emissions at elevated temperatures (Lim et al., 2018). To capture diurnal variation (Liu et al., 2022), these gases were sampled in three daily sessions, which were morning (04:00–07:00), afternoon (12:00–15:00), and evening (18:00–21:00). CO and CO_2 were measured once daily at 04:00 for 15 minutes, while Pb and $PM_{2.5}$ were collected continuously over 24 hours (04:00–03:59 the next day) to obtain average concentrations for comparison with national standards. Monitoring was conducted at four locations (A–D; Figure 1), representing different site conditions: active zones (A, D), roadside access (B), and inactive zone (C) (Yousefian et al., 2020). These points also coincide with worker activity areas, indicating potential exposure. Points A and B were monitored on July 31, 2024, while points C and D were monitored the following day. Meteorological parameters (temperature, humidity, wind velocity, and atmospheric pressure) were recorded during sampling. BTEX, SO_2, Pb, $PM_{2.5}$, NH_3, and H_2S samples were analyzed on August 5–8, 2024, while NO_2, CO, and CO_2 were measured on-site using portable analyzers.

BTEX in ambient air was sampled following NIOSH 1501-2003 using whole-air sorbent trapping with a vacuum pump (0.5 LPM) and charcoal tubes which analysed by GC-FID. SO_2, NO_2, CO, CO_2, Pb, and $PM_{2.5}$ were monitored according to Indonesian National Standards (SNI): SNI 7119.7:2017 (SO_2), SNI 7119.2:2017 (NO_2), SNI 7119.10:2011 (CO and CO_2), SNI 7119-4:2017 (Pb), and SNI 7119.14:2016 ($PM_{2.5}$). SO_2 was collected with an impinger (0.5 LPM, 1 hour) using the pararosaniline method and analyzed using spectrophotometer (550 nm). NO_2 was absorbed in 10 ml Griess-Saltzman solution (0.4 LPM, 1 hour) and analyzed using spectrophotometer. CO and CO_2 were measured on-site with an NDIR sensor (15 min). Pb and $PM_{2.5}$ were collected with a high-volume air sampler (1.1–1.7 m^3/min, 24 hours) using TSP and $PM_{2.5}$ filters; Pb was extracted by acid digestion and analyzed by flame AAS, while $PM_{2.5}$ was determined gravimetrically (15–25 °C). H_2S was sampled with cadmium hydroxide absorbent and analyzed by the Methylene Blue method. NH_3 was measured (SNI 19.7119.1–2005) by passing air (1 LPM, 1 hour) through H_2SO_4, then analyzed using colorimeter with indophenol reaction.

Data were collected from workers at the dumpsite using a questionnaire administered by the researcher. The questionnaire gathered demographic data, health conditions, and medical history (Adetona et al., 2016; Njoku et al., 2019). It was adapted from the PhenX Toolkit Protocol ID 090901: Personal and Family History of Respiratory Symptoms and Diseases for adult subjects. The questionnaire was printed in Indonesian and delivered to respondents in the same language. Based on the NIOSH Occupational Exposure Sampling Strategy Manual standard, a minimum of 30 participants were required (Ashley, 2016). A total of 47 respondents, including landfill workers and scavengers, participated in the survey. Questionnaire data collection was conducted on July 31, 2024, during the ambient air monitoring campaign.

Data analysis

The concentrations of BTEX, SO_2, NO_2, CO, CO_2, $PM_{2.5}$, Pb, H_2S, and NH_3 were evaluated against their respective thresholds and compared for different zones and sampling periods. Spearman's correlation test was conducted to assess the influence of meteorological conditions (temperature, humidity, wind velocity, and atmospheric pressure) on each compound. Spatial models were used to create concentration distribution maps for pollutants exceeding the thresholds at the dumpsite based on monitoring data. Data reported by landfill workers and scavengers were analyzed using descriptive statistical methods to identify their demographic characteristics, health conditions, and medical histories.

Descriptive analysis involved comparing the concentration of each monitored pollutant with its respective threshold. The thresholds for SO_2, NO_2, CO, Pb, and $PM_{2.5}$ were based on Government Regulation No. 22 of 2021 concerning the Implementation of Environmental Protection and Management (Appendix VII). For H_2S and NH_3, the thresholds were based on the Decree of the Indonesian Minister of Environment No. 50 of 1996 concerning Odor Level Standards. The reference thresholds for BTEX were based on the guidelines of the American Conference of Governmental Industrial Hygienists (ACGIH). Pollutants that exceeded their thresholds were further analyzed using spatial modelling.

Spatial distribution analysis of pollutant concentrations was performed in ArcGIS v.10.8 software. Sample point data containing coordinates and pollutant concentration values were obtained from sampling locations in the study area. The analysis involved interpolating the sample point data to generate spatial distribution maps using the inverse distance weighting (IDW) method (Abbasi et al., 2020; Miri et al., 2016; Dehghani et al., 2018). This method relies on positional differences to interpolate spatial variations in pollutant concentrations, excluding the effects of pollutant transportation and transformation mechanisms. The interpolation results were visualized using a color ramp to represent the concentration variations. These maps illustrate the spread patterns of pollutants and identify areas with high and low pollutant concentrations.

The correlation between pollutant concentrations and meteorological conditions was assessed using Spearman's Correlation Test with a significance level of 0.05 (Bose and Chowdhury, 2023). Temperature, humidity, wind speed, and atmospheric pressure parameters were obtained from the monitoring observations. Before the analysis in R using the "Hmisc" package, all observed data were converted to an ordinal format. Concentrations below the limit of detection (LoD) were replaced with LoD values. A correlation test was not conducted for CO, CO_2, Pb, and $PM_{2.5}$, owing to insufficient observational data.

Data reported by workers at the dumpsite were descriptively analyzed. Mean and standard deviation were calculated for height and weight parameters. Other parameters, such as demographic conditions and disease complaints, were analyzed by calculating the frequency and percentage of each response to the questionnaire. This study did not asses pollutant concentration data to health effects.

RESULTS AND DISCUSSION

Profile of ambient air pollution in Sarimukti dumpsite

Average ambient CO_2 and CO concentrations at the Sarimukti dumpsite were

1,448,678 ± 83,767 μg/m³ and 916 ± 835 μg/m³, respectively. BTEX concentrations, decreased in order, were xylene (1.74 ± 1.50 ppm), toluene (0.85 ± 0.76 ppm), benzene (0.41 ± 0.41 ppm), and ethylbenzene (0.01 ± 0.01 ppm). Average ammonia level (1.258 ± 0.425 ppm) was higher than H_2S (0.009 ± 0.003 ppm). Pb concentrations were below LoD at all sites. BTEX, H_2S, and NH_3 concentrations were lowest at Point B (afternoon) and peaked at Point D (morning). SO_2 ranged from 26.2 μg/m³ (Point C, morning) to 43.4 μg/m³ (Point A, afternoon), while NO_2 ranged from 28.6 μg/m³ (Point C, night) to 55.7 μg/m³ (Point A, afternoon). $PM_{2.5}$ concentrations were highest at Point B (117 μg/m³) and lowest at Point C (86.1 μg/m³). Benzene exceeded the threshold at Point C (morning and evening) and Point D (all sessions), ranging from 0.64 to 1.02 ppm. Toluene and xylene remained below their thresholds, with a peak of 2.21 ppm, and 4.84 ppm respectively at Point D (morning). H_2S stayed within its threshold, while NH_3 exceeded its threshold at Point D (2.03 ppm, morning). $PM_{2.5}$ exceeded the standard at all sites. Ambient air monitoring results and the meteorological conditions during sampling are provided in Table 1 and Table 2 respectively. The pollutants exceeded the thresholds are illustrated in Figure 2.

Xylene was the dominant BTEX compound at the dumpsite, consistent with findings by Yousefian et al. (2020) and Zhang et al. (2021). According to Dehghani et al. (2018), the benzene-to-toluene (B:T) ratio can help identify emission sources, with B:T > 0.5 suggesting non-traffic sources, while B:T ≤ 0.5 indicates dominance of vehicle emissions. Heavy-duty vehicles such as dump trucks, excavators, and compactors that operate intensively in active zones are contributing to BTEX emissions (Duan et al., 2014). In this study, B:T ratios ranged from 0.00–0.13 (Point A), 1.0–3.0 (Point B), 0.81–1.00 (Point C), and 0.46–0.50 (Point D). The low B:T ratios at Points A and D indicate BTEX emissions mainly from vehicles during waste unloading and compaction, while higher ratios at Points B and C suggest BTEX emissions were from waste decomposition and volatilization of organics (Wang et al., 2021). Observations during the monitoring campaign, confirmed intense vehicle activities around Points A and D, such as dump trucks, excavators and compactors located in active zones.

BTEX, H_2S, and NH_3 peaked at th active zone (Point D, morning) with concentrations of 1.02 ppm, 2.21 ppm, 4.84 ppm, 0.015 ppm, and 2.03 ppm, respectively, aligned with Fang et al. (2022), who reported high odorous emissions in areas with fresh waste. The peaks occurred in the morning session, when temperatures and wind speeds were consistently the lowest during monitoring, which favored pollutant accumulation (Ghosh et al., 2023; Liu et al., 2022). This finding is in accordance with Slominska et al. (2014), but contrasting with Duan et al. (2014), who found peaks at higher temperatures.

Although Point A and Point D were located in the active zone, the average benzene concentration at Point A exhibited a lower level compared to Point C (inactive zone). This finding is opposite to studies that suggested fresh waste areas and uncovered waste surfaces were the significant trace

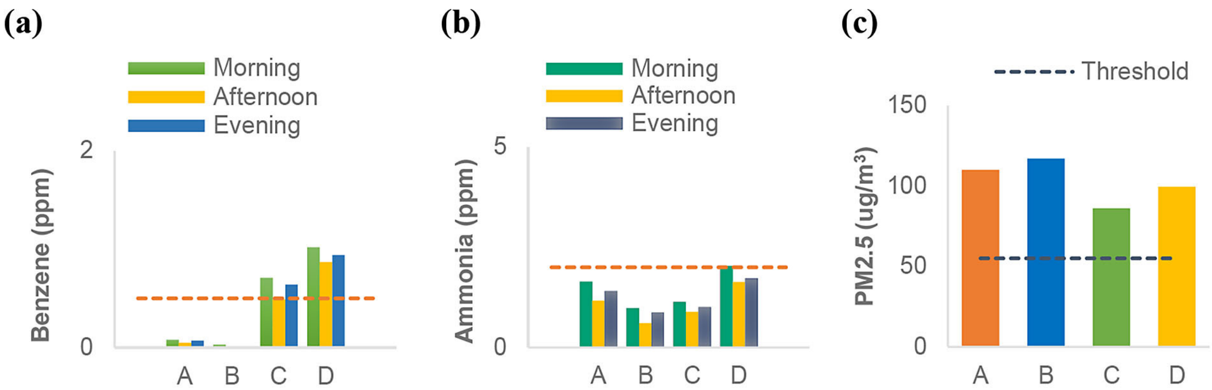

Figure 2. Pollutants exceeding the ambient air quality standards. (a) Benzene, with the threshold of 0.5 ppm (1600 μg/m³) according to ACGIH, (b) NH_3 with the ambient standard of 2 ppm (1390 μg/m³) according to the Decree of the Minister of Environment of Indonesia No. 50 of 1996, and (c) $PM_{2.5}$ with an ambient standard of 55 ug/m³ according to Attachment VII of Government of Indonesia Regulation No. 22 of 2021

Table 1. Ambient air monitoring

Point	Session	Benzene (ppm)	Toluene (ppm)	Ethylbenzene (ppm)	Xylene (ppm)	SO_2 (µg/m³)	NO_2 (µg/m³)	H_2S (ppm)	NH_3 (ppm)	CO (µg/m³)	CO_2 (µg/m3)	Pb (µg/m³)	PM2.5 (µg/m³)
A	1	0.08	0.59	<0.01	2.43	33.8	51.6	0.012	1.64				
A	2	0.05	0.77	<0.01	1.89	43.4	55.7	0.007	1.17	172	1421684	<0.001	110
A	3	0.07	0.71	<0.01	1.44	31.2	35.4	0.008	1.41				
B	1	0.03	<0.01	<0.01	0.59	34.2	39.5	0.008	0.98				
B	2	<0.01	<0.01	<0.01	<0.004	33.6	43.9	0.004	0.61	1489	1475672	<0.001	117
B	3	<0.01	<0.01	<0.01	<0.004	30.5	32.2	0.005	0.87				
C	1	0.71	0.88	<0.01	1.22	26.2	40.8	0.011	1.13				
C	2	0.49	0.49	<0.01	0.83	28.3	41.1	0.008	0.89	1775	1547656	<0.001	86.1
C	3	0.64	0.72	<0.01	0.9	26.8	28.6	0.01	1.01				
D	1	1.02	2.21	<0.01	4.84	28.1	38	0.015	2.03				
D	2	0.87	1.74	<0.01	2.92	32.3	44.2	0.008	1.63	229	1349700	<0.001	99.5
D	3	0.94	2.03	0.06	3.77	30.2	34.9	0.01	1.72				
Min		0.03	0.49	0.06	0.59	26.2	28.6	0.004	0.61	172	1349700	0	86.1
Max		1.02	2.21	0.06	4.84	43.4	55.7	0.015	2.03	1775	1547656	0	117
MEAN		0.41	0.85	0.01	1.74	31.5	40.5	0.009	1.258	916	1448678	0.001	103.2
SD		0.408	0.762	0.014	1.503	4.61	7.72	0.003	0.425	835	83766.8	0	13.45
Threshold Limit Value - Time Weighted Average (ACGIH)		0.5	20	20	100	-	-	-	-	-	-	-	-
Indonesia National Ambient Standard		-	-	-	-	150	200	0.02	2	10000		2	55

gas emission sources, and that soil cover was effective for reducing trace gas concentrations (Duan et al., 2021; Lakhouit and Al Rashed, 2022). The cause of the inconsistencies exhibited by this study was not identified. Except, it implied the effect of confounding factors, such as meteorological conditions, activities, and waste characteristics, on landfill gas emission profile variations.

Spatial distribution modelling

Spatial distribution modeling was conducted for parameters exceeding the reference thresholds, namely benzene, ammonia, and $PM_{2.5}$. These models can serve as a basis for predicting the potential distribution of pollutants and identifying areas where landfill workers are at risk of exposure. The modeling method used was IDW, which considers only the distance between the emission source at the sampling point and the surrounding area to model the pollutant concentration distribution. This approach does not account for other factors that influence spatial variations in pollutant concentrations, such as waste composition, landfill operations, meteorological conditions, and other relevant variables (Ko et al., 2015).

The spatial distribution of benzene in ambient air showed moderate concentrations (0.64–0.80 ppm) in the northern part of the dumpsite, as depicted in Figure 3. Ammonia concentrations ranged from moderate (1.63–1.83 ppm) to high (1.83–2.03 ppm) in the dumpsite area's eastern part, with the highest concentrations observed in the morning (Figure 4). In contrast, $PM_{2.5}$ exhibited a high concentration distribution (111.18–116.99 µg/m³) around sampling Point B, in the southeastern part of the dumpsite (Figure 5). These maps give an initial prediction for the distribution of landfill gas emissions as a source of hazards (Siddiqua et al., 2021). It can be considered to guide further validation studies and to develop the distribution map for risks caused by landfill gas emissions across the dumpsite area.

This result shows the potential risk of air pollution exposure to landfill workers, specifically from benzene, ammonia, and $PM_{2.5}$. Benzene is a carcinogenic compound categorized in group I by IARC (International Agency for Research on Cancer). The long-term effects of benzene exposure can potentially cause bone marrow damage and induce genetic damage, leukemia, and lymphatic diseases (Ji et al., 2020). Although ammonia is

Table 2. Meteorological conditions during ambient air monitoring

Point	Session	Benzene (ppm)	Toluene (ppm)	Ethylbenzene (ppm)	Xylene (ppm)	SO_2 (μg/m³)	NO_2 (μg/m³)	H_2S (ppm)	NH_3 (ppm)	CO (μg/m³)	CO_2 (μg/m3)	Pb (μg/m³)	PM2.5 (μg/m³)
A	1	0.08	0.59	<0.01	2.43	33.8	51.6	0.012	1.64				
A	2	0.05	0.77	<0.01	1.89	43.4	55.7	0.007	1.17	172	1421684	<0.001	110
A	3	0.07	0.71	<0.01	1.44	31.2	35.4	0.008	1.41				
B	1	0.03	<0.01	<0.01	0.59	34.2	39.5	0.008	0.98				
B	2	<0.01	<0.01	<0.01	<0.004	33.6	43.9	0.004	0.61	1489	1475672	<0.001	117
B	3	<0.01	<0.01	<0.01	<0.004	30.5	32.2	0.005	0.87				
C	1	0.71	0.88	<0.01	1.22	26.2	40.8	0.011	1.13				
C	2	0.49	0.49	<0.01	0.83	28.3	41.1	0.008	0.89	1775	1547656	<0.001	86.1
C	3	0.64	0.72	<0.01	0.9	26.8	28.6	0.01	1.01				
D	1	1.02	2.21	<0.01	4.84	28.1	38	0.015	2.03				
D	2	0.87	1.74	<0.01	2.92	32.3	44.2	0.008	1.63	229	1349700	<0.001	99.5
D	3	0.94	2.03	0.06	3.77	30.2	34.9	0.01	1.72				
Min		0.03	0.49	0.06	0.59	26.2	28.6	0.004	0.61	172	1349700	0	86.1
Max		1.02	2.21	0.06	4.84	43.4	55.7	0.015	2.03	1775	1547656	0	117
MEAN		0.41	0.85	0.01	1.74	31.5	40.5	0.009	1.258	916	1448678	0.001	103.2
SD		0.408	0.762	0.014	1.503	4.61	7.72	0.003	0.425	835	83766.8	0	13.45
Threshold Limit Value - Time Weighted Average (ACGIH)		0.5	20	20	100	-	-	-	-	-	-	-	-
Indonesia National Ambient Standard		-	-	-	-	150	200	0.02	2	10000		2	55

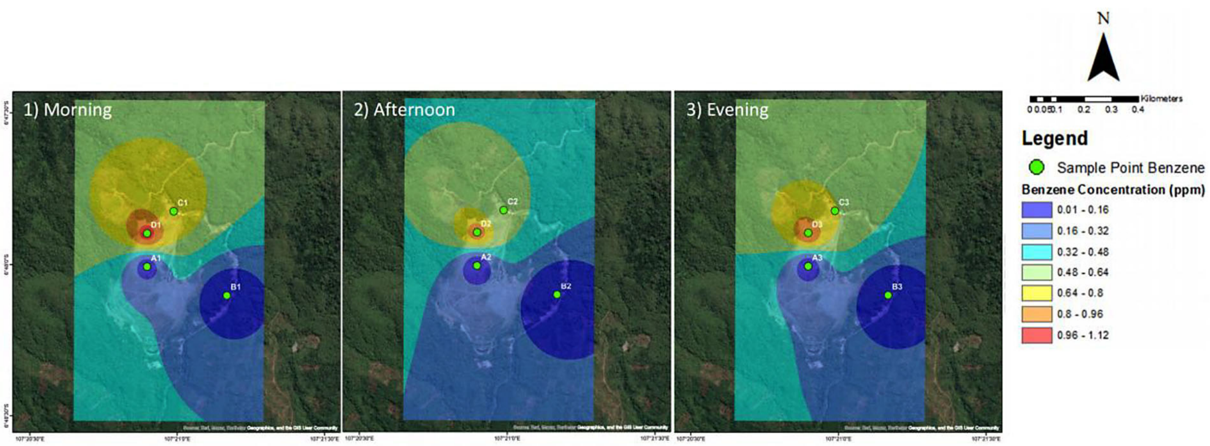

Figure 3. Interpolated Benzene concentrations at Sarimukti Dumpsite at various times of the day. (1) Morning concentration, (2) Afternoon concentration, and (3) Nighttime concentration. Shading represents different levels of benzene concentration (ppm), with contours indicating the concentration gradients. Green circles indicate the sampling points used for interpolation

not a major component causing odor nuisance in landfills, it is likely to travel to the surrounding area (ATSDR, 2001). Low-level ammonia exposure, with concentrations as little as 0.16 mg/m3, was found to be associated with subtle, sub-clinical, and pre-pathologic changes in kidney function (Neghab et al., 2019). $PM_{2.5}$ exposures in a dumpsite with concentrations ranging from 87.5 to 1080 μg/m³ potentially affected the health of workers, such as coughs and headaches (Abidin et al., 2023). It was also found that $PM_{2.5,}$ with an average annual concentration of 122.30–501.76 μg/m³ can pose acute and chronic health effects for infants and children (Opara et al., 2021).

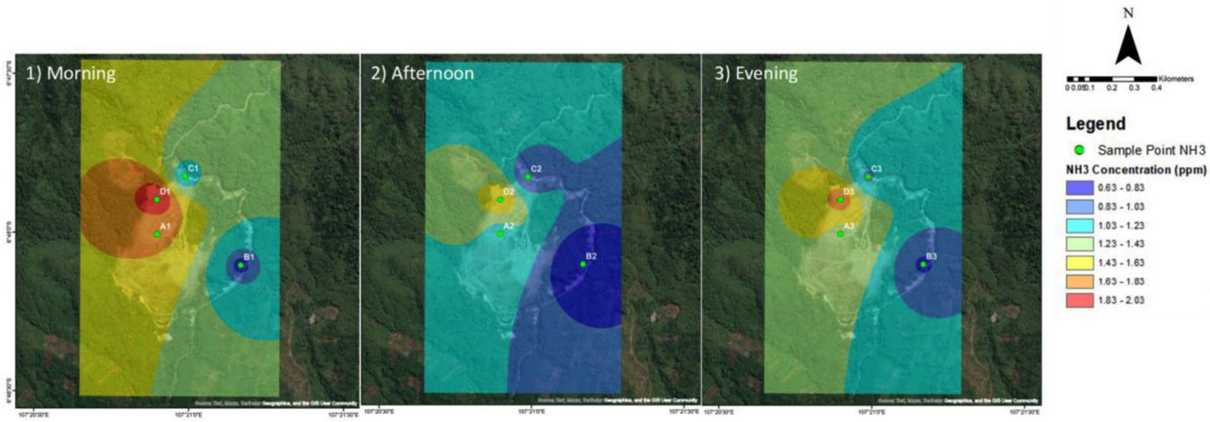

Figure 4. Interpolated NH_3 concentrations at Sarimukti Dumpsite at different times of the day. (1) Morning Concentration, (2) Afternoon Concentration, and (3) Night Concentration. The shading indicates different NH_3 concentrations (ppm), with contours indicating the concentration. Green circles indicate the sample points used for interpolation

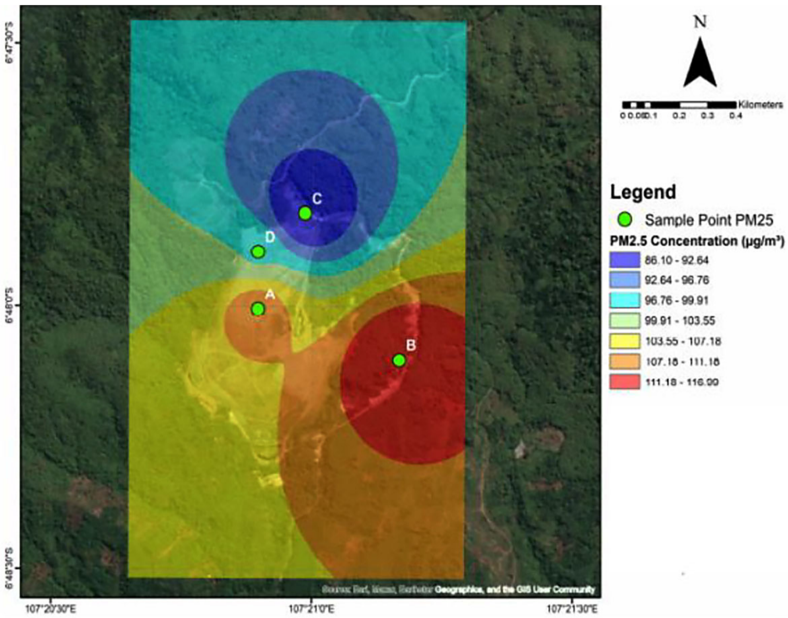

Figure 5. Interpolated $PM_{2.5}$ concentrations at Sarimukti Dumpsite for 24-hour concentration

Correlation between pollutants and meteorological parameters

The correlation between the pollutants and meteorological parameters was analyzed using the Spearman correlation test, as shown in Figure 6. The result revealed that the BTX concentrations had a strong positive relationship with each other. A strong positive correlation was also exhibited between BTX and major odorous compounds, namely H_2S and NH_3. It contradicts the evidence of low correlation between complex odor and VOCs (volatile organic compounds) in open dumpsites (Lim et al., 2018).

Among the gas emissions at the dumpsite, benzene had a strong inverse relationship with atmospheric pressure (-0.75, $p = 0.005$). This differs from that of Khademi et al. (2022), who revealed that BTEX emissions show a positive correlation with wind speed and a negative correlation with temperature. Ethylbenzene generally revealed the weakest relationship with all meteorological parameters, with correlation coefficients of -0.13, 0.13, -0.13, and -0.09 for temperature, humidity, wind velocity, and atmospheric pressure, respectively.

H_2S showed a strong relationship with all meteorological parameters. The correlation

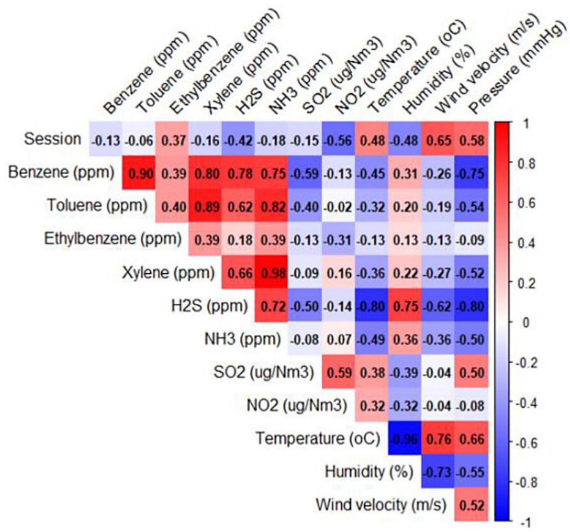

Figure 6. Spearman correlation coefficient (ρ) for gaseous pollutants and meteorological parameters

coefficients of H_2S with temperature, humidity, wind speed, and atmospheric pressure were -0.80, 0.75, -0.62, and -0.80, respectively, with p-values less than 0.05. The high solubility of H_2S in water explains its elevated concentration in the morning (Ko et al., 2015). At all four monitoring points, the average relative humidity in the morning was the highest (79.9 ± 3.66%) compared with the other times of the day. During the same period, the average wind speed (1.000 ± 0.1225 m/s) and average temperature (22.0 ± 0.93 °C) were the lowest among other monitoring sessions. Under high relative humidity, H_2S is predominantly present in water vapor in the air. Low wind speeds prevent the dispersion of H_2S, causing it to remain concentrated in the dumpsite area. Additionally, lower temperatures indicate reduced solar radiation, which inhibits the transformation of H_2S into ozone or SO_2 (Duan et al., 2014).

Consistent with the study of Bose and Chowdhury (2023) in India, NO_2 in this study did not show a strong relationship with meteorological conditions. Meanwhile, Raza et al. (2021) showed that PM levels increase with an increase in temperature during the dry season in Pakistan, whereas this study revealed that $PM_{2.5}$ had no significant relationship with any meteorological parameter.

Comparison with other studies

A comparison of meteorological conditions and landfill gas concentrations during sampling from various locations is presented in Tables 3 and 4, respectively. The meteorological conditions during sampling in this study were similar to those of other dumpsites in developing countries. Therefore, another factor, such as sampling locations, was expected to cause the difference in BTEX concentrations. Yousefian et al. (2020) observed higher concentrations of BTEX compared to this study because of different sampling locations, in which this study did not include waste separation and recycling facilities. Sampling methods, and the operational activities during sampling can also contribute to the variation of pollutant concentration among these studies. Landfills in China, South Korea, and Iran were all equipped with landfill gas collection systems, but the landfill in South Korea had the lowest average concentrations of toluene and xylene. Duan et al. (2014) explained that the source of BTEX emissions in landfill in China due to vehicle activity, as in the current study. Hence, BTEX concentrations in landfills in China and this study are higher than in South Korea.

BTEX and H_2S concentrations in this study were lower than those reported in dumpsites in other developing countries. Kenya recorded the highest levels of BTEX and H_2S concentrations among other developing countries alongside the highest temperatures (Chikezie et al., 2019), which supports the evidence of temperature effect on H_2S emissions in landfill (Ko et al., 2015). In contrast, NH_3 concentrations in this study were relatively high compared to other studies. Waste characteristics, and local meteorology are the major driver for NH_3 emissions in landfills (Yi et al., 2021). In a South Korean landfill, the waste was dominated by industrial and construction, resulting in low NH_3 (Lim et al., 2018). The nitrogen-rich food waste without daily soil cover that was observed from this study caused higher NH_3 emissions (Fang et al., 2012; Ko et al., 2015). High humidity and low wind speeds further contributed to NH_3 accumulation (Yousefian et al., 2020).

SO_2 and NO_2 concentrations in this study were relatively high, comparable to the Nigerian site, which was caused by biomass burning and vehicle emissions (Daramola and Makinde, 2024; WHO, 2021). $PM_{2.5}$ levels in this study were similar to those in Nigeria; Yogyakarta, Indonesia; and Pakistan, with sources including heavy vehicle activities and unpaved roads (Abidin et al., 2023).

In conclusion, the differences in pollutant levels across studies reflect variations in waste

Table 3. Meteorological conditions recorded during sampling

Reference	Landfill	Temperature (°C)	Relative humidity (%)	Atmospheric pressure (mmHg)	Wind speed (m/s)
This research	Dumpsite, Indonesia	21.1–31.2	25–83	725.1–729.7	0.05–2.05
Uche (2021)	Dumpsite, Nigeria	30.84–34.05	53.57–58.7	NA	3.2–5
Yousefian et al. (2020)	Landfill. Iran	NA	NA	NA	NA
Khademi et al. (2022)	Landfill, Iran	16.5	30.3	899.2	2.05
Chikezie et al. (2019)	Dumpsite, Nigeria	32.05–37.65	57.80–64.00	NA	0.6–2.25
Mwaura et al. (2021)	Dumpsite, Kenya	NA	NA	NA	NA
Duan et al. (2014)*	Landfill, China	30.6 ± 6.4	62.4± 17.8	NA	1.49 ± 0.61
Hoang et al. (2022)	Landfill, Vietnam	18–30	77–88	NA	NA
Opara et al. (2021)	Dumpsite, Nigeria	28–29	>94.5	NA	1–1.9
Okuo and Ighodaro (2019)	Dumpsite, Nigeria	26 - 30.4 (28.5)	NA	NA	NA
Ghobakhloo et al. (2024)	Waste recycling, Iran	NA	NA	NA	NA
Raza et al. (2021)	Dumpsite, Pakistan	30–38	33–50	NA	0.56–2.4
Abidin et al. (2023)	Dumpsite, Indonesia	31.1–33.2	54.5–66.3	744.3–745.6	1.7–2.6
Daramola and Makinde (2024)	Dumpsite, Nigeria	32.9–47.1	NA	NA	NA
Lim et al. (2018)*	Landfill, South Korea	25–29	NA	763	<0.5
Durmusoglu et al. (2010)	Landfill, Turkey	13–28	NA	NA	NA

Note: *only for monitoring during summer season

composition, meteorological conditions, and operational activities. Higher plastic content and vehicle activity increase BTEX, SO_2, NO_2, and $PM_{2.5}$. The level of odorous gases like H_2S and NH_3 depend on waste type, soil cover, and meteorological conditions. Waste containing high sulfur and nitrogen, along with high temperature, will emit higher H_2S and NH_3 concentrations. The presence of soil cover will reduce H_2S and NH_3 emissions. However, high humidity and low wind speed will cause accumulation of H_2S and NH_3 in ambient air, resulting in higher concentrations.

Characteristics of landfill workers

A total of 48 respondents participated in the questionnaire administered by the researchers. Only the data from 47 respondents were analyzed, as one respondent did not complete more than 50% of the questions. Selected answers to the questionnaire, which consisted of 176 questions, were used in this study. Table 5 summarizes the general characteristics of the respondents, including the landfill officers and scavengers.

All respondents were male, with 11 individuals (23.4%) categorized as informal workers or scavengers and 36 individuals (76.6%) as landfill officers. Workers' ages were evenly distributed across the 20–30, 31–40, and 41–50-year age ranges, with the oldest respondent being a 50-year-old landfill officer. None of the workers had more than 20 years of experience in landfill. Most landfill officers had worked for 10–20 years, whereas most informal workers had less than 10 years of experience.

Among the respondents, 40 (85.1%) were active smokers and 26 (55.3%) smoked 10–20 cigarettes daily. Measurements of the respondents' weight and height were taken directly by the researchers, yielding averages of 60.99 ± 11.05 kg and 165.39 ± 6.43 cm, respectively. One respondent, identified as an outlier with a weight of 90 kg and height of 189 cm, was excluded from analysis. After excluding the outlier, the adjusted averages were 60.35 ± 10.28 kg and 164.93 ± 5.69 cm.

Table 4. Concentrations of landfill gas emissions in ambient air from monitoring results

References	Landfill	Benzene (ppm)	Toluene (ppm)	Ethylbenzene (ppm)	Xylene (ppm)	SO_2 (μg/m^3)	NO_2 (μg/m^3)	CO (μg/m^3)	CO_2 (μg/m^3)	Pb (μg/m^3)	PM2.5 (μg/m^3)	H_2S (ppm)	NH_3 (ppm)
This research	Dumpsite, Indonesia	0.41 ± 0.408	0.85 ± 0.762	0.01 ± 0.014	1.74 ± 1.503	31.5 ± 4.61	40.5 ± 7.72	916 ± 835	1448678 ± 83766.8	0.001	103.2 ± 13.45	0.009 ± 0.003	1.26 ± 0.425
Uche (2021)	Dumpsite, Nigeria					0.05 to 0.04	0.0015 to 0.0571	0.0125 to 0.169	9038 to 10329		0.0084 to 0.064	0.029 to 0.106	0.036 to 0.246
Yousefian et al. (2020)	Landfill, Iran	3.66	10.88	1.91	9.00								
Khademi et al. (2022)	Landfill, Iran	2.34 ± 2.60	3.43 ± 3.06	13.7 ± 10.67	2 ± 2.9								
Chikezie et al. (2019)	Dumpsite, Nigeria					1.62		1.42				1.82	2.70
Mwaura et al. (2021)	Dumpsite, Kenya							11.46 to 16.61				0.25 to 0.5	
Duan et al. (2014)*	Landfill, China	6.26 to 19.42	12.74 to 29.45	7.60 to 30.86	11.75 to 37.08								
Hoang et al. (2022)	Landfill, Vietnam											91.97 to 128.42	
Opara et.al. (2021)	Dumpsite, Nigeria										122.3 to 501.76		
Okuo & Ighodaro (2019)	Dumpsite, Nigeria	2.98 to 12.55	1.53 to 4.85	1.22 to 7.29	0.75 to 2.86								
Ghobakhloo et al. (2024)	Waste recycling, Iran									0.06 to 0.298	458 to 2745		
Raza et al. (2021)	Dumpsite, Pakistan								798.12 to 928.27		127.1 to 307.1		
Abidin et al. (2023)	Dumpsite, Indonesia										87.5 to 1080		
Daramola & Makinde (2024)	Dumpsite, Nigeria					43.82 to 109.27	237.4 to 255.84	0.52 to 0.55			94.12 to 94.29		
Lim et al. (2018)*	Landfill, South Korea		0.00864		0.00186								0.2278
Durmusoglu et al. (2010)	Landfill, Turkey	43.92	337.45	55.25	78.60								

Note: *only for monitoring during summer

Table 6 shows that most respondents reported no illnesses related to air pollution exposure. Only 17 individuals (36.2%) reported experiencing symptoms of coughing or phlegm, which were the most frequently reported symptoms. None of the respondents reported chronic bronchitis. Cases of non-communicable diseases such as pneumonia, asthma, heart disease, and high blood pressure were rare, and only reported by one (2.1%), two (4.3%), two (4.3%), and six (12.8%) respondents, respectively. All respondents with pneumonia, asthma, or heart disease were landfill officers, while two informal workers (4.3%) reported high blood pressure.

Abidin et al. (2023) reported that most workers at the Piyungan dumpsite, Indonesia experienced symptoms of dust-related diseases, including coughing, headaches, eye irritation, difficulty breathing, and wheezing. However, in this study, most respondents reported no such symptoms.

Study contributions and limitations

This study provides comprehensive monitoring data for SO_2, NO_2, CO, CO_2, $PM_{2.5}$, Pb, H_2S, NH_3, and BTEX at a dumpsite in a developing country, which have not been previously available. As a preliminary study, it did not provide a deeper analysis of the temporal and spatial variations of pollutants in the dumpsite and its surrounding areas. Further research is encouraged to conduct monitoring campaigns in different seasons for comparison. For simple spatial interpolation based on the distance between sampling and prediction points, this study used IDW to estimate the spatial distribution of benzene, NO_2, and $PM_{2.5}$. With limited data, and hence high variance, using IDW was considered more suitable than other spatial interpolation methods such as Kriging. This is because Kriging depends

Table 5. Characteristics of respondents who were landfill workers, both formal and informal, who worked during the monitoring campaign

Variables	Total	
	Frequency, n	%
Gender		
Man	47	100
Woman	0	0
Age (years)		
20-30	15	31.91
31-40	18	38.3
41-50	14	29.79
>50	0	0
Length of work		
<10 years	24	51.06
10-20 years	23	48.94
>20 years	0	0
Smoking habit		
Yes	40	85.11
No	7	14.89
Number of cigarettes/day		
<5/day	4	8.51
5-10/day	9	19.15
10-20/day	26	55.32
Body weight - mean (SD)	60.99 (11.05) kg	
Height – mean (SD)	165.39 (6.43) cm	

Table 6. Self-reported diseases suffered by landfill workers

Disease	Frequency, n (%)	
	Yes	No
Cough	17 (36.17)	26 (55.32)
Sputum	17 (36.17)	28 (59.57)
Cough without phlegm	9 (19.15)	36 (76.6)
Wheezing	3 (6.38)	41 (87.23)
Chest pain	8 (17.02)	35 (74.47)
Bronchitis	3 (6.38)	33 (70.21)
Pneumonia	1 (2.13)	32 (68.09)
Chronic bronchitis	0 (0)	42 (89.36)
Emphysema	1 (2.13)	42 (89.36)
Asthma	2 (4.25)	41 (87.23)
Heart disease	2 (4.25)	41 (87.23)
High blood pressure	6 (12.77)	37 (78.72)

on a variogram that summarizes the variation in the data (Ebdon, 1996; Griffith, 1988). Therefore, it is unsuitable for data with high variation that exhibited in this study. To consider the effect of meteorological factors on pollutant dispersion, modeling can be performed using more robust tools such as AERMOD and Calpuff.

An improvement of the method used to characterize landfill workers is also recommended for future studies. Data on the health impacts of air pollution exposure were collected using self-report questionnaires, which are prone to bias. Future studies should include direct health performance measurements, such as lung function tests using spirometers (Tehrani et al., 2024), to better assess respondents' physiological conditions.

Finally, further research on landfill gas emission exposure risk assessment is necessary, especially given the elevated concentrations of benzene, ammonia, and $PM_{2.5}$ observed in this study. This knowledge is critical for determining the level of risk and implementing appropriate controls during landfill operations.

CONCLUSION

BTEX, SO_2, NO_2, CO, CO_2, $PM_{2.5}$, Pb, H_2S, and NH_3 were identified in the ambient air at the Sarimukti dumpsite area. BTX, H_2S, and NH_3 had the highest concentrations in the active zone during the morning (04:00–07:00). Among the pollutants, only H_2S showed a significant correlation with meteorological parameters, including temperature, relative humidity, wind speed, and atmospheric pressure. The findings of this study confirm the presence of BTX as a carcinogenic compound along with odor nuisance in dumpsites. All pollutant concentrations were below their respective thresholds, except for benzene, ammonia, and $PM_{2.5}$. Compared to landfills and dumpsites in other locations, Sarimukti dumpsite exhibited low concentrations of BTEX and H_2S but relatively high concentrations of SO_2, NO_2, and NH_3. The concentration of $PM_{2.5}$ at Sarimukti dumpsite was comparable to levels observed at other landfills and dumpsites in Nigeria, Iran, and Pakistan. The elevated levels of these pollutants were attributed to the composition of waste, which was predominantly food waste, the absence of daily soil cover, and high levels of heavy vehicle activity from garbage trucks and excavators. Despite the elevated pollutant concentrations observed during the study, most workers did not report any symptoms of illness.

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